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ABSTRACT

Objectives: To establish the magnitude of deficits in working memory (WM) and short-term memory (STM) in those with a moderate-to-severe traumatic brain injury (TBI) relative to age-matched, healthy controls, and to explore the moderating effects of time since injury and age at injury on these impairments. **Method:** Twenty-one studies that compared the WM and/or STM abilities of individuals with at least a moderate TBI relative to healthy controls were included in a random effects meta-analysis. Measures used to examine memory performance were categorized by modality (visuo-spatial, verbal) and memory system (WM, STM). **Results:** Individuals with TBI had significant deficits in verbal STM (Cohen's $d = .41$), visuo-spatial WM (Cohen's $d = .69$) and verbal WM (Cohen's $d = .37$) relative to controls. Greater decrements in verbal STM and verbal WM skills were associated with longer time post-injury. Larger deficits were observed in verbal WM abilities in individuals with older age at injury. **Conclusion:** Evidence for WM impairments following TBI is consistent with previous research. Larger verbal STM and verbal WM deficits were related to a longer time post-injury suggesting that these aspects of memory do not 'recover' over time and instead, individuals might show increased rates of cognitive decline. Age at injury was associated with the severity of verbal WM impairments with larger deficits evident for injuries that occurred later in life. Further research needs to chart the long-term effects of TBI on WM, and to compare the effects of injury on verbal relative to visuo-spatial memory.

Keywords: TBI, traumatic brain injury, working memory, cognition

INTRODUCTION

A traumatic brain injury (TBI) is a sudden non-progressive injury to the brain caused by an external force resulting in sustained neurological damage (e.g., road traffic accident, fall, violence/assault). It is a leading cause of death and disability in children and adults globally (e.g., Rutland-Brown, Langlois & Thomas, 2006; World Health Organisation, 2008). Each year there are approximately 2.5 million TBIs in the US (Faul, Xu, Wald, & Coronado, 2010) and around 200,000 in the UK (Health & Social Care Information Centre, 2010). The severity of TBI varies, with mild injuries making up around 80% of all cases (e.g., Kraus & Chu, 2005).

The regions of the brain most susceptible to damage in TBI are the frontal and temporal lobes and related neural pathways (e.g., Wallesch et al., 2001; Gale, Baxter, Roundy, & Johnson, 2005; Salmond, Chatfield, Menon, Pickard, & Sahakian, 2005). Reduced cortical metabolism can occur in the absence of structural abnormalities, particularly in the prefrontal cortex (PFC) and the anterior cingulate (e.g., Fontaine, Azouvi, Remy, Bussel, & Samson, 1999). The long-term prognosis following a mild TBI is relatively good (Carroll et al., 2004). Moderate-to-severe injuries, however, typically result in difficulties related to fronto-temporal dysfunction including emotional problems such as aggression, depression, and anxiety (e.g., Hibbard, Uysal, Kepler, Bogdany & Silver, 1998; Jorge, et al., 2004) and cognitive impairments in memory and attention (e.g., Vallet-Azouvi, Pradat-Diehl & Azouvi, 2012; Lezak, 1995).

One of the most pronounced of this sequelae is difficulties in working memory (WM; McHugh et al., 2008), the cognitive system used to simultaneously process and store information over the short-term. WM provides crucial support for the management and maintenance of goal-directed behaviour (e.g., Lehto, 1996; Curtis & D'Esposito, 2003), enabling us to carry out complex cognitive tasks such as reasoning and comprehension (e.g., Burgess, Gray, Conway & Braver, 2011; McVay & Kane, 2012). There are many alternative models of WM, but the most enduring is the multi-component model of Baddeley and Hitch (1974; Baddeley 2000; Baddeley, Allen, & Hitch,

2011). This consists of a central executive responsible for attentional control within and beyond WM and two specialized limited-capacity stores for verbal and visuo-spatial material (phonological loop and visuo-spatial sketchpad, respectively) with a multi-modal episodic buffer that integrates these representations (Baddeley, 2000). The capacity of the phonological loop and the visuo-spatial sketchpad are measured by short-term memory (STM) tasks that require the temporary storage of information. The central executive is measured by WM tasks that require both storage and processing, the latter of which is supported by the executive component. Thus the three main components of the Baddeley and Hitch model can be measured by assessments of verbal and visuo-spatial STM and verbal and visuo-spatial WM (e.g., Alloway, Gathercole & Pickering, 2006). The episodic buffer has so far proven difficult, if not impossible, to reliably measure (e.g., Nobre et al., 2013).

The WM impairments that are commonly reported in survivors of moderate-to-severe TBI (e.g., McDowell, Whyte & D'Esposito, 1997; Levin, et al., 2002; Perlstein, et al., 2004; Phillips, Parry, Mandalis, & Lah, 2015) are far from clearly understood due to the complex interacting cognitive and neural systems that contribute to WM task performance (e.g., Oberauer, 2012). Markedly distinct profiles of WM deficit have now been identified across a variety of developmental cognitive disorders (see Gathercole & Holmes, 2014 for a review), but because most studies of individuals with TBI have assessed only a subset of components of WM, the precise nature of deficits within the complex WM system is not as yet known.

The most consistent finding to date is that individuals with TBI show impairments in the central executive (e.g., Christodoulou, et al., 2001; Asloun, et al, 2008), the component of WM most strongly associated with PFC function (e.g., D'Esposito, et al., 1995; Goldman-Rakic, Cools & Srivastava, 1996). Many of these studies, however, include only verbal measures that either embed processing requirements within a storage task (e.g., backward recall that requires the immediate serial recall of items in reverse-order), or require stored items to be updated as in Paced Serial Order Addition and

n-back tasks. Very few studies have assessed both verbal and visuo-spatial WM abilities in TBI groups, relative to healthy controls, and there are mixed findings in those that have. For example, Vallet-Azouvi et al. (2007) report impairments in verbal but not visuo-spatial WM in adults with a severe TBI (see too Perbal et al., 2003). In contrast, others have observed a broader pattern of impairments in TBI that extends across both verbal and visuo-spatial WM (e.g., Moran & Gillon, 2004; Chapman, et al., 2006).

Similarly inconsistent results have been reported when the severity of STM and WM impairments are considered in moderate-to-severe TBI groups relative to healthy controls. While some studies report equivalent deficits in both STM and WM abilities (Leclercq, et al., 2000; Azouvi, et al., 2004; Gorman, et al., 2012; Carlozzi, Grech & Tulskey, 2013), others reveal greater decrements in WM than STM (Perbal et al., 2003; Moran & Gillon, 2004). In some cases, survivors of severe TBI are reported to have an impaired WM with an intact STM (e.g., Chapman et al., 2006). The selective or more pronounced impairments in WM could arise as a consequence of the additional processing demands of the WM tasks that are not present in STM tasks. Indeed, several studies have shown that survivors of TBI have pronounced difficulties in executive functioning (Levin & Hanten, 2005; Kurowski et al., 2013).

The reasons for the variability in findings across studies are unclear. One possibility is that the severity of TBI predicts WM ability, with more severe injuries leading to poorer performance (Hanten et al., 2003; Perlstein et al., 2004) while moderate injuries are associated with greater variability in performance (Perlstein et al., 2004). The age at which the TBI occurred might also predict WM ability. Little is known about whether age at injury substantially impacts on WM, especially in adults, but several studies with children have demonstrated poorer cognitive outcomes in those who are injured at a younger age (Anderson & Moore, 1995; Roncadin, Guger, Archibald, Barnes & Dennis, 2004). This is consistent with the process of neurocognitive stalling in which cognitive development is slowed following injury causing children to 'lag' behind their same-aged

peers (Chapman, 2006). Factors contributing to this might include limited opportunities for skill attainment before injury (due to age), difficulties developing or acquiring new skills, and the increased demands of new learning after injury to compensate for lost function and developing new ways of coping (Gamino, Chapman & Cook, 2009; Savage, 2005). Importantly, difficulties in executive processes such as WM often become most pronounced during adolescence when the disrupted maturation of the frontal lobes is most evident (Sowell, Thompson, Holmes, Jernigan & Toga, 1999; Teichner & Golden, 2000). It is not yet known whether an early age of injury disrupts the subsequent development of all cognitive processes to the same extent, though there is some evidence that aspects of WM might be differentially affected. For example, Gorman et al. (2012) found that verbal and visuo-spatial STM and verbal WM abilities were not influenced by age of injury in children, whereas visuo-spatial WM ability was.

Another potential moderator of WM performance following TBI is time elapsed since injury. In a review of acquired brain injury in children, Taylor and Alden (1997) concluded that cognitive impairments remained relatively constant or worsened over time (see too Brookshire, Chapman, Song & Levin, 2000). More recent research, however, suggests that time since injury might interact with the severity of the TBI. Levin et al. (2004) found that while verbal WM ability steadily improved in the first 24-months following injury for children with a mild-to-moderate TBI, children with more severe injuries only showed improvements in the first 12-months post-injury and then a deterioration in the subsequent 12-months. Studies of adults with TBI suggest an increased risk of dementia post-injury, with prodromal symptoms including cognitive decline in WM abilities (Gardner, et al., 2014; Godbolt et al., 2014). In combination, this suggests that both children and adults might experience reduced cognitive function over time post-injury.

The present study aimed to resolve some of the inconsistencies in the literature and to quantify the magnitude and nature of WM impairments in TBI. The primary goal of this meta-analysis was to examine whether child and adult survivors of TBI show a specific pattern of WM deficits related to

domain (verbal, visuo-spatial) or memory system (STM, WM) when compared to healthy, age-matched comparison groups. The influence of time since, and age at, injury on performance in each of these aspects of WM was also investigated. Due to the limited number of studies that have compared WM performance between TBI groups relative to healthy controls, especially children, a meta-analytical approach is essential as it allows for the aggregation of data across studies thus providing greater statistical power. It also allows for the detection of even the smallest relationships between variables and identifies meaningful patterns across as few as two studies (Valentine, Pigott & Rothstein, 2010).

METHOD

A literature search was carried out to identify articles relevant for this review (up to August 2015). Initially three electronic databases (Embase, Medline, and Psychinfo) were searched. The search terms used were: 'working memory' or 'WM' or 'short-term memory' or 'STM' or 'cognitive profile' and 'traumatic brain injur*' or 'TBI' or 'brain injur*'. The reference lists of any relevant articles identified were used to identify further articles and a citation search on author names was also conducted.

Inclusion criteria

The studies found were compared against our inclusion criteria. Articles were included if: they assessed WM or STM in individuals who had survived at least a moderate TBI (a list of the studies and how they classified TBI can be seen in Table 3, Appendix A), they compared performance against that of a healthy, age-matched comparison group (this criterion was chosen to enable any evidence of 'atypical' WM/STM profiles to be detected and to maintain a degree of homogeneity in the comparison groups), they were from peer reviewed journals and were available in English. In addition, some studies were excluded if the WM/ STM measure used was conflated with another cognitive measure (e.g., general executive functioning was assessed rather than WM or STM) or we were unable to extract means and standard deviations from the article even after contacting the

authors. Twenty-one studies met the inclusion criteria, the full references for each of these studies are included in the online supplemental materials (Appendix B).

Data abstraction

For each article included, the following variables were recorded: age of sample, size of sample, memory measures used, means and standard deviations for memory tasks, time since TBI, and age at TBI. In several cases either time since injury or age at injury were not reported, therefore, these were calculated (age at injury = age at assessment minus time since injury; time since injury = age at assessment minus age at injury). To assess the difference in scores between the TBI group and the healthy comparison group, effect sizes were calculated using Cohen's *d* (Cohen, 1988). For the purpose of analysis, information on the type of WM measure used was recorded and the measures were divided into the following memory categories: verbal STM, visuo-spatial STM, verbal WM and visuo-spatial WM according to the criteria defined by Baddeley (2000). In some cases authors used multiple measures to assess a single memory component; in this instance a mean of the effect sizes was calculated.

Categorisation

A full list of the measures used in each study can be found in the online supplemental material (Table 4, Appendix A).

Verbal STM. Ten studies were included for analysis. Vallat-Azouvi, et al. (2007) used three tasks to assess verbal STM, so twelve tasks are reported in total. Eleven of these were digit, letter, or word recall tasks that involved the participant repeating a series of aurally presented digits, letters, or numbers in serial order. The other measure required the immediate non-serial recall of a list of 15 words presented orally.

Visuo-spatial STM. Six studies met the criteria for inclusion in analysis. Five used spatial span tasks to measure visuo-spatial STM that require the repetition of a series of locations (usually on a

matrix) in serial order. The other study used a task that required the examinee to view a series of abstract symbols before having to select, in the same order as presented, the same symbols from a larger array.

Verbal WM. Seventeen studies that assessed verbal WM were identified with a variety of tasks used. Two studies each used three measures of verbal WM (Vallat-Azouvi, et al., 2007; Sanchez-Carrion et al., 2008) and another used two measures (Gorman, et al., 2012), so twenty-two tasks are reported in total. An n-back paradigm was used on seven occasions; in this task the participant was presented with a sequence of verbal stimuli (typically a letter), and had to then indicate when the current stimulus matched the one from n steps earlier in the sequence (all of these tasks were either 2- or 3-back tasks). Six studies used a backward digit recall measure that required the participant to respond to a series of auditory digits in the reverse order. Two studies used letter-number sequencing (the re-ordering of an initially un-ordered set of auditory presented letters and numbers) and two used paced auditory serial addition/running span tasks (a series of single digits are presented and the participant must add each new digit to the one presented prior to it). The other tasks used were a random number generation task (the generation of a random sequence of single digits with the sequence not including a prevalence of repetitions or adjacent number values), a dual-task digit span task (that required the remembering of digits in serial order while carrying out a tracing task) and a Brown-Peterson task (Brown, 1958) that necessitated the remembering of a series of consonants interspersed with mentally effortful interference to block verbal rehearsal (completing mental arithmetic calculations). Another study used a reading span task that required the participant to read aloud a series of unconnected sentences and then to recall the final word of each sentence; the participant could recall the words in any order they chose with the exception that the final word from the last sentence read could not be recalled first. The final measure was a listening span task requiring the serial repetition of the last word from a string of words presented in small blocks (e.g., if the words presented in the first block were “dog, lock, water” and then in the second block, “pill, wool, rice”, a correct response would be “water, rice”).

Visuo-spatial WM. Of the five studies included in the analysis, two used a backwards order spatial span task that required the remembering a series of locations in the reverse order. Another used a self-ordered ordered pointing task, where a different picture must be selected each time from a series of visual arrays, and another required the participant to remember a series of locations on a grid while making judgement decisions on the positions of the locations (i.e., if they were presented vertically, horizontally, or diagonally). In the final task, the examinee is shown two grids in sequence that contain blue and red circles before adding or subtracting the location of the circles on an empty grid based on a set of rules (e.g. If two blue circles appear in the same cell on the first two grids then they have to be subtracted from the array when responding on the empty grid).

Analysis

The meta-analyses were conducted using the Comprehensive Meta-Analysis program version 3 (Borenstein, Hedges, Higgins & Rothstein, 2005). Confidence intervals were calculated for the effect sizes, and heterogeneity was quantified using the I^2 statistic. A random effects model was chosen for all analyses due to the heterogeneity of the studies included.

Separate random-effects meta-regression analyses were used to assess the impact on memory of two potential moderator variables: time since TBI and age at TBI. As time since injury is likely to be confounded by age at injury and visa-versa (i.e., at time of assessment an earlier age at injury also leads to a longer time since injury), age at injury was covaried in the time since injury moderator analysis, and time since injury was covaried in the age at injury analysis. This enabled the contribution of each variable to be considered independently of the other. To investigate if the studies included were representative of the population of completed studies, publication bias was investigated using a series of Begg's funnel plots.

RESULTS

When duplicates were removed 752 articles were identified of which 226 were selected for preliminary review. Of the 226, 21 articles met the inclusion criteria and were included in the meta-analysis. Six of these studies were with children with TBI and the remaining 15 were with adult participants. Details of the studies included in this meta-analysis can be in Table 1, which includes sample sizes of the studies included, their effect sizes (d), time since injury (in months) and age at injury (in years).

TABLE 1 ABOUT HERE

Table 2 shows the results of the meta-analysis. The effect sizes shown are the difference between TBI groups and healthy comparison groups, with a positive effect size indicating that the scores for the healthy comparison group were higher than that of the TBI group. Effect sizes were interpreted as: $d=.20$ being a small effect, $d=.50$ a moderate effect and $d=.80$ a large effect (Cohen, 1988). Forest plots for each aspect of memory examined can be found in the online supplemental material (see Appendix C, Figures 1-4).

Results (Table 2) show that the healthy comparison groups performed significantly better than the TBI individuals on all memory measures, apart from visuo-spatial STM. For significant findings, effect sizes ranged from a small-moderate .37 to a moderate-large .69.

TABLE 2 ABOUT HERE

Publication bias

Begg's funnel plots (online supplemental material, Appendix D, Figures 5-8) showed publication bias in verbal WM only ($p<0.01$).

Moderator analyses

To explore whether time since injury and age at injury explained variance in effect sizes, these variables were examined in separate weighted meta-regression analyses.

Results showed that time since TBI (in months) explained a significant amount of the variance of verbal STM ($\beta = .005, p < .05$) and verbal WM ($\beta = .005, p < .01$). Larger effect sizes were associated with longer time since injury.

When age at TBI (in years) was examined, a significant amount of the variance of verbal WM ($\beta = .018, p < .05$) was accounted for, with effect sizes greater the older the age at injury.

Neither moderator variable explained variance in visuo-spatial STM or visuo-spatial WM.

DISCUSSION

This first meta-analysis of WM and STM impairments in adult and child survivors of moderate-to-severe TBI has produced three main findings. First, individuals with moderate-to-severe TBI are impaired in verbal STM and verbal and visuo-spatial WM compared to neurotypical controls, with no deficits in visuo-spatial STM. Second, time since injury predicts verbal STM and verbal WM abilities. In all cases, older injuries are associated with greater deficits. Third, age at injury predicts verbal WM performance, with more pronounced impairments observed in those injured at an older age. These findings will be discussed in turn.

Finding significant impairments in both visuo-spatial and verbal WM is indicative of a domain-general WM impairment and is consistent with a deficit in the central executive component of Baddeley and Hitch's WM model. This pattern of deficits can be explained by the prevalence of TBI affecting the PFC (e.g., Oni et al., 2010), a region of the brain associated with executive control (Duncan & Owens, 2000) that is activated in healthy brains during WM tasks (e.g., Clayton & D'Esposito, 2006). Deficits were also observed in verbal STM. This is consistent with previous reports

of specific impairments in verbal aspects of STM (i.e., phonological loop) in children following TBI (Anderson & Catroppa, 2005; Anderson, Catroppa, Rosenfeld, Haritou, & Morse, 2000; Raghubar, Barnes, Prasad, Johnson & Ewing-Cobb, 2013), which could arise from damage to parts of the ventral and dorsolateral PFC that support the storage of verbal information (Curtis & D'Esposito, 2003).

Visuo-spatial STM abilities (i.e., the visuo-spatial sketchpad of the Baddeley and Hitch model) were spared following TBI, possibly because the majority of visuo-spatial information storage occurs in posterior regions of the cortex (i.e., parietal and inferior temporal cortices) that are less often affected by TBI than prefrontal regions that are important for WM and verbal STM tasks (Curtis & D'Esposito, 2003). In this context, difficulties occurring in visuo-spatial WM in the absence of visuo-spatial STM deficits may arise due to the additional executive demands of WM tasks that rely on the same prefrontal areas of the brain that are most susceptible to damage. It should be noted that this interpretation is speculative as very few of the studies reported detailed analysis of the brain networks affected by the TBI.

Time since injury moderated the severity of deficits in verbal STM and verbal WM, with a longer period of time since injury associated with greater difficulties. This is consistent with previous studies showing that, particularly in the case of childhood TBI, some cognitive deficits increase over time. For example, perceptual skills have been reported to differ more than 16-years post-injury in young adults (Ryan et al., 2014). Similarly, Nadebaum, Anderson, and Catroppa (2007) found that five years after injury only children with severe TBIs still had executive difficulties with children with mild-to-moderate injuries returning to age-appropriate levels. Severe childhood TBI can result in deficits that a child 'grows into' over time and can lead to a negative cascade of effects on development (Anderson & Moore, 1995; Anderson et al., 2009; Mazzola & Adelson, 2002). By this account, a TBI can result in an individual failing to reach the appropriate cognitive milestones resulting in impairments that extend beyond those seen at the time of injury to later developmental time points.

Age at injury was associated with the extent of verbal WM impairments, with more pronounced deficits present when injuries occurred later in life. This provides support for the plasticity hypothesis (e.g., Huttenlocher & Dabholkar, 1997) that a younger age at injury is associated with better recovery due to neural plasticity and functional reorganization (see Kolb, 2013). It might also suggest that typical age-related decline in memory capacity in adults (e.g., Salthouse & Babcock, 1991) is exacerbated by a TBI, at least for verbal WM. Indeed it has been shown that TBI is a risk factor for the later development of neurodegenerative diseases such as Alzheimer's disease and dementia (see Jellinger, 2004; Van Den Heuvel, Thornton, & Vink, 2007, for reviews).

Before concluding, however, that these data are therefore inconsistent with the early vulnerability hypothesis of TBI (e.g., Anderson & Moore, 1995), which predicts poorer outcomes for individuals who are injured in childhood (e.g., Farmer, et al., 1999; Conklin, et al., 2008; Anderson et al., 2000; 2004), it is important to note that the scope of this meta-analysis is constrained by the studies available. All studies collected data at a single time-point, and in the absence of longitudinal data that tracks cognitive function across development it is not possible to draw strong conclusions about how cognitive impairments manifest over time (see Anderson et al., 2011). The analysis of age at injury is also confounded by the age of the participants at time of assessment in that individuals with older injuries were also older at the time of assessment (i.e., no studies examined WM/STM performance in adult survivors of childhood brain injury, or matched age at assessment despite differences in age at injury). Finally, the studies available were predominantly conducted with adult groups, which may have biased the results.

Limitations

This study included a comprehensive search of the literature, however, despite our requests to authors for unpublished studies this review is constrained by the use of published data only. This introduces the possibility of publication bias, which was indeed present in the category of verbal WM. Inclusion of unpublished data would likely have resulted in smaller effect sizes due to the

tendency against publishing research where the results are not statistically significant (Rosenthal, 1995; Rosenberg, 2005).

Other limitations include the under-representation in our analyses of both studies comparing visuo-spatial abilities between TBI survivors and healthy controls and studies investigating WM performance in children with TBI. This increases the chances of finding both false positives and false negatives. Related to this, well-validated and widely used measures were used across the studies to assess verbal memory (e.g., digit recall was used by 9 of the 11 studies examining verbal STM), yielding relatively consistent effect sizes. The assessment of visuo-spatial memory, however, was more variable. For example, 5 out of 6 studies assessed visuo-spatial STM using a well-validated task, spatial span, which yielded a small effect size. In contrast, the effect size for the single study employing a less established measure (symbol span) yielded a large effect size (see Table 4, Appendix A of supplemental material for a meta-analysis of the tasks included in this study). Future research will benefit from the consistent use of WM/STM tasks across studies improve the signal-to-noise ratio (McCauley et al., 2012).

To maintain a degree of homogeneity only studies using healthy comparison groups were included. Several studies were therefore excluded as their controls were individuals with orthopedic injury (e.g., Newsome et al., 2007; Schwartz et al., 2003; Raghubar et al., 2012). Although this choice of control group is common in TBI research as it provides a suitable control for nonspecific risk factors (e.g., pre-injury risk factors; Taylor, et al., 2002) we chose to include studies with healthy controls to enable us to quantify impairments in TBI survivors relative to individuals with 'typical' brain development.

A related complication is the general heterogeneity of TBI, which introduces between-participant variability. To minimize this, we only included studies with participants with moderate or severe TBI, however, it would have also been useful to include injury severity as a moderator variable, particularly as it may be related to memory ability (e.g., Perlstein, et al., 2004). This was not

possible, however, as very few studies reported mean injury severity data (e.g., Glasgow Coma Scale scores, see Table 5, appendix A). Finally, in the case of the adult studies, it is possible that the participants included were those still known to services (i.e., those with on-going difficulties). This potentially excludes those with good outcomes and may have negatively skewed the findings.

Conclusion

The outcomes of this meta-analysis clearly show that a moderate-to-severe TBI results in deficits in verbal and visuo-spatial WM and verbal STM abilities. In addition, the more time elapsed since injury and the older the age at which the injury occurred both have a potentially negative effect on WM. The clinical, educational, and vocational implications of these deficits in individuals with TBI is not yet well understood; however, the findings suggest that WM should be assessed in routine clinical practice in individuals following a TBI, and considered when developing an understanding of the individuals' everyday difficulties and developing plans for intervention (e.g., WM training; Lundqvist, Grundström, Samuelsson, & Rönnerberg, 2010; Hellgren, Samuelsson, Lundqvist, & Börso, 2015). Future research should focus on longitudinal studies of WM and STM following TBI in both children and adults, using common data elements, to further delineate the impact that time since injury and age at injury have on memory performance.

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