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The Effects of Pediatric Traumatic Brain Injury on Verbal and Visual-Spatial Working Memory

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Abstract

The purpose of this study was to investigate the effects of pediatric traumatic brain injury (TBI) on verbal and visual-spatial working memory (WM). WM tasks examined memory span through recall of the last item of a series of stimuli. Additionally, both verbal and visual-spatial tests had a dual-task condition assessing the effect of increasing demands on the central executive (CE). Inhibitory control processes in verbal WM were examined through intrusion errors. The TBI group ($n = 73$) performed more poorly on verbal and visual-spatial WM tasks than orthopedic-injured children ($n = 30$) and non-injured children ($n = 40$). All groups performed more poorly on the dual-task conditions, reflecting an effect of increasing CE load. This effect was not greater for the TBI group. There were no group differences in intrusion errors on the verbal WM task, suggesting that problems in WM experienced by children with TBI were not primarily due to difficulties in inhibitory control. Finally, injury-related characteristics, namely days to follow commands, accounted for significant variance in WM performance, after controlling for relevant demographic variables. Findings suggest that WM impairments in TBI are general rather than modality-specific and that severity indices measured over time are better predictors of WM performance than those taken at a single time point. (*JINS*, 2012, *18*, 29–38)

Keywords: Traumatic brain injury, Pediatric, Working memory, Inhibitory control, Dual-task, Outcome

INTRODUCTION

Working memory (WM) has been defined as the mental workspace in which task-relevant information is monitored, processed, and maintained to respond to immediate environmental demands (Baddeley & Logie, 1999). WM is presumed to be important for the operation of a range of higher cognitive and academic functions including discourse and reading comprehension, mathematics, complex learning, and reasoning (Daneman & Carpenter, 1980; Engle, 2002). The frontal lobes are implicated in WM (Clayton & D'Esposito, 2006; Collette & van der Linden, 2002; Goldman & Alexander, 1977; Loose, Kaufmann, Auer, & Lange, 2003), with functional neuroimaging studies showing activity of the dorsolateral prefrontal cortex and more posterior and inferior regions of frontal lobes during performance of WM tasks (Cohen et al., 1997). Given the high occurrence of frontal lobe injuries in traumatic brain injury (TBI) (Bigler, 1990; Levin et al., 1997; Oni et al., 2010; Wilde et al., 2005), WM is particularly vulnerable to the effects of TBI. TBI in childhood affects cognitive development in general (see Babikian & Asarnow, 2009, for a review), and also disrupts the development of WM (Levin et al., 2002, 2004; Newsome et al., 2008). Thus, a better understanding of how childhood TBI affects WM could have implications for understanding disruptions in the acquisition and development of several cognitive and academic skills in this population. The current study investigated verbal and visual-spatial WM in children with TBI, the effects of increasing central executive load on WM performance, and the role of inhibitory control processes in WM performance.

There are several models of WM (see Miyake & Shah, 1999 for a review); however, Baddeley's multi-component model (Baddeley, 1996) is often used in studies of typical and atypical WM development. This model comprises a central executive, or CE (responsible for selective attention, divided attention, switching of attention, and retrieval of information from long term memory), a phonological loop (a temporary storage system that briefly holds acoustic information unless refreshed by rehearsal), and a visuo-spatial sketchpad (analogous to the phonological loop, except that it maintains visual information). Because different components of WM

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are implicated in the processing of different types of information, these components may be related to performance on different cognitive and academic tasks. For example, verbal WM has been related to reading, reading comprehension, and some aspects of mathematics (reviewed in Swanson & Jerman, 2006; Swanson, Zheng, & Jerman, 2009), whereas visual-spatial WM has been related to particular aspects of mathematical learning (reviewed in Raghubar, Barnes, & Hecht, 2010).

Other models (e.g., Engle, 2002) equate WM with executive attention and propose that WM resources are determined by the ability to focus attention on relevant information and inhibit or ignore context-irrelevant information, referred to as inhibitory control. Intrusion errors, which reflect the recall of processed, but task-irrelevant information, are often used to assess inhibitory control processes in WM (Carretti, Cornoldi, De Beni, & Romano, 2005; Cornoldi et al., 2001; Cornoldi & Mammarella, 2006; De Beni & Palladino, 2000; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998; Palladino, Cornoldi, De Beni, & Pazzaglia, 2001; Pimperton & Nation, 2010).

Most of the research on WM in TBI has concerned verbal WM capacity and few studies have systematically investigated the integrity of the components of WM as specified in the multi-component and executive attention models. For example, little is known about the effects of pediatric TBI on visual-spatial WM, on the operation of the CE, and on the processes that operate within WM such as inhibitory control.

Many of the studies that investigate WM in TBI use N-back or digit span backwards tasks, which provide a single measure of WM – often verbal WM. Children with TBI are significantly more impaired on verbal WM tasks than typically developing comparison children (Conklin, Salorio, & Slomine, 2008; Hanten, Levin, & Song, 1999; Levin et al., 2002, 2004; Mandalis, Kinsella, Ong, & Anderson, 2007) with more severe injuries related to more severe verbal WM deficits (Levin et al., 2002, 2004; Roncadin, Guger, Archibald, Barnes, & Dennis, 2004). The current study tests whether pediatric TBI has similar effects on both verbal and visual-spatial WM.

Little is known about the effects of pediatric TBI on the CE. Mandalis et al. (2007) attributed WM errors to a CE deficit in switching attention. Roncadin et al. (2004) found that as item load increased, more severely head-injured children performed more poorly on a verbal WM task. However, as there was no control group, it is unknown whether increasing CE load particularly affects children with TBI. One way to examine the effects of TBI on the CE is to experimentally manipulate the degree of required CE processing by comparing WM performance under regular and dual-task conditions. A dual-task places an additional processing load on WM because it requires significant concurrent processing of information along with storage of information to be recalled at a later time. In the current study, verbal and visual-spatial WM performance was tested under both regular and dual-task conditions.

Because frontal lobes have been implicated in inhibitory control processes (Bell & Fox, 1992; Dempster, 1993; Diamond, 1991; Fuster, 1989; Luna et al., 2001; Luria, 1973; Milner, 1964) and inhibitory control is often impaired after pediatric TBI (Dennis, Guger, Roncadin, Barnes, & Schachar, 2001), it is possible that WM deficits in children with TBI are also related to problems in inhibitory processes. Therefore, consistent with numerous other studies (Carretti et al., 2005; Cornoldi et al., 2001; Cornoldi & Mammarella, 2006; De Beni & Palladino, 2000; De Beni et al., 1998; Palladino et al., 2001; Pimperton & Nation, 2010) we investigated inhibitory control processes in verbal WM as indexed by intrusion errors.

Injury-related variables affect a range of neurocognitive outcomes after childhood TBI. Injury severity predicts deficits in verbal WM after TBI in children (Levin et al., 2002, 2004; Roncadin et al., 2004). In particular, studies have found that duration of impaired consciousness is more strongly related to some outcomes than are measures taken at a single point in time such as the Glasgow Coma Scale (Leblanc et al., 2005; Massagli et al., 1996; McDonald et al., 1994; Teasdale & Jennett, 1974). This may be because duration of impaired consciousness more directly reflects impaired cerebral functioning, which may be the best predictor of more enduring cognitive impairments. However, the relation of duration of impaired consciousness to deficits in visual-spatial WM, inhibitory control, and the CE has not been studied. Furthermore, a younger age at injury has been related to greater deficits in neurocognitive functions such as attention, expressive language, and reading (Anderson & Moore, 1995; Anderson, Morse, Catroppa, Haritou, & Rosenfeld, 2004; Barnes, Dennis, & Wilkinson, 1999; Ewing-Cobbs et al., 1998; Taylor & Alden, 1997). However, little is known about whether age at injury affects WM (but see Roncadin et al., 2004). It has also been suggested (Taylor & Alden, 1997) that time since injury predicts performance on neurocognitive tasks, including verbal WM (Levin et al., 2004). However, it is not clear whether both age at injury and time since injury predict verbal or visual-spatial WM performance.

This study examined performance on verbal and visual-spatial WM tasks with and without dual-task components closely matched in their processing and response requirements in children with pediatric TBI compared to children with orthopedic injury, and children without injury. We hypothesized that: (1) The TBI group would perform more poorly than both comparison groups on both verbal and visual-spatial WM and dual-tasks; (2) All three groups would perform more poorly under dual-task conditions, but that dual-task performance would be negatively impacted to a greater extent for the TBI group; (3) Children in the TBI group would have a higher number of intrusion errors on the verbal WM dual-task, reflecting inhibitory dyscontrol, than children in the comparison groups; and (4) Injury-related variables would predict WM performance even after accounting for relevant demographic variables such as age at test and socioeconomic status.

METHOD

Participants

Participants included 73 children who sustained TBI, 30 children with orthopedic injuries, and 40 non-injured comparison children. Children in the TBI group were injured between the ages of 1 and 16 years, and evaluated between approximately 2 and 12 years post-injury. Age at test ranged from 6 to 18 years. Children were recruited from two cohorts of participants: a long-term follow-up cohort who were injured and enrolled in previous projects from 1994 to 1998 and a prospective cohort injured from 2004 to 2007. Inclusionary criteria for children in the TBI group were as follows: (1) TBI resulting from acceleration-deceleration or blunt impact injuries caused by vehicular accidents, falls, or impact with a blunt object; (2) moderate and severe TBI, defined as the lowest post-resuscitation GCS score of 3–12, and complicated mild TBI defined as the lowest post-resuscitation GCS score of 13–15, with neuroimaging evidence of parenchymal injury; (3) skeletal or body Abbreviated Injury Score ≤ 2 in children with complicated mild or moderate TBI to minimize any confounding influence of severe orthopedic injury on accurate assessment of GCS scores and outcome; and (4) bilingual or primarily English-speaking.

Exclusionary criteria for the TBI group were as follows: (1) children with injury mechanisms occurring with low frequency that have differing outcomes than acceleration/deceleration injuries (e.g., penetrating brain injuries); (2) children of illegal immigrants and families residing outside the catchment area due to difficulty maintaining enrollment; and (3) children with major developmental or psychiatric disorders, including mental retardation and pervasive developmental disorders. Exclusionary criteria were determined with a brief questionnaire administered to parents. Exclusionary criteria 2 and 3 were also applied to the comparison groups, as was the additional criterion of no previous head or facial injuries.

Children in the TBI group were recruited from the Level 1 Pediatric Trauma Center at Children's Memorial Hermann Hospital in Houston, Texas. After determining that the child met the inclusion criteria, informed written consent was obtained from the child's guardian. In accordance with guidelines established by the Institutional Review Board at the University of Texas Health Science Center at Houston, oral assent was obtained from children 6 years of age, written assent was obtained from children ages 7–11, and written adolescent consent was obtained for participants ages 12–18. From the original cohort of 75 children injured and enrolled in previous projects between 1994 and 1998, 34 were contacted and elected to participate in the study. Four children who sustained non-accidental trauma were excluded from the present analyses, leaving 30 participants. For the cohort injured from 2004 to 2007, 348 individuals were screened in the emergency room. Of those individuals, 259 did not meet the inclusion criteria. Of the remaining 89 patients with TBI that were eligible for the study, 17 were not contacted before discharge and 16 did not want to participate. Of the 56 patients who were enrolled in the study, 13 did not complete some or all of the neuropsychological testing at the evaluation. Therefore, a total of 73 children with TBI were included in the final sample.

The two comparison groups were composed of 30 children who sustained orthopedic injuries with no head or facial injuries and 40 non-injured children recruited from the community. Children in the orthopedic group were recruited from the Level 1 Pediatric Trauma Center at Children's Memorial Hermann Hospital in Houston, Texas between 2004 and 2007. Three hundred thirty-eight individuals were screened in the emergency room, and 194 did not meet the inclusion criteria. Of the 144 eligible children, 46 elected not to participate and 63 were not contacted before discharge. Of the 35 children enrolled, five did not complete some or all of the neuropsychological testing. Forty community comparison children without head or orthopedic injuries were recruited via fliers posted at libraries and at Women, Infants, and Children programs at the University of Texas Medical School at Houston. Children with orthopedic injuries were evaluated at least 2 years post-injury. Informed consent for comparison groups was obtained in the same manner as the TBI group. The two comparison groups differed significantly on one of the WM measures; consequently, we decided to use a two control group design.

Descriptive statistics for the three groups are presented in Table 1. The group difference in age at testing was not significant ($F(2,140) = 2.42$; $p = .09$) but was included as a covariate because the measures of interest in this study are not age-standardized. There was a significant difference in SES between groups ($F(2,140) = 6.62$; $p < .01$), with the TBI group having the lowest SES, followed by orthopedic injured children. Thus, SES was covaried in all analyses. IQ was estimated using the Vocabulary and Matrix Reasoning subtests of the WASI (Wechsler, 1999). Univariate analysis of variance revealed a significant group difference on IQ ($F(2,140) = 12.88$; $p < .01$), with contrasts revealing a significant difference between the TBI group and a combination of the two comparison groups, but no significant differences between the two comparison groups. The correlation between SES and IQ was significant ($r = 0.49$; $p < .01$). An IQ difference between TBI groups and comparison groups is a common finding in the pediatric TBI literature (Jaffe et al., 1992). However, IQ was not covaried because it does not meet the requirements for a covariate when applied to an acquired injury (Dennis et al., 2009). Injury-related variables for the TBI group and the orthopedic group are also provided in Table 1. Children with GCS scores of 13–15 had parenchymal findings on CT scans, and were classified as complicated mild TBI. The duration of impaired consciousness was determined as the number of days the GCS motor scale score was below 6, and will be referred to as days to follow commands (DFC).

Measures and Procedures

Category listening span task (CLS)

The CLS assesses verbal WM. It was developed by De Beni et al. (1998), based on Daneman and Carpenter (1980) and adapted and translated into English for this study. The CLS is composed of five levels of one, two, three, four, or five strings of three words with the number of word strings

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Table 1. Demographic and injury-related variables for TBI and comparison groups

Demographic variables	TBI ($n = 73$) Mean (*SD*) Range	Orthopedic ($n = 30$) Mean (*SD*) Range	Non-injured ($n = 40$) Mean (*SD*) Range
Age at test (years)	13.41 (3.23)	12.48 (2.82)	12.08 (3.53)
	6.58–18.92	8.58–17.67	6.58–18.67
SES	38.27 (13.19)*	41.02 (14.60)*	47.90 (13.19)*
	8–63	20–66	8–66
IQ	98.30 (16.60)*	108.13 (13.50)*	112.83 (13.68)*
	57–138	83–140	83–140
Vocabulary T-score	47.50 (13.35)	54.13 (9.98)	57.00 (10.84)
	20–69	33–72	34–74
Matrix Reasoning T-score	47.97 (8.50)	54.90 (7.32)	57.33 (7.47)
	28–63	34–74	43–75
Injury-related variables			
Age at injury (years)	9.72 (3.86)	10.41 (2.78)	
	1.42–16.00	6.5–15.58	
Years since injury	3.73 (2.81)	2.02 (0.12)	
	1.92–12.17	1.92–2.42	
Lowest GCS score			
13–15	5**	—	
9–12	15**	—	
3–8	53**	—	
Days to follow commands	6.14 (9.55)	—	
	0–41		

Note. *$p < .01$.
**Total number of participants in the severity group.

corresponding to a particular WM span. Each level consists of two trials, for a total of 10 trials. The child is asked to recall the last word in each string, in order, at the end of the trial. For example, in a two-span trial, the examiner might say "pill, lock, water" then say the next word string "chin, wool, rice." A correctly performed trial at a span of two would be to recall "water" and "rice" in that order. A ceiling was established when both trials at a level were incorrect. The basal was established as the lowest level at which both trials were correct. Percent accuracy was computed (number of trials correct, divided by 10, which is the total number of possible correct trials) because we compared performance on the CLS with performance on the CLS dual-task, which had a different number of possible trials (discussed below).

Category listening span dual-task (CLS-DT)

The CLS-DT is a measure of verbal WM with a dual-task component, which increases CE load. The CLS-DT is structured similarly to the CLS and is composed of five levels of one, two, three, four, or five strings of three words. Each level consists of four trials, for a total of 20 possible trials. In addition to recalling the last word in each string at the end of the trial, the child must tap the table at the end of each string if an animal name is said. Testing was discontinued when the child missed two or more trials at a given level. The basal was the lowest level at which three or four trials were correct. Percent accuracy was computed (number of trials correct divided by 20) to compare CLS and CLS-DT scores. One child from each group was eliminated from analyses because they did not complete the dual-task processing requirements (e.g., either tapped for all trials or did not tap for any trials).

Visuospatial span (VSS; Cornoldi et al., 2001*)*

Because the VSS was created with the same processing demands as the CLS, it allows for a more direct comparison of verbal and visual-spatial WM than often occurs in studies comparing these two modalities of WM. The experimenter touches three contiguous positions in a four by four matrix of small square blocks. VSS is composed of five levels of one, two, three, four, or five strings of three blocks, with the number of strings corresponding to a particular WM span. Each level consists of two trials, for a total of 10 trials. The child recalls the location of the last block touched in each string, in order, at the end of each trial. The same basal and ceiling rules from the CLS were applied to the VSS. Percent accuracy was measured as the number of correct trials divided by 10.

Visuospatial span dual-task (VSS-DT)

For the VSS-DT, in addition to recalling the last blocks tapped in each string, the child is asked to tap the table if the positions are in a linear pattern (horizontal, vertical, or diagonal). The task is composed of five levels of one, two, three, four, or five string series or memory spans, with four trials per level for

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a total of 20 trials. The same basal and ceiling rules from the CLS-DT were applied to the VSS-DT. Percent accuracy was computed as the total number of trials correct, divided by 20. Two children in the TBI group did not tap appropriately and were eliminated from analyses.

Intrusion error measurement. Intrusion errors were calculated as the number of non-final words that were incorrectly recalled from either the same trial, or previous trials of the CLS-DT, divided by the total number of opportunities the participant had to make an intrusion error. The advantage of calculating a percentage score for intrusion errors is that it accounts for differences in WM span. Intrusion errors were not obtained for the VSS-DT.

Procedure. Participants were examined individually at the University of Texas Health Science Center at Houston, as part of a study investigating academic outcomes in children following TBI. As part of a 4-hr battery, CLS and VSS were administered in the same order toward the middle of the battery, but were not administered successively.

Overview of statistical analyses

A 3 group (TBI *vs.* Orthopedic *vs.* Non-injured) × 2 material (verbal *vs.* visual-spatial) × 2 task type (WM *vs.* dual-task WM) repeated measures analysis of covariance (ANCOVA) was performed on the percentage of correctly answered trials, covarying age at test and SES, to investigate the effect of group on verbal and visual-spatial WM under lower and higher CE demands.

To determine whether there were group differences on the percentage of intrusion errors, a 3 group (TBI *vs.* Orthopedic *vs.* Non-injured) ANCOVA was performed on the percentage of intrusion errors, covarying for SES. Age at test was not covaried because developmental differences in WM span were addressed by using the percentage score previously discussed.

Lastly, hierarchical regression analyses were performed to determine whether injury-related variables predicted variance in performance on CLS, CLS-DT, VSS, VSS-DT, and CLS-DT intrusion errors over and above that predicted by demographic variables for the TBI group. We were interested in examining both age at injury and time since injury. However, in a cross-sectional design, time since injury is confounded by its linear dependence on age at test and age at injury (i.e., it is equal to the difference of the two). Therefore, we elected to examine the impact of age at injury. Age at injury correlated significantly with age at test ($r = .73$; $p < .01$) and time since injury ($r = -.66$; $p < .01$); time since injury and age at test were not significantly related ($r = .04$; $p > .1$).

In the hierarchical model, the first step included demographic predictors (age at test and SES). The second step included DFC and age at injury. Partial F tests were calculated to determine the significance of the change in R^2 for the regression including demographic variables only, and that including demographic variables and injury-related characteristics. *T*-values determined which unique predictors contributed to the variance. Because the CLS-DT intrusion error distribution is positively skewed, a generalized linear model with a Poisson distribution and log link function was used for this regression.

RESULTS

Working Memory Accuracy

The effect of group membership on accuracy was significant ($F(2,138) = 8.12$; $p < .01$, $\eta_p^2 = .12$). Planned contrasts were run comparing the TBI group to both comparison groups, and comparing the orthopedic group to the non-injured group. There were significant differences between the TBI group and the comparison groups on the CLS, VSS, and VSS-DT measures, with the TBI group performing more poorly on these measures. However, there was not a significant difference between the TBI and comparison groups on the CLS-DT, while the difference between the orthopedic group and non-injured group on CLS-DT was significant. However, no interactions in the ANCOVA were significant, suggesting that these group differences did not depend on material or task. A significant effect of task was found, with all groups performing more poorly on the dual-task ($F(2,138) = 13.52$; $p < .01$; $\eta_p^2 = .09$). Overall, there were no systematic differences in performance between the orthopedic and non-injured comparison groups. Both raw and least squares means and standard deviations of the percentage of correct responses by group are presented in Table 2.

Intrusion Errors

There was no effect of group. Raw and least squares means and standard deviations are presented in Table 2.

Injury-Related Factors and Working Memory

Hierarchical regression analyses examined the relation of demographic and injury-related variables for the TBI group on the four WM tasks and intrusion errors of the CLS-DT. Table 3 displays the *t*-values of the predictors and the R^2 and change in R^2 values.

CLS

In the first step of the hierarchical regression analysis, the demographic characteristics were significant predictors of CLS performance ($F(2,70) = 24.31$; $p < .01$; $R^2 = .41$), with both age at test and SES being significant unique predictors. In the second step, injury-related variables accounted for significant additional variance (*Partial* $F(2,68) = 3.33$; $p < .01$; R^2 change = .05), with DFC as the only significant unique predictor.

CLS-DT

Demographic variables were significant predictors of CLS-DT performance ($F(2,70) = 33.85$; $p < .01$; $R^2 = .49$), with both age at test and SES being significant unique predictors.

Table 2. Total correct percentages for the category listening span (CLS) tasks and visuospatial span (VSS) tasks for TBI and comparison groups

	TBI ($n = 73$) Raw mean (*SD*) Least squares mean	Orthopedic ($n = 30$) Raw mean (*SD*) Least squares mean	Non-Injured ($n = 40$) Raw mean (*SD*) Least squares mean
CLS % correct	62.5 (19.4)	70.3 (13.3)	66.5 (17.8)
	62.3	71.4	66.0
CLS-DT % correct	54.8 (24.7)	64.2 (20.3)	51.7 (21.4)
	54.3	65.7	51.6
% of CLS-DT intrusion errors	8.5 (9.7)	5.6 (7.2)	7.9 (6.2)
	8.1	5.6	8.8
VSS % correct	65.1 (20.4)	73.3 (18.1)	66.8 (19.3)
	64.0	74.6	67.7
VSS-DT % correct	60.5 (22.7)	69.0 (19.5)	64.6 (20.9)
	59.3	70.6	65.5

Injury-related characteristics were significant predictors of CLS-DT performance (*Partial* $F(2,68) = 4.31$; $p < .01$; R^2 *change* = .06), with only DFC being a significant unique predictor.

VSS

Demographic variables accounted for significant variance in VSS performance ($F(2,70) = 20.38$; $p < .01$; $R^2 = .37$), but only age at test was a significant unique predictor. The addition of injury-related characteristics was not significant.

VSS-DT

Demographic variables accounted for significant variance in VSS-DT performance ($F(2,70) = 45.45$; $p < .01$; $R^2 = .56$), with both age at test and SES providing unique variance. Injury-related variables were significant predictors of VSS-DT performance (*Partial* $F(2,68) = 7.63$; $p < .01$; R^2 *change* = .08), with both DFC and age at injury providing unique variance. Less favorable performance was associated with a greater number of days to follow commands and younger age at injury.

Table 3. Hierarchical regression models of demographic and injury-related variables

	Step 1		Step 2	
Working memory measure	Predictors	R^2	Predictors	R^2 Change
CLS	AT: 5.30**	0.41**	AT: 3.56**	0.05**
	SES: 3.50**		SES: 11.05**	
			AI: 0.56	
			DFC: −2.57*	
CLS-DT	AT: 6.32**	0.49**	AT: 4.82**	0.06**
	SES: 4.04**		SES: 4.00**	
			AI: −0.07	
			DFC: −2.89	
CLS-DT Intrusions	AT: 6.03*		AT: 3.25	
	SES: 1.93		SES: 1.69	
			AI: 0.03	
			DFC: 6.42*	
VSS	AT: 5.72**	0.37**	AT: 3.32**	.01
	SES: 1.76		SES: 1.53	
			AI: 0.99	
			DFC: −0.72	
VSS-DT	AT: 7.67**	0.56**	AT: 4.52**	.08**
	SES: 4.18**		SES: 3.97**	
			AI: 2.11*	
			DFC: −3.50**	

Note. Chi-square values are presented for CLS-DT Intrusions, *$p < .05$, **$p < .01$.
AT = age at testing; SES = socioeconomic status; AI = age at injury, DFC = days to follow commands.

Intrusion Errors

The same predictor variables were entered into a hierarchical regression predicting percentage of intrusion errors for the CLS-DT. A generalized linear model with a Poisson distribution and a log link function was used. Demographic variables accounted for significant variance ($\chi^2(2) = 9.35$; $p < .01$) with only age at test providing unique variance ($\chi^2(1) = 5.92$; $p < .05$). Injury-related variables were significant predictors of intrusion errors ($\chi^2(2) = 19.87$; $p < .01$), with only DFC accounting for unique variance ($\chi^2(1) = 5.66$; $p < .05$).

DISCUSSION

Difficulties in WM after pediatric TBI could arise for several reasons having to do with the type of material to-be-remembered, the status of different aspects of WM such as the CE and inhibitory processes, and injury-related variables such as DFC and age at injury. All of these were investigated in the current study of WM comparing children with TBI to children with orthopedic injuries and non-injured children. We found that TBI reduced both verbal and visual-spatial WM to a similar extent. Increases in CE load did not differentially affect children with TBI. Difficulties in inhibitory control, as measured by intrusion errors in recall, did not distinguish the groups and did not account for the group differences in WM performance. Lastly, we found that injury-related characteristics, particularly DFC, predicted WM performance, even after controlling for relevant demographic variables.

Consistent with our hypotheses and with findings from other studies (Conklin et al., 2008; Levin et al., 2002, 2004; Roncadin et al., 2004) children with TBI recalled fewer items on WM tasks than did typically developing children. A unique contribution of this study is the finding that TBI affected verbal and visual-spatial WM to similar extents, suggesting that TBI does not have domain-specific effects on WM. TBI likely affects verbal and visual-spatial WM similarly because of what both types of WM have in common rather than because of what differentiates them; that is, both require concurrent storage and manipulation of information, which draws on similar CE processes (Gathercole, Pickering, Ambridge, & Wearing, 2004).

Increasing the load of the CE in the dual-task conditions affected recall for all children. Contrary to our predictions, the effect of increasing CE processing was not relatively greater for the TBI group. Because the only other pediatric TBI study to have varied CE load did not include a comparison group (Roncadin et al., 2004) possible differential effects of CE load on recall for children with TBI compared to children without head injury could not be determined. Our findings are similar to those of Vallat-Azouvi, Weber, Legrand, and Azouvi, (2007) who studied verbal and visual-spatial span in adults with TBI and a comparison group under both regular recall and dual-task conditions. TBI affected both verbal and visual-spatial memory span, but the TBI group was not differentially affected by the dual-task. Although the effects of TBI (severity, location, and extent of frontal injury) on the CE have not been thoroughly studied, the present findings combined with those from Vallat-Azouvi et al. (2007) suggest that declines in WM performance may reflect a more general deficit in WM, rather than a specific CE deficit following TBI.

What accounts for the lower WM span after TBI? Based on some models of WM, deficits in WM can arise from problems in either attentional focus or inhibitory control (Engle, 2002). Given that inhibitory control processes have been related to prefrontal cortex and anterior cingulate functioning (Posner, Rothbart, Sheese, & Tang, 2007), and that these areas of the brain are also frequently damaged by TBI (Oni et al., 2010; Wilde et al., 2005, 2010), we hypothesized that WM difficulties in TBI would reflect problems in inhibitory control as assessed by intrusion errors. We did not find support for this hypothesis. Intrusion errors, which consisted of recalling a word that was not one of the last words spoken in either the same or a previous trial, were comparable across groups. Rather, the lower WM span in the TBI group was related to recall of fewer target words than the comparison groups. Therefore, it is possible that children with TBI had more difficulty encoding the to-be-recalled last words in the word strings, possibly reflecting difficulties in attentional focus processes in WM, rather than in inhibitory control processes. However, because difficulties in inhibitory control after pediatric TBI have been reported for phonological WM (e.g., false alarm errors on phonological N-back tasks, Levin et al., 2002) and attention (Dennis et al., 2001; Konrad, Gauggel, Manz, & Scholl, 2000a, 2000b; Leblanc et al., 2005), it is also possible that intrusion errors do not always provide a sensitive measure of inhibitory control processes in WM. Future studies might address this issue by systematically varying the degree of phonological or semantic similarity between target and non-target items to determine the conditions under which TBI is associated with difficulties in inhibitory processes in WM.

As expected, injury-related characteristics predicted both verbal and visual-spatial WM, even after controlling for demographic variables. However, these variables accounted for a modest amount of variance in WM outcomes. The single strongest and most consistent unique predictor was DFC. This finding is consistent with studies that have found that indices of severity that are measured over time, are more strongly related to some outcomes than are measures taken at a single point in time (Leblanc, et al., 2005; Massagli et al., 1996; McDonald et al., 1994). More direct quantitative measures that capture the location and extent of brain injury would be useful for better specifying the relation of TBI to WM deficits.

Age at injury only accounted for unique variance for visual-spatial recall in the dual-task condition. Younger age at injury was associated with lower WM span, even after accounting for age at testing. With regard to age at injury, Roncadin et al. (2004) found that age at injury was related to verbal WM, but only for children with moderate TBI. The reason for these variable findings is not entirely clear. In both studies, age at injury was treated as a continuous variable. Because cognitive skills and areas of brain undergoing active development at the time of injury are thought to be more susceptible to disruption than already established abilities and their neural substrates (Dennis, 1988; Ewing-Cobbs, Miner, Fletcher, & Levin, 1989; Taylor & Alden, 1997), it is possible that age at injury affects WM within particular developmental time windows rather than across the developmental continuum. Research on the typical development of WM has identified significant development of WM before age 6 (Alloway, Gathercole, & Pickering, 2006; Garon, Bryson, & Smith, 2008; Gathercole et al., 2004; Nichelli, Bulgheroni, & Riva, 2001) and developmental changes in maintenance and manipulation of information in school-aged children and adolescents (Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006). Information on the developmental trajectory of WM, in conjunction with developmental studies of core neural substrates such as dorsolateral and ventromedial prefrontal and superior parietal cortices (Crone et al., 2006; Gogtay et al., 2004; Huttenlocher, 1990; Mrzlijak, Uylings, van Eden, & Judas, 1990) might be used to determine theoretically derived units of analysis for subsequent studies of age at injury in relation to WM.

There are limitations to the present study. The groups were not comparable in terms of key demographic variables. The mean IQ of our TBI and orthopedic control groups was average, while our non-injured group's mean IQ was above average. If IQ scores of all groups were comparable, it is possible that the WM performance of non-injured participants would have more closely resembled that of the TBI group. SES was also higher in the comparison group. Using ANCOVA, we controlled for the effects of SES on WM scores. Given the significant correlation between IQ and SES ($r = 0.49$), this approach likely also secondarily reduced the impact of IQ on WM scores. Another limitation is that our sample was cross-sectional and examined children with chronic injuries. The results of Levin et al. (2004) suggest that there may indeed be a differential effect of injury severity over time, with severely injured children demonstrating declines in WM performance between 12 months and 24 months post-injury, which may be related to arrested development and disrupted myelination that varies by time since injury (Ewing-Cobbs et al., 2008). Future studies should examine WM performance longitudinally using growth curve models to examine whether performance patterns change over time in children with different demographic and injury characteristics. Future studies might also use functional or structural neuroimaging techniques to characterize the integrity, activation, and connectivity of networks supporting WM, and provide information on how these networks are disrupted by pediatric TBI.

To the extent that both verbal and visual-spatial WM have been implicated in academic tasks such as reading comprehension and various aspects of mathematics (reviews in Raghubar et al., 2010; Swanson & Jerman, 2006; Swanson et al., 2009), the findings suggest that one potential source of difficulties in academic skills in children with TBI are impairments in WM. We have argued elsewhere (Barnes, Fuchs, & Ewing-Cobbs, 2010) that academic difficulties of children with TBI may be related to impairments in domain general neuropsychological abilities such as attention and memory rather than to specific disabilities in reading or mathematics. Studies that investigate the possible contribution of domain-general cognitive abilities such as WM to difficulties in school experienced by children with TBI could have practical significance for understanding their academic functioning and for determining potential targets for intervention (Holmes, Gathercole, & Dunning, 2009).

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