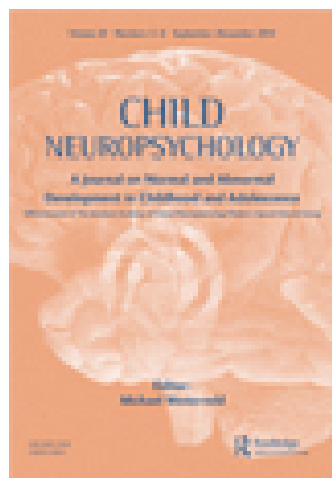


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## Child Neuropsychology: A Journal on Normal and Abnormal Development in Childhood and Adolescence

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/ncny20>

### The effect of age-at-testing on verbal memory among children following severe traumatic brain injury

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Published online: 08 May 2015.

To cite this article: Tamar Silberg, Jaana Ahonniska-Assa, Miriam Levav, Roni Eliyahu, Tamar Peleg-Pilowsky, Amichai Brezner & Eli Vakil (2015): The effect of age-at-testing on verbal memory among children following severe traumatic brain injury, *Child Neuropsychology: A Journal on Normal and Abnormal Development in Childhood and Adolescence*, DOI: [10.1080/09297049.2015.1028348](https://doi.org/10.1080/09297049.2015.1028348)

To link to this article: <http://dx.doi.org/10.1080/09297049.2015.1028348>

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## The effect of age-at-testing on verbal memory among children following severe traumatic brain injury

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Memory deficits are a common sequelae following childhood traumatic brain injury (TBI), which often have serious implications on age-related academic skills. The current study examined verbal memory performance using the Rey Auditory Verbal Learning Test (RAVLT) in a pediatric TBI sample. Verbal memory abilities as well as the effect of age at-testing on performance were examined. A sample of 67 children following severe TBI (age average =  $12.3 \pm 2.74$ ) and 67 matched controls were evaluated using the RAVLT. Age effect at assessment was examined using two age groups: above and below 12 years of age during evaluation. Differences between groups were examined via the 9 RAVLT learning trials and the 7 composite scores conducted out of them. Children following TBI recalled significantly less words than controls on all RAVLT trials and had significantly lower scores on all composite scores. However, all of these scores fell within the low average range. Further analysis revealed significantly lower than average performance among the older children (above 12 years), while scores of the younger children following TBI fell within average limits. To conclude, verbal memory deficits among children following severe TBI demonstrate an age-at-testing effect with more prominent problems occurring above 12 years at the time of evaluation. Yet, age-appropriate performance among children below 12 years of age may not accurately describe memory abilities at younger ages following TBI. It is therefore recommended that clinicians address child's age at testing and avoid using a single test as an indicator of verbal memory functioning post TBI.

**Keywords:** Verbal memory; Rey Auditory Verbal Learning Test (RAVLT); Pediatric TBI; Age effect.

Memory problems have been described as one of the most impaired cognitive domains following pediatric traumatic brain injuries (TBI; Anderson, Catroppa, Morse, & Haritou, 1999; Catroppa & Anderson, 2007; Kinsella et al., 1997; Schroder, 2005; Yeates, 2000). It

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We wish to thank all of our colleagues and students in the Neuropsychological Assessment Unit, Department of Pediatric Rehabilitation, Edmond and Lily Safra Children's Hospital, who contributed to this study and especially, Ariela Eilam, PhD, Talma Peretz, MA, Judy Tahir, MA, and Shay Frank, MA. We would also like to thank the research assistant Adi Zakay, MA, for her help with the data entry. We are very grateful to Efrat Shadmi, PhD, for her valuable comments on the manuscript.

No potential conflict of interest was reported by the author(s).

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has also been well documented that memory problems significantly affect children's ability to learn and retain new information, which is essential for success upon their return to school (Lajiness-O'Neill, Erdodi, & Bigler, 2010). More specifically, the level of memory impairment has been reported to be related to the level of injury severity, placing children following severe TBI at high risk for problems in the acquisition of new academic skills (Fay et al., 1994; Jaffe et al., 1992).

Age at injury has been one of the most documented factors related to general cognitive outcome (Anderson, Catroppa, Morse, Haritou, & Rosenfeld, 2000; Anderson & Moore, 1995; Dennis, Barnes, Donnelly, Wilkinson, & Humphreys, 1996) and also to the severity of memory impairments among pediatric brain injury patients (Anderson, Catroppa, Morse, Haritou, & Rosenfeld, 2005; Lajiness-O'Neill et al., 2010). Children injured prior to school age seem to make a slower recovery and demonstrate poorer cognitive outcomes compared to older children (Anderson, Catroppa, Rosenfeld, Haritou, & Morse, 2000). Specifically, focal brain lesions of various origins prior to two years of age have been associated with significant cognitive impairments compared to focal lesions after the age of 2 (Anderson et al., 2009).

However, not only age at injury but also the time elapsed since injury and the age at testing are important factors in the assessment of long-term cognitive outcomes following pediatric TBI (Gil, 2003). Impairments in memory, attention, and executive functions (EF), which often manifest during initial recovery stages, tend to improve during the first year after injury and reach a plateau in the forthcoming years (Catroppa & Anderson, 2002; Van Heugten et al., 2006). However, the effects of brain insult acquired at an early age may also demonstrate increasing damage even several years after the injury (Anderson, Morse, Catroppa, Haritou, & Rosenfeld, 2004; Eslinger, Biddle, Pennington, & Page, 1999; Gil, 2003; Westmacott, MacGregor, Askalan, & Deveber, 2009), when the individual faces difficulties in adjusting to increasing environmental demands (Brenner et al., 2007). However, few studies have considered the *age-at-testing effect* on the child's cognitive outcome (Anderson, Brown, Newitt, & Hoile, 2011; Levin et al., 1988).

The development of cognitive functions throughout childhood and adolescence make it difficult to estimate the influence of pediatric TBI on memory functions. It has been well documented in the literature that most cognitive abilities improve extensively during early childhood (commonly until the age of 11–12 years) and continue to improve at a more gradual rate until they are well stabilized during adulthood (18–20 years) (Diamond, 2006; Ginstfeldt & Emanuelson, 2010). The improvement of memory skills throughout childhood may be linked to the maturation of memory-related neuro-anatomical structures (Anderson & Lajoie, 1996; Pressley & Schneider, 1997; Sowell, Delis, Stiles, & Jernigan, 2001). For example, the ability to register information, to learn, and to remember all improve with age, with the nature of this progress consistent with the ongoing myelination of perihippocampal and frontal lobe regions (Anderson & Lajoie, 1996; Sowell et al., 2001). In a similar manner, changes in attention, which are often related to memory abilities, are more pronounced in the early years (8–10) and tend to stabilize in later years (11 and above) (Schneider, Knopf, & Stefanek, 2002; Vakil, Blachstein, Sheinman, & Greenstein, 2008). Additionally, flexibility, goal setting, and information processing—all related to EF abilities and pertinent to memory performance—have been reported to be relatively mature by 12 years of age (Anderson & Catroppa, 2005; Duff, Schoenberg, Scott, & Adams, 2005). Memory strategies are also known to be associated with frontal lobe maturation. Neuroimaging studies have demonstrated that frontal activation can serve as a predictor of subsequent memory performance

(Frackowiak et al., 2004). Moreover, frontal lobe lesions are associated with deficits in employing effective encoding and retrieval strategies, greater susceptibility to interference, and difficulty in monitoring recall for redundant or incorrect information, resulting in poor recall of the source of information (Sohlberg & Mateer, 2001).

However, since memory is a multidimensional construct (Squire, 2004), some aspects of memory might be affected following pediatric TBI, whereas others might be preserved (Catroppa & Anderson, 2007). Immediate verbal memory is often preserved in most pediatric patients with TBI, while delayed memory is reported to be significantly more impaired (Catroppa & Anderson, 2007; Vakil, Blachstein, Rochberg, & Vardi, 2004). For example, children with TBI demonstrated deficient recall and recognition on the California Verbal Learning Test for Children (CVLT-C) but relatively intact immediate memory compared to healthy controls (Jaffe et al., 1992, 1994; Levin et al., 1993; Yeates, Blumenstein, Patterson, & Delis, 1995). Additionally, pediatric TBI has been associated with proactive interference (Donders & Minnema, 2004), although other results have also been reported (Yeates et al., 1995). TBI severity has been reported as being associated with a lower rate of acquisition and more gradual deceleration in the rate of acquisition on the CVLT-C (Warschawsky, Kay, Chi, & Donders, 2005). Moreover, a cluster analysis of CVLT-C revealed that, although children following TBI demonstrated similar patterns of learning and memory as healthy peers, their level of performance was related to injury severity (Mottram & Donders, 2005).

In the current study, the effect of severe pediatric TBI on verbal memory was examined using the Rey Auditory Verbal Test (RAVLT; Rey, 1964; Schmidt, 1996). The RAVLT is a widely used measure of verbal learning and memory functions (Rosenberg, Ryan, & Prifitera, 1984), translated into Hebrew (Vakil & Blachstein, 1997), validated for use with children (Bishop, Knights, & Stoddart, 1990; Forrester & Geffen, 1991; Vakil, Blachstein, & Sheinman, 1998) and with children following TBI (Kinsella et al., 1997; Vakil et al., 2004).

Several memory measures can be extracted from RAVLT, both by scores of individual trials as well as by computing composite scores from the different trials within the same sample, enabling assessment of a range of verbal memory processes and differentiation between impaired and preserved memory functions. Additionally, RAVLT measures seem to be sensitive to developmental trajectories in verbal memory. For example, Vakil, Greenstein, and Blachstein (2010) found that, among the different verbal memory measures, derived indices of learning (total learning [TL], corrected TL, and learning rate) were most sensitive to age at testing among typically developing children.

In a previous study using the RAVLT among a sample of children following TBI, various memory deficits, such as inefficient organization and learning strategies and deficient retrieval efficiency were found for the TBI group compared to noninjured controls (Vakil et al., 2004). However, since the sample of children with TBI in Vakil's study was relatively small ( $n = 25$ ) and did not enable dividing the groups into age-dependent subgroups, the possible effect of age at testing on verbal memory after TBI was not examined.

In this study, verbal memory functions among children following pediatric TBI were evaluated and compared with typically developing age peers. The goal of the current study was to examine the impact of age at testing on verbal memory abilities among school-age children following severe TBI. Based on the developmental trajectories reported in various cognitive domains including memory (Vakil et al., 1998), EF (Diamond, 2006), and attention (Vakil et al., 2008), a developmental "cut-off point" was determined and the sample was divided into two subgroups—above and below 12 years at the time of the assessment—and the differences between these two age groups on verbal memory performance were examined.

## METHODS

### Participants

The study followed a retrospective design with a sample of 67 children (42 boys and 25 girls) following TBI, aged 8 to 17 years ( $M = 12.3$ ,  $SD = 2.74$ ). In the current study, we used a case-control design consisting of a group of children and adolescents with severe TBI and a group of typically developing (TD) controls sampled from the Israeli standardization sample (presented in the study of Vakil et al., 1998). TD controls were compared to participants in the TBI group with respect to extraneous factors such as age and gender. Age was chosen to be the continuous comparison variable and thus participants in the control group were selected if they were within the specified age range of children in the TBI group (i.e., Age + 1 year) (Last, 1995). The children in the TBI group were recruited from a larger sample of children ( $N = 105$ ) admitted to a Neuropsychological Unit at a Pediatric Rehabilitation Department in central Israel for extensive neuropsychological assessment following TBI. Details from medical files regarding the nature of injury revealed that 54 children (81%) were injured due to motor-vehicle accidents; 6 children (9%) were injured due to a fall from height; 3 (4 %) were injured as a result of a falling object; and 4 children (6%) had missing data regarding the nature of injury.

Inclusion criteria were the following: (a) age at assessment between 8–18 years; (b) a diagnosis of severe TBI according to the Length of Coma (LoC) duration >24 hours; (c) neuropsychological assessment at least 1 year postinjury. Children with hearing or vision impairments were excluded from the sample. Additional exclusion criteria were (a) a psychiatric diagnosis (in addition to the head injury) and (b) injury during infancy (i.e., before the age of 3).

Participants in both groups were proficient in Hebrew. Mothers' of children in the TBI group were moderate to highly educated ( $M = 13.6$ ;  $SD = 2.1$  years of education), and the majority of children were referred to the Pediatric Rehabilitation Department from the central area of Israel. Parents' of children from the TBI group signed a "Consent for Release Information" form, which allowed the authors to extract the relevant information from the children's medical files. Demographic and injury-related data were collected from the patients' medical records and are presented in Table 1.

Although no detailed socioeconomic information was available for the standardization sample, children in this sample were recruited from public schools in central Israel ranked in the middle socioeconomic-status (SES) range according to the Israeli Ministry of Education scale (Vakil et al., 1998).

All study procedures were approved by the hospital's Institutional Review Board.

**Table 1** Demographic and Injury-Related Characteristics of Children in the TBI Group ( $n = 67$ ).

	Age at injury (years)	LoC (days)	Age at assessment (years)	Time since injury (years)	IQ postinjury (-score)
Mean	9.63	11.37	12.3	2.66	-0.27
<i>SD</i>	3.23	16.5	2.75	1.83	0.19
Range	4.01–16.39	1–70	8.27–17.92	1–10.4	-2– 3

## Tests and Procedures

The Hebrew version of the RAVLT (Vakil & Blachstein, 1997) was administered in the standard fashion (see Lezak, Howieson, Bigler, & Tranel, 2005). The test consisted of 15 common nouns read to participants at the rate of one word per second, on five consecutive trials (Trials 1–5). Participants were asked to remember as many words as possible. Each trial was then followed by free recall. On Trial 6, an interference list of 15 new common nouns was presented, followed by free recall of these new nouns. On Trial 7, participants were once again asked to recall the first list. Twenty minutes later participants were asked to recall the first list (Trial 8). Following this, they were required to identify the 15 words from the first list out of 50 words presented verbally (also including the 15 words in the second list and 20 new common nouns) (Trial 9; Vakil et al., 2004).

**General Intelligence (IQ).** Children in the TBI group were assessed with the Hebrew version of the Wechsler Intelligence Scale for Children (Cahan, 1998 [WISC-R95]; Wechsler, 2003 [WISC-4]). Five children were assessed with the Kaufman Assessment Battery for Children (K-ABC; Kaufman & Kaufman, 1983a; 1983b) and five children, aged 16–17, were assessed with the Wechsler Adult Intelligence Scale (Wechsler, 1997 [WAIS-III]).

**Injury Severity Level.** Injury severity was determined according to the duration of coma (LoC).

## Data Analysis

Statistical analyses were performed using the Statistical Package for the Social Sciences version 19.0 for Windows (SPSS-19).

Following Vakil et al. (2010), seven composite scores were constructed out of the nine trials of the RAVLT, including TL (total number of words recalled over the first five trials), Corrected TL (total number of words recalled in the five learning trials minus five times the number of words recalled in the first trial), Learning Rate (Trial 5 minus Trial 1), Proactive Interference (Trial 1 minus Trial 6), Retroactive Interference (Trial 5 minus Trial 7), Retention (Trial 5 minus Trial 8), and Retrieval Efficiency (Trial 9 minus Trial 8).

The associations between child- and injury-related variables (i.e., IQ postinjury, time since injury, LoC duration, and child's age at injury) and the different memory scores derived from the RAVLT (immediate memory [Trial 1] and the seven composite scores) in the TBI group were determined using Pearson correlations.

In order to examine the effect of pediatric TBI on verbal memory, the seven composite scores as well as immediate memory were converted into *z*-scores based on the control group age averages. Accordingly, the larger the *z*-score, the more it deviated from the performance of matched, healthy peers.

In order to examine age effects on verbal memory, the sample was divided into two age groups of above and below 12 years of age (8–11.11 years, *n* = 66; 12–17 years, *n* = 68, divided evenly between the TBI and control groups) according to the neurodevelopmental trajectories of the different cognitive domains. Independent *t*-tests were

conducted between the two age groups on all RAVLT learning trials as well as on the seven composite scores.

In addition, among the TBI group, independent *t*-tests were conducted in order to control for additional group differences related to either child- and/or injury-related variables (intellectual level [IQ], time since injury, injury severity level, and age at injury).

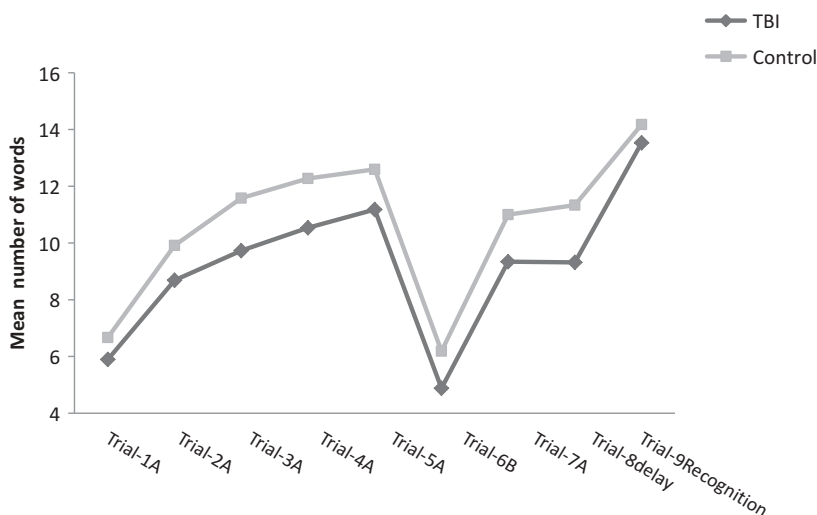
Finally, as the current study employed a retrospective design using medical files, a multiple imputation technique (one-time stochastic regression) was used to complete the missing data, which was less than 8% for all measures collected (Enders, 2010). This procedure allows utilization of the full sample and provides an unbiased parameter estimate, as long as the imputation is executed completely at random (Missing Completely at Random [MCAR]). Little's test for MCAR showed,  $X^2(68) = 64.36$ ,  $p = .603$  (Little, 1998), indicating that the data were imputed completely at random.

## RESULTS

In order to enable a comparison between the current study and previous studies of verbal memory among children following severe TBI, group differences between the entire TBI and control participants are presented first, followed by analyses of the two age groups of below and above 12 years of age.

### Differences in Learning Rates Between the TBI and Control Groups

A 2 x 5 mixed analysis of variance (ANOVA) was conducted in order to examine differences in learning curves with Group Type (TBI vs. Control) as the between-subjects variable and the Five Learning Trials of the RAVLT as the within-subjects variable (see Figure 1).



**Figure 1** Mean number of words recalled in the different trials of the RAVLT by children with TBI and matched controls.



A significant main effect was found for Learning,  $F(4, 528) = 314.54, p < .001, \eta^2 = .7$ , as well as for Group Type, with the children in the control group recalling significantly more words ( $M = 10.56; SD = 1.5$ ) compared to children in the TBI group ( $M = 9.21; SD = 1.7$ ),  $F(1, 132) = 16.13, p < .001, \eta^2 = .11$ .

Additionally, a significant Group-by-Learning interaction was found,  $F(4, 528) = 3.14, p < .05, \eta^2 = .02$ , in which the positive increase in recalled words among the control group was steeper than that of the TBI group.

### Composite Scores Converted into z-Scores

The additional trials (6–9) were converted into composite z-scores. Scores ranged between  $z = -0.86$  and  $z = -0.145$ , indicating that the control group outperformed the TBI group on all measures examined. Independent  $t$ -tests between the four composite scores revealed significant differences between the TBI and control groups in the retention and retrieval efficiency composite scores,  $t(132) = 2.09, p = .04, t(132) = 2.52, p = .01$ , respectively. However, all z-scores were less than 0.9 deviations from age-appropriate scores indicating that the performance of the TBI group remained within the lower end of the average range.

### Performance on the RAVLT According to Age-at-Assessment Groups

In order to enable the evaluation of the age-at-testing effect on RAVLT immediate learning and composite scores, we compared children from the young TBI group (below 12 years of age) and children from the old TBI group (above 12 years of age) on all child- and injury-related factors (i.e., IQ postinjury, age at injury, time elapsed since injury, injury severity level). No significant differences were found between groups on all the above-mentioned factors, except for the age-at-injury factor, in which, not surprisingly, the mean age at injury for children in the young TBI group was significantly younger than the mean age at injury for children in the older TBI group (see Table 2).

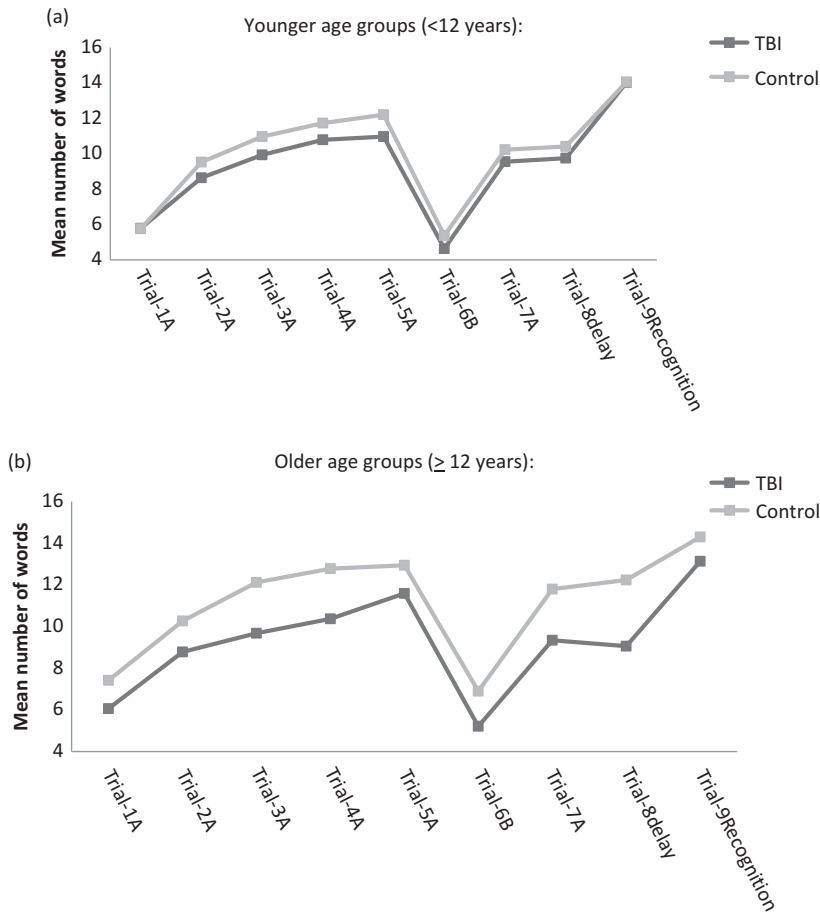
### Differences in Learning Rates Between the TBI and Control Groups

As in the entire sample analysis, differences in learning curves between the participants with TBI and the typically developing participants were examined for each age group (i.e., young children <12 years and older children  $\geq 12$  years) using a 2 x 5 mixed ANOVA with Type

**Table 2** Differences between the Two Age Groups Following TBI on Various Child- and Injury-Related Variables.

Injury-related factors	Mean (SD)		<i>t</i>	<i>p</i> value
	Below 12 yrs ( <i>n</i> = 33)	Above 12 yrs ( <i>n</i> = 34)		
<i>Age groups</i>				
IQ postinjury (z-score)	−0.24 (0.91)	−0.3 (1.13)	0.21	.83
Time since injury (years)	2.54 (1.37)	2.82 (2.35)	−0.6	.55
LoC (days)	11.04 (16.5)	11.82 (16.84)	−0.18	.86
GCS	5.74 (2.151)	6.83 (3.55)	−1.45	.15
Age at Injury (years)	7.75 (1.64)	12.24 (3.1)	−7.7	.001

Note. LoC = Length of Coma; GCS = Glasgow Coma Scale.



**Figure 2** (a) Mean number of words recalled on the different trials of the RAVLT by young children with TBI and matched controls; (b) mean number of words recalled on the different trials of the RAVLT by older children with TBI and matched controls.

of Group (TBI vs. control) as the between-subjects variable and the first Five Trials of the RAVLT as the within-subjects variable (see Figure 2a and b, respectively).

Among children in the young age group, a significant main effect was found for Learning,  $F(4, 264) = 204.9, p < .001, \eta^2 = .73$ , indicating an improvement in verbal recall as a result of repeated learning. However, in contrast to the whole sample analysis, no significant main effect was found for Group Type,  $F(1, 66) = 2.95, p > .05, \eta^2 = .04$ , indicating that the young children in both the TBI and control groups did not differ in recall of verbal memory. In addition, no significant Group-by-Learning interaction was found among children in the young age group,  $F(4, 264) = 1.51, p = .201, \eta^2 = .02$  (see Figure 2a).

Among the older children (12 years of age and above), a significant main effect for learning was found,  $F(4, 528) = 314.54, p < .001, \eta^2 = .7$ . A significant main effect was also found for group type with the children in the control group recalling significantly more words ( $M = 11.04$ ;  $SD = 1.8$ ) compared to children in the TBI group ( $M = 9.15$ ;  $SD = 2.16$ ),  $F(1, 54) = 13.3, p < .001, \eta^2 = .2$ . Additionally, a significant

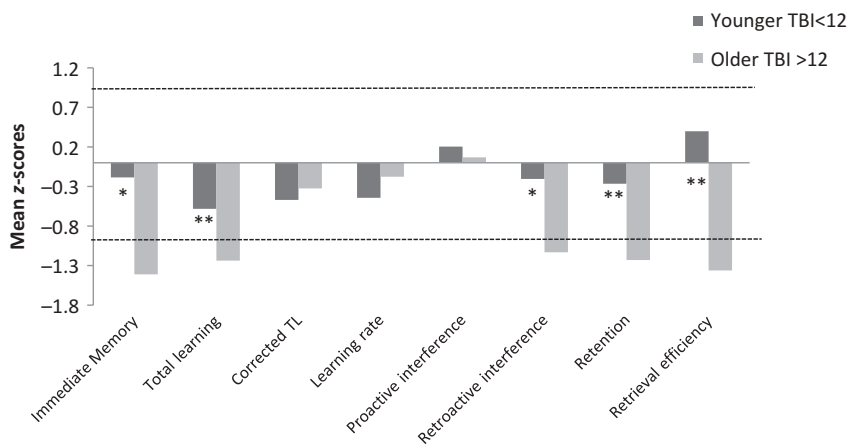
Group-by-Learning interaction was found,  $F(4, 216) = 2.9, p < .05, \eta^2 = .05$  indicating that, as in the whole sample analysis, the positive rising of the curve among the control group was steeper than that of the TBI group (see Figure 2b).

### Composite Scores Converted into z-Scores

**Comparison Between Younger and Older Children Following Severe TBI.** Due to significant differences in age of injury between the two groups, we added age of injury as a covariate into the analyses. The assumptions for an analysis of covariance (ANCOVA) were met. In particular, the homogeneity of the regression effect was evident for the covariate, and the covariate was linearly related to the dependent measure. As can be seen in Figure 3, the younger TBI group performed within the average range (i.e.,  $-1 \leq z \leq 1$ ) on all RAVLT composite scores. These results indicate that, in the TBI group, children below 12 years of age at the time of the assessment performed within the same range as their age-compared peers. However, such an effect was not found for the older TBI group, in which adolescents following TBI performed below the normal range (i.e.,  $-1 \geq z$ ) on the immediate memory trial,  $F(1, 65) = 7.4, p < .01, \eta^2 = .11$ , and on the TL,  $F(1, 65) = 6.9, p < .05, \eta^2 = .1$ , retroactive interference,  $F(1, 65) = 4.9, p < .05, \eta^2 = .08$ , retention,  $F(1, 65) = 10.01, p < .01, \eta^2 = .15$ , and retrieval efficiency composite factors,  $F(1, 65) = 6.11, p < .01, \eta^2 = .1$ .

**Correlations Between Child- and Injury-Related Variables and RAVLT Scores Following TBI.** As can be seen in Table 3, injury-severity level, as determined by LoC duration, negatively correlated with Immediate Memory, TL, Corrected TL, Learning Rate, and Retrieval Efficiency scores. No significant correlation was found between LoC duration and between Retention and Interference scores.

General intelligence (IQ) postinjury was positively correlated with Immediate Memory and TL scores.



**Figure 3** Mean z-scores on the RAVLT composite scores of children in the young and old TBI group.

Notes. Borders represent within average range z-scores.

\* $p < .05$ . \*\* $p < .01$ . \*\*\* $p < .001$ .

**Table 3** Correlations between Child- and Injury-Related Factors and Scores on the Rey Auditory Verbal Learning Test (RAVLT).

RAVLT Measures	Child- and Injury-related variables			
	Age at injury (years)	Time since injury (years)	LoC (days)	IQ post injury (z- score)
Immediate memory	.24*	-.15	-.24*	.23*
TL	.22*	-.23*	-.42***	.31**
Corrected TL	.02	-.12	-.26*	.14
Learning rate	.1	-.15	-.23*	.17
Proactive interference	.02	.07	-.02	-.11
Retroactive interference	.10	.12	-.01	-.02
Retention	.07	.10	-.01	.05
Retrieval efficiency	-.23*	.26*	.249*	-.12

Note. RAVLT = Rey Auditory Verbal Learning Test; LOC = Length of Coma.

\* $p < .05$ . \*\* $p < 0.01$ . \*\*\* $p < .001$ .

Child's age at injury was related to the number of words recalled within the first trial, as well as with the TL and Retrieval Efficiency composite scores. The correlations indicate better results for older children at the time of injury (see Table 3).

## DISCUSSION

The present study examined the age-at-testing effect on verbal memory abilities among school-age children following severe TBI.

As reported in previous studies (Vakil et al., 2004; Warschausky et al., 2005; Yeates, 2000), our study demonstrated impaired verbal memory performance among children following severe TBI, compared to matched healthy peers. More specifically, the children in the TBI group recalled significantly fewer words than children in the control group on all trials of the RAVLT.

A more thorough examination of the results, using the RAVLT composite scores, revealed that children following TBI had significantly lower scores on all verbal memory components such as learning, retention of information over time, and retrieval efficiency, compared to matched healthy peers. However, although lower than controls, these standardized scores fell within the lower end of the average, indicating that the performance of the TBI group was within the average range.

Following that, we examined the age-at-testing effect on verbal memory abilities among school-age children following severe TBI. To this end, we divided the children in the sample into two groups of below and above 12 years of age, according to the significant developmental trajectories related to memory, attention, and EF abilities documented in the literature (Anderson & Catroppa, 2005; Schneider et al., 2002; Vakil et al., 1998). We found that children in the younger age group demonstrated a significant learning curve, indicating that as a result of rehearsal, young children in both groups improved in verbal memory performance. Moreover, children in the younger age group performed within the normal range on all composite scores compared to matched healthy peers, as indicated by their within average z-scores.

Among the older children (aged 12 and above), a significant learning curve was also observed, indicating that, both in the control and the TBI groups, children recalled significantly more words as a result of repeated learning. However, in contrast to the younger age group, older children with TBI recalled significantly less words compared to matched controls and their verbal memory performance deviated from the normal range in most measures, including immediate memory, TL, retroactive interference, retention, and retrieval efficiency composite scores. We elaborate on the possibilities for such differences below.

### Immediate Memory

Several reasons may account for the impairment in initial learning after severe TBI in the adolescent group. First, as attentional deficits are known to be sensitive to development (Greenstein, Blachstein, & Vakil, 2010), the difficulties of the older children with severe TBI to attend to the material may have been more prominent and thus have influenced their performance, compared with typically developing peers (Allen et al., 2010). Second, capacity limitations, which are expected to decrease with age, may not do so following TBI and, thus, limit the amount of information learned or the efficiency in which it can be processed among older children following TBI.

The results of differences in immediate memory between the older children in the TBI group and controls are inconsistent with previous results reported by Vakil et al. (2004). In their study, scores reflecting immediate memory in the TBI group were not significantly different than those of the control group, a finding evident in the younger age group in the current study. However, the lack of difference in Vakil's sample might be related to the inability to examine age differences due to the relatively small TBI sample ( $n = 25$ ) reported in their study.

### Total Learning

The significant difference in TL between the older children in the TBI group and their matched peers can be understood in light of the positive relationship between performance on EF tasks and the RAVLT among adults, described by Chang et al. (2010). The authors suggest that, since words on the RAVLT lists are inherently disorganized, participants must actively structure the encoding of the information for effective storage and retrieval. With age, such strategies are expected to develop, resulting in enhanced verbal memory performance. It is possible that as a result of a TBI, older participants (age 12 years and above) lack the age-appropriate learning skills, which in turn hampers their ability to increase the amount of words recalled across trials. The deficiency in increasing the number of words recalled across trials, together with the above-mentioned immediate recall deficit, may have resulted in the relatively wide deviation (1.2  $z$ -score points) from matched healthy peers in TL.

### Retroactive Interference

Retroactive interference (RI) occurs when later-learned information interferes with earlier learned material (Hedden & Park, 2001). In the CVLT and the RAVLT, RI is measured via comparison between the trials of List A before and after the interference of List B. Inconsistent findings have been reported regarding RI among the pediatric TBI

population. For example, Donders and Minnema (2004) did not find significant rates of RI among children and adolescents following TBI, compared to a standardization sample. In contrast, Vakil et al. (2004), found significant RI among children following TBI. In the current study, children in the older TBI group demonstrated significantly higher levels of RI, compared to TD peers. Such a significant effect was not evident among the young children following TBI, suggesting an age-dependent RI effect. A possible age-dependent RI effect was previously described by Levy-Gigi and Vakil (2010) who reported higher levels of RI among young TD children (9-year-olds) compared to older TD children (12-year-olds). The authors suggest that interference tasks demand engagement of executive control processes and efficient learning and memory strategies that are not fully matured among young children, resulting in their relatively higher rates of RI. This developmental effect can explain the lack of difference in RI between the young children following TBI and the matched young TD peers in our study. Subsequently, this effect may also explain the more prominent interference effect found in the older TBI group, who did improve in performance and did not reduce the levels of interference as their TD counterparts.

### Retention

The retention deficit presented in the current study among participants older than 12 years old can be understood in terms of a consolidation deficit, in which reduced scores on delayed recall (Trial 8, List A) compared to the last learning trial (Trial 5, List A) are considered an indicator of a forgetting rate. However, as previously mentioned, children in the older age group following TBI also presented a deficit in immediate recall and in recall following repeated learning (Trial 5). Thus, the number of words initially recalled, as well as the number of words recalled following practice was, from the start, lower than that of their peers. Therefore, the assumption that lower scores on delayed recall reflect poor consolidation rather than retrieval or encoding difficulties is problematic. Rather, it is more reasonable to conclude that the retention deficit presented in the current study is related to the relatively lower number of words initially remembered. This standpoint is supported when taking into account the significantly lower recognition rates also found in the older TBI group discussed below.

### Retrieval Efficiency

Findings on typically developing children demonstrate that older children tend to improve on verbal memory tasks and use more efficient retrieval strategies that, in turn, enhance their performance (Bjorklund, Dukes, & Brown, 2009; Kobasigawa, 1974; Levy-Gigi & Vakil, 2010). Thus, the large deviation in performance between the older participants with TBI and their matched healthy peers might indicate impairment in efficient retrieval strategies, which are expected to develop during adolescence when more pathways or associations exist to access the information (Kail, 1990). In the same manner, the lack of difference in retrieval efficiency between the younger participants with TBI compared to their matched healthy peers might be due to the fact that among young children, the recollection and retrieval strategies are generally weaker, possibly resulting in a negligible effect of TBI on performance. In addition, despite the widely accepted view that a significant advantage of recognition over recollection indicates a retrieval deficit pronounced via the retrieval efficiency composite score (Duchnick, Vanderploeg,

& Curtiss, 2002; Lezak et al., 2005; Vakil et al., 2004), others have suggested that marked encoding difficulties, such as the ones presented among adolescents following TBI, might also contribute to a discrepancy between recall and recognition (Delis, Kramer, Kaplan, & Ober, 2000). The results of significant differences in immediate memory in the older TBI group might be in accordance with this view.

In general, the current findings support earlier results reported by Levin et al. (1988), who interpreted the impaired memory functioning among older children one year post-TBI compared to adequate memory functions among younger children, as a consequence of typical memory development. According to the authors, since verbal memory continues to develop into adolescence, the impairments are evident only in older ages when these abilities emerge. As other studies also supported relatively late stabilization of verbal memory abilities (Schneider et al., 2002; Vakil et al., 2004), a reasonable conclusion would be that the lack of difference in performance between the young TBI group and their young healthy peers may indicate the nature of gradually emerging memory skills in typical populations rather than the lack of injury effect on verbal memory abilities among young children. Thus, a possible implication suggested by the current results is related to the limited sensitivity of the RAVLT to the consequences of head trauma in young children. It is possible that the initial number of words recalled among young healthy children was, from the start, relatively low, causing a latent *floor effect* when compared to young clinical groups such as TBI. In order to examine this assumption, future studies should evaluate verbal memory abilities among young children using other verbal memory tests (e.g., sentence memory tests and story memory tests), with preference to tests that were developed especially for young children. If deficits would be detected using other verbal tests among the pediatric TBI population, it would support the assumption regarding the lack of sensitivity of RAVLT in young clinical populations.

In the current sample, children in the younger TBI age group were also injured at a significantly younger age compared to children in the older TBI group, making it possible that the differences between the two groups might be related to age at injury. However, when including age at injury as a covariate in the statistical model, significant differences between the age groups were still evident, indicating that the better performance among children in the younger age group was not confounded by child's age at injury. In addition, since most studies on pediatric TBI indicate that younger age at injury is generally associated with poorer cognitive outcomes (Anderson et al., 2005; Anderson, Godfrey, Rosenfeld, & Catroppa, 2012; Levin, Song, Ewing-Cobbs, Chapman, & Mendelsohn, 2001), the expected results should have been in the opposite direction (i.e., better performance for children who were injured at an older age). Therefore, the memory difficulties demonstrated among the older participants cannot be explained by the relationship between age at injury and age at assessment. Moreover, recent findings by Anderson et al. (2012) among survivors of very early TBI indicate that, although severe injury is associated with poorest outcome, injury occurring after 3 years of age seems to be associated with a smaller and a more stable gap between children with severe TBI and their peers. Hence, since all the participants with TBI in this study were above 4 years of age at the time of injury, the effect of age at injury on outcome should be comparable between the two age groups.

The major clinical implication of our findings is that verbal memory difficulties seem to be accurately diagnosed above 12 years of age but possibly underdiagnosed below 12 years of age when using the RAVLT. More specifically, although younger



children with TBI may not show pronounced memory impairment, the results might not represent their actual memory deficit and thus may not predict long-term outcomes. Therefore, while using the RAVLT as a verbal memory measure among young children, clinicians should carefully interpret the findings and avoid using it as a single indicator for verbal memory functioning.

Lastly, in the current study, length of coma was found to be negatively associated with verbal memory abilities in most of the RAVLT composite scores, except for both Interference scores and Retention. These findings are in accordance with previous studies in children as well as among adults, in which injury severity determined by the duration of coma, are one of the most significant predictors of long-term memory problems (Wilson, 1992; Wilson, Vizor, & Bryant, 1991; Yeates, 2000).

### Limitations

The relatively small sample size and the heterogeneity of the sample are the major limitations of this study. Sample heterogeneity is inherent in research with pediatric TBI populations, which is diverse and differs on numerous factors, such as mechanism and locus of injury. Further research should aim to apply imaging protocols in order to control for possible related injury mechanisms. In addition, although data regarding SES is considered a critical variable in child neuropsychological studies, it was not collected in the current study. Therefore, we do not know if there were any SES differences between the age groups that might account for the differences in verbal memory performance. Another limitation of the current study relates to the lack of data regarding omissions and intrusions of words across learning trials. Such information may enable a more thorough examination whether words remembered at different comparison points are from the same pool of encoded items. Particularly, different items may be remembered in the last learning trial (Trial 5) than in delayed recall (Trial 8), which may be more indicative of a deficit in retrieval than consolidation. Finally, the current study followed a retrospective design in which age at testing was used as a between-subject factor. Future studies should aim at examining the effect of age at assessment in a longitudinal design focusing on performance on the verbal memory functions.

### Conclusions

Cognitive deficits or weaknesses may not be detectable at younger ages following TBI; however, they might be more easily noticed over development. This latent long-term effect might possibly result in a developmental and achievement lag between children who sustained a pediatric TBI and typical age peers. Thus, taking into account the effect of child's age at testing, as well as other injury-related factors, on various learning and memory functions could certainly help professionals compose specific rehabilitation and educational interventions attuned to the child's abilities.

Original manuscript received 1 June 2014

Revised manuscript accepted 8 March 2015

First published online 5 May 2015



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