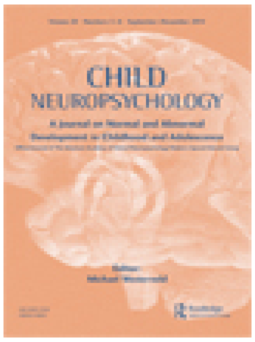

Child Neuropsychology

ISSN: 0929-7049 (Print) 1744-4136 (Online) Journal homepage: https://www.tandfonline.com/loi/ncny20

Characterization of Memory Impairment Following Closed-Head Injury in Children Using the Rey Auditory Verbal Learning Test (AVLT)

Eli Vakil , Haya Blachstein , Judith Rochberg & Moshe Vardi

Child Neuropsychology
2004, Vol. 10, No. 2, pp. 57–66

Psychology Press
Taylor & Francis Group

Characterization of Memory Impairment Following Closed-Head Injury in Children Using the Rey Auditory Verbal Learning Test (AVLT)*

Eli Vakil[1], Haya Blachstein[1], Judith Rochberg[2,3], and Moshe Vardi[2,3]
[1]Psychology Department, Bar-Ilan University, Ramat-Gan, Israel, [2]Loewenstein Rehabilitation Hospital, Ra'anana, Israel, and [3]Sackler Faculty of Medicine, Tel-Aviv University, Tel-Aviv, Israel

ABSTRACT

Memory impairment following closed-head injury (CHI) in children is well documented. Characterization of the memory deficits of children with CHI could contribute to the prediction of academic performance and rehabilitation of these children. Twenty-five children who sustained closed-head injury and 25 matched controls were administered the Rey Auditory Verbal Learning Test (AVLT). The advantage of this memory test is that a number of memory components are measured simultaneously, thus enabling us to study the relations between different aspects of memory within the same patient sample. The findings indicate that the Rey AVLT is a good test for characterization of impaired verbal memory in children following CHI. Transformation of scores derived from the Rey AVLT to *Z*-scores enables us to determine the relative effect of CHI in children on different memory scores. Raw scores were more vulnerable than relational ones, derived as the difference between two raw scores (e.g., learning, Trial 5 – 1), to closed-head injury in children, and scores reflecting word span were the least vulnerable. The results are discussed in terms of the possible contribution of the frontal lobes, which are frequently affected in closed-head injuries, to memory performance.

Memory impairment following closed-head injury (CHI) in children is well documented (Jaffe et al., 1992, 1993; Levin, Eisenberg, Wigg, & Kobayashi, 1982; Levin et al., 1993, 1994; Yeates, Blumenstein, Patterson, & Delis, 1995). Furthermore, Levin and Eisenberg (1979) found memory as the most impaired cognitive domain in children with CHI. The memory literature clearly demonstrates that memory is not a unitary system, but consists of different cognitive sub-processes dependent on several brain regions (Zola-Morgan & Squire, 1993). Kinsella et al. (1997) have shown that memory and learning difficulties could contribute to the prediction of academic performance in children who have sustained CHI. Thus, characterization of the nature of memory deficits in these children with CHI has great therapeutic value in helping children cope with the debilitating consequences of learning and memory deficits.

Several standardized tests of verbal learning and memory, such as the Rey Auditory Verbal Learning Test (AVLT; Lezak, 1995), the California Verbal Learning Test: Children's Version (CVLT-C) (Delis, Kramer, Kaplan, & Ober, 1989), and the Selective Reminding Test (Buschke & Fuld, 1974), simultaneously test several memory domains. The fact that a number of memory

*Supported by the Schnitzer Foundation for Research on the Israeli Economy and Society.
Address correspondence to: Eli Vakil, Ph.D., Psychology Department, Bar-Ilan University, Ramat-Gan 52900, Israel. Tel.: +972-3-531-8594. Fax: +972-3-535-0267. E-mail: vakile@mail.biu.ac.il
Accepted for publication: June 4, 2003.

0929-7049/04/1002-057$16.00 © Taylor & Francis Ltd.
DOI: 10.1080/09297040490911078

components are measured simultaneously (e.g., immediate and delayed recall, learning rate and recognition) enhances the tests' usefulness as diagnostic tools (Lezak, 1995). In addition, these tests offer the advantage of enabling examination of relations between the different aspects of memory within the same sample.

Using the Selective Reminding Test, Levin et al. (1982) found that children who sustained CHI have problems in storage and retrieval of verbal material. Several studies used the CVLT-C to assess the effect of CHI in children on a variety of memory aspects. Jaffe et al. (1992, 1993) reported that children with CHI have deficient recall and recognition when compared to matched controls. Also based on performance on the CVLT-C, Levin et al. (1993, 1994) suggest that the impaired recall observed in children with CHI could be attributed to less semantic clustering and more intrusion errors, as compared to controls. Yeates et al. (1995), also using the CVLT-C, found that children with severe CHI have deficient recognition and immediate and delayed recall compared to controls. However, inconsistent with Levin et al., their young patients were similar to controls in the use of serial and semantic clustering, and also did not differ on consistency in the words-recalled measure. Roman et al. (1998) tested children with the CVLT-C in different stages of recovery, 1 and 3 months post-injury. In this study, as in previous studies, recognition and immediate and delayed recall were impaired in children with CHI. However, unlike Yeates et al. (1995), patients did not show specific retrieval deficit. In other words, the patient group did not show disproportional advantage of recognition as compared to recall. Although it is widely accepted that a significant advantage of recognition over free recall indicates a retrieval deficit (Duchnick, Vanderploeg, & Curtiss, 2002; Lezak, 1995), others have suggested that encoding difficulties could also contribute to such a discrepancy between recall and recognition (Delis, Kramer, Kaplan, & Ober, 2000).

Lannoo, Colardyn, Jannes, and De Soete (2001) used a large neuropsychological battery in order to test the recovery rate (i.e., within the first 50 days, after 6 months, and 2 years post-injury) of adults and children following CHI. Only three memory measures from the Rey AVLT, which was part of this neuropsychological battery, were reported: first learning trial, total score for the first five learning trials, and the delayed trial. The authors report that, although the performance of the patient groups improved over time, they remained impaired as compared to the control group. Kinsella et al. (1997) reported that verbal learning and memory indices derived from the Rey AVLT are good predictors of subsequent needs for special education in children who sustained CHI.

There are several published children's norms for Rey AVLT (Bishop, Knights, & Stoddart, 1990; Forrester & Geffen, 1991; Vakil, Blachstein, & Sheinman, 1998). In light of this and compared with the frequent use of the CVLT-C in children with CHI, the minimal reports about the use of the Rey AVLT to assess children following CHI are quite surprising. The studies by Kinsella et al. (1997) and Lannoo et al. (2001) made very restricted use of the test, failing to take advantage of the rich range of memory aspects that can be measured with this test. The usefulness of the Rey AVLT as a tool for memory assessment is evident from the numerous studies that reported performance on this test by adults who sustained CHI (Blachstein, Vakil, & Hoofien, 1993; Geffen, Butterworth, Forrester, & Geffen, 1994).

The goal of this report is twofold: first, to provide a detailed analysis of the performance of children with CHI on different aspects of verbal learning and memory as measured by the Rey AVLT, and second, to identify the memory measures most vulnerable to CHI. In addition to the large range of memory aspects tapped by the Rey AVLT, in recent years the literature has suggested two additional measures that further increase the usefulness of the test as a tool for memory assessment. These measures will therefore be analyzed and reported in this study as well.

The first measure is executing an additional trial of the Rey AVLT, as suggested by Vakil and Blachstein (1994), in order to test memory for temporal order. Following the recognition task (Trial 9), participants were presented with the 15 first-list words written in an order different from that originally presented. Participants were asked to rewrite the words in their original order. Pearson product moment correlations between the original order in which the word list was presented and the sequence in which participants arranged the words were used as the temporal order score. Norms for children on this score were reported (Vakil et al., 1998). Comparison between the temporal order score and the use of temporal order as a spontaneous encoding strategy (i.e., serial clustering) was determined to be capable of distinguishing between adults with CHI and controls (Vakil, Blachstein, & Hoofien, 1991). This finding is consistent with several other studies, which reported that adults with CHI presented deficient memory, including temporal order judgment, when measured directly (i.e., intentional retrieval is required). However, when memory is tested indirectly (e.g., serial clustering) patients with CHI performed within the normal range (Vakil, Kraus, Boar, & Groswasser, 2002). It is interesting to note that Levin et al. (2000) found that recency judgment was preserved in children with CHI.

The second set of scores added to the standard scores generated from the Rey AVLT is omissions and additions. Blachstein et al. (1993) broke down the learning process into two different components: number of new words ‘‘added’’ and number of words ‘‘omitted’’ from trial to trial. This analysis provides insight into the particular cognitive processes underlying the learning rate (see Method section).

METHOD

Participants

Two groups of children participated in the present study: a control group (without brain damaged) and a group of children with CHI. Twenty-five control children (18 boys and 7 girls) were sampled from the Israeli standardization sample (Vakil et al., 1998) to match the scattering of gender, age, and education of the children with CHI. The control group age ranged from 11 to 17 years ($M = 14.72$, $SD = 1.95$) and their education ranged from 5 to 11 ($M = 8.72$, $SD = 1.95$) years of schooling. The patients with CHI were recruited for the study from a population of patients admitted to the Loewenstein Rehabilitation Hospital (Israel) for rehabilitation following a head injury. To be included in the study, patients must have CT or MRI proven brain damage, and have been in coma for at least 24 hr. This group comprised 25 patients (19 boys and 6 girls), ranging in age from 11 to 18 years ($M = 14.84$, $SD = 2.21$). Their education ranged from 4 to 11 ($M = 8.92$, $SD = 2.14$) years of schooling. Intelligence was measured with the WISC–R (Wechsler, 1991) for all of the children with CHI, except for two who are 18 years old and were administered the WAIS–R (Wechsler, 1981). The severity-of-injury measures of the children with CHI were: length of coma (days, median = 14, interquartiles ranging 4.5–21), Glasgow Coma Scale – GCS obtained upon admission to hospital (median = 6, interquartile ranging 5–7), time after onset (months, $M = 18.51$, $SD = 19.5$). Cause of injury and other demographic information were collected from the patients' medical records and are presented for each patient in Table 1. The IQ score of all the children with CHI was within the normal range, 86–126 ($M = 104.21$, $SD = 11.26$). However, as can be seen in Table 1, there is a large discrepancy between Performance and Verbal IQ, although not always in the same direction. We view the discrepancy itself, regardless of its direction, as an indication of deviation from normal performance.

The groups did not differ significantly either on age, $t(48) = 0.20$, $p > .05$, or educational level, $t(48) = 0.35$, $p > .05$. Participants in both groups were proficient in Hebrew and had no history of mental illness. This study was approved by the hospital's Committee for Human Experiments.

Tests and Procedure

The Hebrew version of the Rey Auditory Verbal Learning Test (AVLT; Vakil & Blachstein, 1997) was administered in standard fashion (see Lezak, 1995). Certified psychologists administered the test as part of a neuropsychological battery given to patients admitted to the Loewenstein Hospital for rehabilitation. The test consists of 15 common nouns that are read to the participants on five consecutive trials (Trials 1–5); participants are asked to remember as many words as possible. Each trial is then followed by free recall. In Trial 6, an interference list of 15 new common nouns is presented, followed by free recall of these new nouns. In Trial 7, participants are asked again to recall the first list. Twenty minutes later participants are again asked to recall the first list (Trial 8). They are then asked 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). To measure ability to remember temporal order, an extra trial (Trial 10) was added to the standard administration (Vakil et al., 1991; Vakil & Blachstein, 1994). In Trial

Table 1. Demographics of the Group of Children With CHI.

Patient	Age[a]	Sex	Educ[a]	Cause of injury	TAO	Coma	GCS	FIQ	VIQ	PIQ
1	11	M	6	MVA	07	14	07	112	116	106
2	10	F	4	MVA	07	20	05	86	84	90
3	18	F	11	MVA	27	06	07			
4	12	M	5	Pedestrian	22	21	03	95	91	100
5	12	M	6	MVA	03	06	06	110	106	112
6	13	F	8	MVA	39	07		110	95	125
7	14	M	9	MVA	53	19	04	93	101	85
8	13	M	8	MVA	56	50	04	101	96	109
9	13	M	7	Fall	02	01	10	92	92	93
10	15	F	9	MVA	18	07	04	120	109	128
11	15	M	9	Fall	05	21		111	114	104
12	15	M	10	Cyclist	05	03	08	111	112	107
13	16	M	11	Cyclist	06	03	05			
14	15	M	10	MVA	04	02	08	114	101	125
15	16	M	10	MVA	47	90	06	95	103	90
16	16	F	10	MVA	06	15	05	101	95	109
17	16	M	11	MVA	29	10	03			
18	17	M	11	Pedestrian	08	21	09	126	140	98
19	18	M	10	MVA	25	06	06			
20	17	M	11	Pedestrian	06	21	07	114	108	119
21	17	M	11	MVA	11	75	07	100	105	92
22	17	F	11	MVA	03	01	06	103	105	102
23	13	M	7	MVA	67	45	05	86	88	85
24	17	M	11	Fall	05	32	08			
25	15	M	7	Pedestrian	05	03	06			

Note. Educ = education (years); MVA = motor-vehicle accident; TAO = time after onset (months); GCS = Glasgow Coma Scale on admission to hospital; FIQ = Full Scale IQ; VIQ = Verbal IQ; PIQ = Performance IQ.
[a]Age and education at testing time.

10, which follows the recognition task, participants were presented with the 15 first-list words written in an order different from that originally presented. Participants were asked to rewrite the words in their original order.

RESULTS

Results are presented in four sections. Each section represents a different category of memory according to the order of test administration: learning, interference, delayed recall and recognition, and temporal order judgment. In each section, different memory measures extracted from the Rey AVLT were analyzed. Figure 1 presents the number of words recalled in the different trials of the Rey AVLT by the children with CHI and control children.

Learning Rate – Trials 1–5

Multivariate tests were used to examine the number of words recalled by the two children groups (CHI vs. control) in the first five trials of the Rey AVLT, with group and learning trials as factors; the former is a between-subjects factor, and the latter is a within-subjects factor. Overall, the control group recalled more words than the group of children with CHI in the first five trials of the test, $F(1, 48) = 13.84$, $p < .001$, $\eta^2 = 0.22$. There was also a significant increase in the number of words recalled from trial to trial, $F(4, 45) = 79.97$, $p < .001$, $\eta^2 = 0.88$. The Group by Learning interaction did not reach significance, $F(4, 45) = 1.73$, $p > .05$, indicating that the groups' learning rate was not reliably different (see Fig. 1).

Very informative results were attained when the number of words recalled in the first trial was

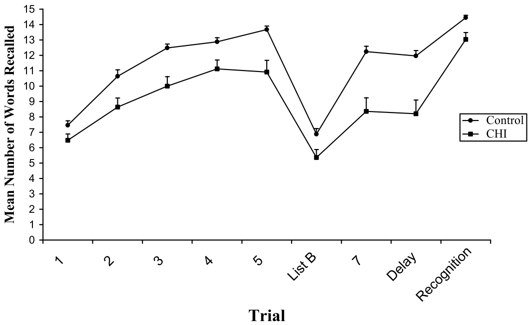

Fig. 1. The number of words recalled in the different trials of the Rey AVLT by children with CHI and control children.

broken down to two components: primacy effect (i.e., first five words of the list) and recency effect (i.e., last five words of the list). The groups did not differ in overall number of words recalled, $F(1, 48) = 1.16$, $p > .05$. Overall, primacy effect was stronger than recency effect, $F(1, 48) = 10.28$, $p < .005$, $\eta^2 = 0.18$. This finding should be interpreted cautiously, because of the significant interaction between Group and Primacy-recency effect, $F(1, 48) = 7.61$, $p < .01$, $\eta^2 = 0.14$. This interaction is due to the fact that, while the control and the patient groups did not differ in the recency effect ($M = 2.04$ and $M = 2.60$, respectively), $t(48) = 1.65$, $p > .05$, the control group showed a greater primacy effect than the patient group ($M = 3.64$ and $M = 2.72$, respectively), $t(48) = 3.16$, $p < .005$. Thus, although the groups did not differ on the overall number of words recalled in the first trial, a more detailed analysis of the results determined that the primacy, but not the recency, effect is impaired in children with CHI.

Blachstein et al. (1993) extracted two additional measures from the five learning trials of the Rey AVLT, "additions" and "omissions". The number of additions is the sum of new words recalled in each trial (N) that were not recalled in the previous trial ($N - 1$). The number of omissions is the sum of words not recalled in a particular trial (N), but that had been recalled in the previous trial ($N - 1$). Such an analysis can provide insight into the source of the impaired learning rate observed in the children with CHI. Interestingly, the children with CHI ($M = 11.88$, $SD = 2.54$) and the control children ($M = 11.52$, $SD = 2.29$) did not differ significantly in the overall number of words added from trial to trial, $t(48) = 0.53$, $p > .05$. However, the overall number of words omitted from trial to trial was significantly higher, $t(48) = 2.74$, $p < .01$, for the children with CHI ($M = 7.48$, $SD = 3.24$) than for the controls ($M = 5.28$, $SD = 2.35$).

Intrusion errors, that is, recall of words that were not presented in the learning list, were reported to occur in the learning process more frequently in children following CHI than in control children (Levin et al., 1993; Yeates et al., 1995, but see Roman et al., 1998). Consistent with these reports, in the present study the sum of intrusions for the five learning trials was significantly higher for the children with CHI ($M = 1.68$, $SD = 1.86$) than for the controls ($M = 0.52$, $SD = 1.42$), $t(48) = 2.48$, $p < .05$.

Proactive Interference – Trial 6 Versus Trial 1

The control group recalled more words in these two trials (1 and 6) than the patient group, $F(1, 48) = 4.97$, $p < .05$, $\eta^2 = 0.09$. Proactive interference was observed, $F(1, 48) = 6.37$, $p < .05$, $\eta^2 = 0.12$, to the same extent for both groups, as indicated by the non-significant interaction, $F(1, 48) = 0.57$, $p > .05$.

Retroactive Interference – Trial 5 Versus Trial 7

As with proactive interference, the control group recalled more words in these two trials (5 and 7) than the group of children with CHI, $F(1, 48) = 15.66$, $p < .001$, $\eta^2 = 0.25$. Retroactive interference was observed, $F(1, 48) = 69.03$, $p < .001$, $\eta^2 = 0.59$. The significant Group by Retroactive interference interaction indicates a stronger retroactive effect for the patient group compared to the controls (see Fig. 1), $F(1, 48) = 4.32$, $p < .05$, $\eta^2 = 0.08$.

Retention – Trial 5 Versus Trial 8

The groups differ significantly on the number of words recalled in the fifth and the eighth (i.e., delayed) trial of the task, $F(1, 48) = 14.58$, $p < .001$, $\eta^2 = 0.23$. Overall, fewer words were recalled in the delayed trial as compared to the fifth trial, $F(1, 48) = 70.37$, $p < .001$, $\eta^2 = 0.59$. The forgetting rate of the two groups did not differ significantly, as indicated by the non-significant Group by Delay interaction, $F(1, 48) = 2.50$, $p > .05$.

Retrieval Efficiency – Delayed Recall (Trial 8) Versus Recognition (Trial 9)

Both main effects and the interaction between them reached significance: the control group remembered more words overall in these two trials (8 and 9) than the patient group, $F(1, 48) = 13.75$, $p < .001$, $\eta^2 = 0.22$. More words were correctly recognized than recalled, $F(1, 48) = 99.32$, $p < .001$, $\eta^2 = 0.67$. As can be seen in Figure 1, the significant interaction, $F(1, 48) = 6.81$, $p < .05$, $\eta^2 = 0.12$, indicates that the difference between recall and recognition was greater for the patient group than for the controls. It is important to note that the groups differed significantly on both delayed recall, $t(48) = 3.64$, $p < .001$, and recognition, $t(48) = 2.88$, $p < .01$.

Temporal Order

Temporal order was evaluated under two retrieval conditions: incidental and intentional. In the incidental retrieval condition, participants were asked to remember the words, and no reference was made to the importance of temporal order when doing so. Pearson product moment correlations between the original order in which the word list was presented and the order in which the words were recalled in the fifth trial, were used as the *incidental* temporal order score. In the intentional retrieval condition (Trial 10), the words were presented in a different order than presented originally, and participants were asked to rewrite the words in the order in which they were originally presented (Vakil & Blachstein, 1994). The correlation between the original order and the order in which participants arranged the words was used as the *intentional* temporal order score. The incidental temporal order score of the control group ($M = 0.47$, $SD = 0.29$) and that of the group of children with CHI ($M = 0.54$, $SD = 0.31$) did not differ significantly, $t(47) = 0.81$, $p > .05$. However, the control participants were significantly more accurate in their intentional memory of temporal order ($M = 0.84$, $SD = 0.16$) than the patient group ($M = 0.62$, $SD = 0.25$), $t(47) = 3.72$, $p < .001$.

Z-Scores

To be able to compare the effect of head injury in children on different scores derived from the Rey AVLT, the scores were converted to *Z*-scores: the larger the *Z*-score, the more it deviates from normal performance (see Fig. 2). As can be seen in this figure, the *Z*-score of incidental temporal order (i.e., 5th trial) was the only negative score, indicating that the children with CHI tended to rely more than controls on temporal order in the fifth trial retrieval. However, this difference did not reach significance, as reported in the previous section. For scores that primarily reflect immediate memory (i.e., first trial, list B, PI), patients deviated less than 0.70 standard deviations from controls. The deviation of the relational scores, derived as a difference between two raw scores (i.e., learning, Trial 5 – 1; delay, Trial 5 – 7; RI; retrieval, Trial 8 – 9), ranged from 0.75 to 1.27 standard deviations. The rest of the scores comprised raw scores that are more than 1.5 standard deviations below normal.

Intercorrelations Between the Different Measures

Pearson correlations were calculated in order to assess the relations between general intelligence (i.e., IQ) and the different memory scores derived from the Rey AVLT in the patient group. Correlations reached significance ($p < .05$) in all

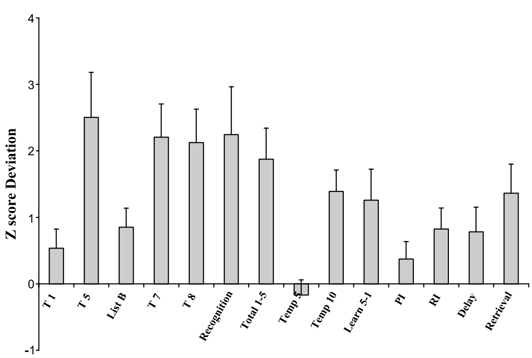

Fig. 2. Scores of children with CHI, derived from the Rey AVLT, converted to *Z*-scores.

the learning trials (Trials 1–5) and in the interference trial (Trial 6), but not with the delayed trial (Trial 8), recognition (Trial 9), or temporal order (Trial 10). Interestingly, IQ was not significantly correlated with the relational scores.

Spearman correlations were computed in order to evaluate the associations between severity of injury, as measured by length of coma, and the different memory scores derived from the Rey AVLT. Length of coma reached significance ($p < .05$) with the total number of words recalled in the first five learning trials; the longer the coma, the fewer words were recalled. Also, the longer the coma, the more words were omitted, and the stronger the retroactive interference. Length of coma was not significantly correlated with the words added (sum of the first five trials), proactive interference, retention, recognition or temporal order scores.

DISCUSSION

The findings of the present study clearly indicate that the Rey AVLT is a very informative test and useful in the characterization of impaired verbal memory following CHI in children. Furthermore, the present findings demonstrate one of the advantages of this test, that is, it allows examination of relations between the different aspects of memory within the same sample. The transformation of the scores derived from the Rey AVLT to *Z*-scores enables us to determine the relative effect of CHI in children on different memory scores. Incidental temporal order is the only score indicating that at retrieval, children with CHI rely on temporal order more than controls (see Fig. 2). However, as reported in the Results section, the difference between the groups on this score did not reach statistical significance. Scores that reflect immediate memory are the least impaired, indicating that word span is relatively preserved following CHI in children. The largest deviation of children with CHI from normal performance was found with the raw memory scores. These scores reflect absolute quantitative performance, while relational scores, which reflect the relative difference, are less impaired. Thus, the groups differ more clearly on absolute performance level and to a lesser degree on the relation between scores which reflects a qualitative difference (i.e., learning rate, forgetting rate, and discrepancy between recall and recognition-retrieval efficiency). The finding that memory difficulties detected in children with CHI using the Rey AVLT are not restricted to a particular memory stage (i.e., encoding or retrieval) indicates impairment of a more basic process that affects different memory aspects. Consistent with the conjecture of frontal lobe damage following CHI in children (Levin et al., 1997), these children seem to have difficulty in applying active or effortful strategy at either the encoding phase or at the retrieval phase of learning.

In general, the results obtained in the present study with the Rey AVLT are consistent with results obtained previously with the CVLT-C, although in some cases the Rey AVLT detected memory deficits in children with CHI not previously detected with the CVLT-C. Consistent with previous studies, impaired recall and recognition (Yeates et al., 1995; Jaffe et al., 1992, 1993) and impaired immediate and delayed recall (Roman et al., 1998) were observed. In contrast with the present findings (i.e., high rate of omissions), Yeates et al. (1995) and Roman et al. (1998) reported consistency of recall to be normal. Also, unlike the present findings, normal primacy effect was reported by Yeates et al. (1995). It is important to note that primacy and recency in the present study were derived only from the first trial (as commonly done in the literature; see Klatzky, 1980), whereas Yeates et al. derived them from the five learning trials. The higher vulnerability of the Rey AVLT over the CVLT-C to memory difficulties may be due to the fact that the former is a more difficult task, in that it requires effortful strategies for encoding and retrieval. The Rey AVLT consists of a list of unrelated words, while the CVLT-C consists of words drawn from four semantic categories, that enable clustering of words, which facilitates encoding and retrieval. The correlation between the Rey AVLT scores and severity of injury as measured by length of coma further strengthens our contention regarding the potential of this test as an informative tool for memory assessment.

Although the control and the patient groups did not differ in the recency effect, the children with CHI had a smaller primacy effect compared to controls. Primacy effect is assumed to represent transfer of information to long-term memory storage, while recency effect represents information stored in working memory (Klatzky, 1980). Accordingly, the results indicate that the children with CHI have difficulty in transferring information to long-term storage.

The overall higher number of words omitted by children with CHI as compared to controls may shed some light on the possible underlying memory deficit as expressed in the overall lower number of words recalled by these children in the five learning trials. Consistent with the impaired primacy effect, the high rate of word omissions may also reflect difficulty in transferring information to permanent long-term storage. This interpretation, which assumes a common mechanism underlying low primacy effect and high rate of words omitted, is supported by the significant correlation between the two, $r(25) = -.43$, $p < .05$. This deficit could also be viewed as an indication of impaired executive functions (e.g., clustering). The frontal lobes that are frequently damaged following CHI in children (Levin et al., 1997) are associated with deficit in executive functioning (Stuss & Benson, 1986). Similar findings with adults who sustained CHI were interpreted as reflecting an inefficient organization and learning strategy (Blachstein et al., 1993). Although, generalization from adult to pediatric studies is problematic and should be taken cautiously, due to the effect of age on learning and memory processes. The extent of frontal lobe damage in children was associated with several memory indices measured with the CVLT (Di Stefano et al., 2000). Children following CHI were reported to employ an inefficient rehearsal strategy (Catroppa & Anderson, 2002).

Studies with patients suffering from frontal lobe damage reported impaired temporal order judgment (McAndrews & Milner, 1991). Thus, the poor intentional temporal order judgment (Trial 10) of the group of patients with CHI provides an additional indication of frontal lobe dysfunction in this patient group. The dissociation between intentional and incidental retrieval of temporal order (with the former being impaired and the latter preserved) found in the present study with children who sustained CHI is consistent with previous reports on adults who sustained CHI (Vakil et al., 1991). The latter dissociation may be explained in light of previous findings which demonstrate that, just as in patients with amnesia, memory is impaired in adults with CHI when tested directly (i.e., intentional retrieval is required). However, when tested indirectly, the performance of patients with CHI falls in the normal range (Vakil et al., 2002).

Although the children with CHI were impaired in recall and recognition, the significant interaction indicates that the former is more impaired (i.e., retrieval efficiency). Contradictory findings derived from the CVLT-C with regard to the effect of CHI in children on ‘‘retrieval efficiency’’ were reported in the literature. In one study (Roman et al., 1998) retrieval efficiency was found to be preserved in these children, but Yeates et al. (1995), as in the present study, found the retrieval efficiency of children with CHI to be impaired. However, we ought to bear in mind that, despite the widely accepted view that a significant advantage of recognition over free recall indicates a retrieval deficit (Duchnick et al., 2002; Lezak, 1995), others have suggested that encoding difficulties could also contribute to such a discrepancy between recall and recognition (Delis et al., 2000). Impaired retrieval efficiency could also be interpreted as reflecting frontal lobe damage. Unlike recognition, recall requires strategic and effortful retrieval, which is mediated by the frontal lobes (Moscovitch, 1989).

Consistent with previous reports (Levin et al., 1993; Yeates et al., 1995, but see Roman et al., 1998), the children with CHI had a higher rate of intrusion errors as compared to controls. There is a debate in the literature with regard to the underlying mechanism of this deficit. Some researchers suggest that intrusion errors reflect deficient retrieval processes (Duchnick et al., 2002), or similar to confabulation, they result from inefficient monitoring, a component of strategic retrieval that is a function mediated by the frontal lobes (Moscovitch & Melo, 1997). Other researchers reported that interference at encoding yielded an increased rate of intrusion errors, indicating that such errors are related to encoding difficulties (Dalla Barba et al., 2002).

In conclusion, the findings reported above indicate that memory deficits characterizing the group of children with CHI resemble memory deficits associated with patients who sustained frontal lobe damage (i.e., inefficient organization and learning strategy, impaired temporal order judgment, deficient retrieval efficiency, and intrusion errors). Our interpretation that some of the findings reflect a frontal lobe deficit in children with CHI should at this stage be viewed as only speculative, because we do not present evidence clearly linking damage to the frontal lobes (using MRI, for instance) with memory deficit. Thus, any claim about the role of frontal lobe injury in memory performance after CHI will require further research.

Finally, we would like to make a cautionary remark with regard to the samples used in the present study. The patient group consists of children admitted to a rehabilitation hospital following CHI. These children are not necessarily representative of all children who have sustained severe head injury. Furthermore, children sustaining head injury are not a random sample of the population. Thus, a group of children selected from a standardization sample might not be the ideal matched control group. A more appropriate control group would probably be a sample of children with orthopedic injuries. These shortcomings limit the generalizability of our findings because they may have exaggerated the differences between the patient and control groups (see Donders & Hoffman, 2002).

REFERENCES

Bishop, J., Knights, R.M., & Stoddart, C. (1990). Rey Auditory Verbal Learning Test: Performance of English and French children aged 5 to 16. *The Clinical Neuropsychologist*, *4*, 133–140.

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

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

Catroppa, C., & Anderson, V. (2002). Recovery in memory function in the first year following TBI in children. *Brain Injury*, *16*, 369–384.

Dalla Barba, G., Mantovan, M.C., Traykov, L., Rieu, D., Laurent, A., Ermani, M., & Devouche, E. (2002). The functional locus of intrusions: Encoding or retrieval? *Journal of Clinical and Experimental Neuropsychology*, *24*, 633–641.

Delis, D.C., Kramer, J.H., Kaplan, E., & Ober, B.A. (1989). *California Verbal Learning Test: Children's version, research edition*. San Antonio, TX: The Psychological Corporation.

Delis, D.C., Kramer, J.H., Kaplan, E., & Ober, B.A. (2000). *California Verbal Learning Test – Second edition, adult version, manual.* San Antonio, TX: The Psychological Corporation.

Di Stefano, G., Bachevalier, J., Levin, H.S., Song, J.X., Scheibel, R.S., & Fletcher, J.M. (2000). Volume of focal brain lesions and hippocampal formation in relation to memory function after closed head injury in children. *Journal of Neurology, Neurosurgery and Psychiatry*, *69*, 210–216.

Donders, J., & Hoffman, N.M. (2002). Gender differences in learning and memory after pediatric traumatic brain injury. *Neuropsychology*, *16*, 491–499.

Duchnick, J.J., Vanderploeg, R.D., & Curtiss, G. (2002). Identifying retrieval problems using the California Verbal Learning Test. *Journal of Clinical and Experimental Neuropsychology*, *24*, 840–851.

Forrester, G., & Geffen, G. (1991). Performance measures of 7- to 15-year-old children on Auditory Verbal Learning Test. *The Clinical Neuropsychologist*, *5*, 345–359.

Geffen, G., Butterworth, P., Forrester, G., & Geffen, L. (1994). Auditory verbal learning test components as measures of the severity of closed-head injury. *Brain Injury*, *8*, 405–411.

Jaffe, K.M., Fay, G.C., Polissar, N.L., Martin, K.M., Shurtleff, H., Rivara, J.B., & Winn, H.R. (1992). Severity of pediatric traumatic brain injury and early neurobehavioral outcome: A cohort study. *Archives of Physical Medicine and Rehabilitation*, *73*, 540–547.

Jaffe, K.M., Fay, G.C., Polissar, N.L., Martin, K.M., Shurtleff, H., Rivara, J.B., & Winn, H.R. (1993). Severity of pediatric traumatic brain injury and neurobehavioral recovery at one year: A cohort study. *Archives of Physical Medicine and Rehabilitation*, *74*, 587–595.

Kinsella, G.J., Prior, M., Sawyer, M., Ong, B., Murtagh, D., Eisenmajer, R., Bryan, D., Anderson, V., & Klug, G. (1997). Predictors and indicators of academic outcome in children 2 years following traumatic brain injury. *Journal of the International Neuropsychological Society*, *3*, 608–616.

Klatzky, R.L. (1980). *Human memory* (2nd ed.). San Francisco: W.H. Freeman.

Lannoo, E., Colardyn, F., Jannes, C., & De Soete, G. (2001). Course of neuropsychological recovery from moderate-to-severe head injury: A 2-year follow-up. *Brain Injury*, *15*, 1–13.

Levin, H.S., Culhane, K.A., Fletcher, J.H.M., Mendelsohn, D.B., Matthew, A.L., Harward, H.N., Chapman, S.B., Bruce, D.A., Bertolion-Kusnerik, L., & Eisenberg, H.M. (1994). Dissociation between delayed alteration and memory after pediatric head injury: Relationship to MRI findings. *Journal of Child Neurology*, *9*, 81–89.

Levin, H.S., Culhane, K.A., Mendelsohn, D., Lilly, M.A., Bruce, D., Fletcher, J.H.M., Chapman, S.B., Harward, H., & Eisenberg, H.M. (1993). Cognition in relation to MRI in head injured children and adolescents. *Archives of Neurology*, *50*, 897–905.

Levin, H.S., & Eisenberg, H.M. (1979). Neuropsychological impairment after closed-head injury in children and adolescents. *Journal of Pediatric Psychology*, *4*, 389–402.

Levin, H.S., Eisenberg, H.M., Wigg, N.R., & Kobayashi, K. (1982). Memory and intellectual ability after head injury in children and adolescents. *Neurosurgery*, *11*, 668–673.

Levin, H.S., Mendelsohn, D., Lilly, M.A., Yeakley, J., Song, J., Scheibel, R.S., Harward, H., Fletcher, J.H.M., Kufera, J.A., Davidson, K.C., & Bruce, D. (1997). Magnetic resonance imaging in relation to functional outcome of pediatric closed-head injury: A test of the Ommaya-Gennarelli Model. *Neurosurgery*, *40*, 432–441.

Levin, H.S., Song, J., Scheibel, R.S., Fletcher, J.H.M., Harward, H.N., & Chapman, S.B. (2000). Dissociation of frequency and recency processing from list recall after severe closed-head injury in children and adolescents. *Journal of Clinical and Experimental Neuropsychology*, *22*, 1–15.

Lezak, M.D. (1995). *Neuropsychological assessment* (3rd ed.). New York: Oxford University Press.

McAndrews, M.P., & Milner, B. (1991). The frontal cortex and memory for temporal order. *Neuropsychologia*, *29*, 849–859.

Moscovitch, M. (1989). Confabulation and the frontal systems: Strategic vs. associative retrieval in neuropsychological theories of memory. In H.L. Roedinger & F.I. Craik (Eds.), *Varieties of memory and consciousness: Essays in honor of Endel Tulving* (pp. 133–160). Hillsdale, NJ: Erlbaum.

Moscovitch, M., & Melo, B. (1997). Strategic retrieval and the frontal lobes: Evidence from confabulation and amnesia. *Neuropsychologia*, *35*, 1017–1034.

Roman, M.J., Delis, D.C., Willerman, L., Magulac, M., Demadura, T.L., De La Pena, J.L., Loftis, C., Walsh, J., & Kracun, M. (1998). Impact of pediatric traumatic brain injury on components of verbal memory. *Journal of Clinical and Experimental Neuropsychology*, *20*, 245–258.

Stuss, D.T., & Benson, D.F. (1986). *The frontal lobes*. New York: Raven Press.

Vakil, E., & Blachstein, H. (1994). A supplementary measure in the Rey AVLT for assessing incidental learning of temporal order. *Journal of Clinical Psychology*, *50*, 240–245.

Vakil, E., & Blachstein, H. (1997). Rey AVLT: Developmental norms for adults and the sensitivity of different memory measures to age. *The Clinical Neuropsychologist*, *11*, 356–369.

Vakil, E., Blachstein, H., & Hoofien, D. (1991). Automatic temporal order judgment: The effect of intentionality of retrieval on closed-head-injured patients. *Journal of Clinical and Experimental Neuropsychology*, *13*, 291–298.

Vakil, E., Blachstein, H., & Sheinman, M. (1998). Rey AVLT: Developmental norms for children and the sensitivity of different memory measures to age. *Child Neuropsychology*, *4*, 161–177.

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

Wechsler, D.A. (1981). *Wechsler Adult Intelligence Scale – Revised*. New York: The Psychological Corporation.

Wechsler, D.A. (1991). *Wechsler Intelligence Scale for Children – Third edition*. San Antonio, TX: The Psychological Corporation.

Yeates, K.O., Blumenstein, E., Patterson, C.M., & Delis, D.C. (1995). Verbal learning and memory following pediatric closed-head injury. *Journal of the International Neuropsychological Society*, *1*, 78–87.

Zola-Morgan, S., & Squire, L.R. (1993). Neuroanatomy of memory. *Annual Review of Neuroscience*, *16*, 547–563.