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Patterns of verbal learning and memory in traumatic brain injury

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Abstract

CVLT and WMS–R Digit Span variables were used to calculate indexes of seven specific short- and long-term memory processes: working memory span and central executive functions, and long-term memory encoding, consolidation, retention, retrieval, control abilities. Scores on these indexes were then cluster-analyzed to determine whether subtypes of memory performance exist that correspond to deficits in these theoretical memory constructs. Parallel analyses were conducted with two large samples ($N = 150$ and $N = 151$) of individuals who had sustained a traumatic brain injury (TBI). Findings showed that TBI results in subgroups of memory disorders with specific deficits in consolidation, retention, and retrieval processes. Control problems (keeping track of list *versus* non-list items) only appeared in conjunction with retrieval deficits. Working memory span and central executive functioning (i.e., the ability to manipulate information in working memory) do not appear to be deficits characteristic of TBI as no such clusters emerged in the analyses. By using specific indexes of memory processes, and in contrast to previous studies, patterns of memory dysfunction were found that correspond to deficits in theoretically meaningful memory constructs. (*JINS*, 2001, *7*, 574–585.)

Keywords: TBI, Memory deficits, Consolidation, Retention, Retrieval, CVLT

INTRODUCTION

Memory and learning impairment is often present following traumatic brain injury (TBI), although the presentation of deficits can be influenced by a variety of factors (Crosson et al., 1988; Deshpande et al., 1996; Levin et al., 1990). While early research on memory impairment following TBI focused primarily on identifying the presence and severity of memory problems, more recent research has focused on identifying patterns of learning and memory disorders in TBI (Crosson et al., 1989; Deshpande et al., 1996; Haut & Shutty, 1992; Millis & Ricker, 1994). The California Verbal Learning Test (CVLT) has often been used to explore these patterns because it was designed to provide information on a variety of verbal learning processes as well as recall abilities (Delis et al., 1987; Haut & Shutty, 1992). For example, the CVLT includes a recognition task in addition to recall tasks to help dissociate retrieval difficulties from retention problems.

One method of exploring patterns of learning and memory performance on the CVLT following TBI has been to use cluster analytic procedures. Haut and Shutty (1992) cluster-analyzed CVLT scores from 70 individuals who had sustained closed head injuries. Results yielded three groups which the authors concluded represented three distinct patterns of verbal learning and memory performance within the TBI population. However, Millis and Ricker (1994) noted that while each of the groups differed on absolute level of performance, they did not differ on pattern. They suggested that these results were caused by a restriction in the verbal learning domains examined. Based on CVLT factor analytic studies (e.g., Delis et al., 1988), Millis and Ricker found that, with one exception, all the variables in the Haut and Shutty study represented the same general verbal-learning factor.

Therefore, Millis and Ricker (1994) attempted to determine whether different patterns of performance emerged in TBI when CVLT variables that represented different verbal-

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learning domains were selected. They selected five CVLT variables for cluster analysis, one representing each of five different factors found by Delis et al. (1988). Results of this cluster analysis yielded five subgroups but only four were considered interpretable due to a small number of participants in one of the clusters. The four groups were found to have distinct patterns of memory deficits. The *Active* group was characterized by use of an active semantic encoding strategy, while the *Passive* group tended to rely on serial position. The *Disorganized* group produced high rates of false positive responses, had low discriminability and consistency scores, and showed a large proactive interference effect. The *Deficient* group was the most impaired and was characterized by slow acquisition rate with rapid forgetting which was felt to suggest encoding difficulties.

Deshpande et al. (1996) conducted a replication of the Millis and Ricker (1994) investigation in a separate sample of TBI survivors. In addition to using the same CVLT variables as those used by Millis and Ricker, several cluster-analytic methods were employed to examine the stability of cluster solutions. Results of the various cluster-analytic methods generally converged on a five group solution. Four of the groups corresponded to the *Active*, *Passive*, *Disorganized*, and *Deficient* groups of Millis and Ricker and one group, comprised of only 4 individuals, corresponded to both the Disorganized and Deficient patterns.

These studies by Millis and Ricker (1994) and Deshpande et al. (1996) represent a significant step forward in our understanding of the impact of TBI on learning and memory processes. However, the findings are somewhat limited because the identified patterns of Active, Passive, Disorganized, and Deficient do not reflect current models of specific verbal learning and memory disorders (e.g., deficits in consolidation, retrieval, retention, etc.). Wiegner and Donders (1999) attempted to remedy this situation by using confirmatory factor analysis to fit eight different theoretical memory models to CVLT data obtained from 150 individuals who had sustained mild, moderate, or severe brain injuries. *Z*-score values for 14 CVLT variables thought to reflect level of performance and learning strategy were selected for analysis. The four-factor model comprised of Attention Span, Learning Efficiency, Delayed Recall, and Inaccurate Recall was judged to best fit these variables. The authors then selected the one CVLT variable from each of the four factors that had the highest factor loading and cluster-analyzed these marker scores. Results of this analysis yielded four groups. Two groups were judged to differ only in level of performance while the other two were deemed to differ in pattern. The patterns of performance for these latter two groups were similar on all marker variables except for number of intrusions during cued recall (Inaccurate Recall factor). Thus, some support was found for differential patterns of learning and memory abilities following TBI but mainly the data revealed differences in overall level of learning and memory abilities.

One of the reasons why there has been little or no evidence of differential memory patterns may reside in the nature of the measures employed. Haut and Shutty (1992), Millis and Ricker (1994), Deshpande et al. (1996), and Wiegner and Donders (1999) all used scales measuring single aspects of learning and memory processes. However, many memory processes are relational. For example, retention can only be defined in relation to the amount of information acquired at some earlier time. Similarly, deficits in retrieval can be understood more clearly when comparing cued (or prompted recall) performance with free recall. The memory factor of Delayed Recall found by Wiegner and Donders provides no information on whether deficits in delayed recall ability are a function of difficulties in consolidation, retention, retrieval, or an interaction of these and/or other learning processes. It may be that the examination of more direct measures of these processes would yield information regarding the specific nature of the memory difficulties associated with TBI. Furthermore, patterns of deficits indicating specific problems in consolidation *versus* retention *versus* retrieval would have implications for alternative rehabilitation approaches.

The present study attempted to determine if memory disorder subtypes exist within TBI that correspond to deficits in underlying current conceptualizations of theoretical memory constructs. Limitations of previous cluster-analytic studies were addressed by developing direct measures of working memory span and central executive abilities, and long-term memory (LTM) processes of encoding, consolidation, retention, and retrieval (Albert et al., 1981; Baddeley, 1976; Cermak & Butters, 1972). CVLT variables (Delis et al., 1987) along with the Digit Span subtest of the Wechsler Memory Scale-Revised (WMS–R; Wechsler, 1987) were used to derive these indexes. Index scores were then cluster-analyzed to identify homogeneous patterns of memory performance in TBI survivors. Finally, to demonstrate the validity of these memory disorder clusters, external correlates of the different memory cluster groups were examined.

METHODS

Research Participants

Participants were 301 individuals who had sustained a nonpenetrating head injury with resultant TBI. For the purposes of this study, they were divided into those evaluated and treated at VA medical centers ($N = 151$) *versus* at military medical centers ($N = 150$). All individuals were on active military duty or were military veterans enrolled in the Defense and Veterans Head Injury Program (DVHIP). The DVHIP is a collaborative treatment and research project between the Department of Defense (DoD) and the Department of Veterans Affairs (VA). Four VA medical centers (Tampa, Florida; Minneapolis, Minnesota; Palo Alto, California; and Richmond, Virginia) and three DoD medical centers (Walter Reed Army Medical Center, San Diego Naval Hospital, and Wilford Hall Air Force Medical Center) comprise the DVHIP clinical treatment and research centers.

Because of differences in the organizations' missions, VA treatment facilities tend to see a greater proportion of individuals who have sustained more severe brain injuries (69% of the sample experienced coma and/or post-traumatic amnesia for longer than 1 week) while DoD treatment facilities tend to see individuals who have sustained mild to moderate brain injuries (63% of the sample experienced coma and/or post-traumatic amnesia for 1 week or less).

Brain injury was confirmed by documentation in the medical record of some traumatic event in conjunction with subsequent loss of or alteration of consciousness, a Glasgow Coma Scale score (GCS; Teasdale & Jennett, 1974) of less than 15 or post-traumatic amnesia greater than 1 min, and/or positive signs of traumatic changes of the brain on CT or MRI scans. Table 1 presents demographic characteristics and basic descriptive information for these two samples.

All individuals underwent standard comprehensive medical and neuropsychological evaluations as part of their routine clinical care. Participants were selected for inclusion in this study if (1) they had emerged from post-traumatic amnesia at the time of evaluation, (2) they had completed the CVLT and the Digit Span subtest of the WMS–R, (3) there was no indication of a significant language disorder, and (4) either the individual or his or her legal guardian had given written informed consent to participate in the research.

Table 1. Demographic characteristics by site

Variable	VA ($N = 151$)		DoD ($N = 150$)	
Age in years [*M* (*SD*)]	32.3	(12.1)	30.6	(13.6)
Weeks since injury [*M* (*SD*)]	46.4	(181.6)	56.8	(100.5)
Gender [*N* (%)]				
Male	136	(90.1)	124	(82.7)
Female	15	(9.9)	26	(17.3)
Race [*N* (%)]				
White	109	(74.7)	103	(76.3)
Black	24	(16.4)	15	(11.1)
Hispanic	5	(3.4)	10	(7.4)
Asian	3	(2.1)	4	(3.0)
Other	5	(3.4)	3	(2.2)
Education level [*N* (%)]				
Less than 12 years	19	(13.4)	3	(2.4)
12 years	56	(39.4)	53	(42.4)
13–15 years	49	(34.5)	45	(36.0)
16 years	6	(4.2)	16	(12.8)
Greater than 16 years	1	(0.7)	7	(5.6)
Vocational training	11	(7.7)	1	(0.8)
Cause of injury [*N* (%)]				
Motor vehicle accident	92	(91.1)	42	(89.4)
Assault	9	(8.9)	5	(10.6)
Post-traumatic amnesia (including coma) [*N* (%)]				
1–15 min	3	(2.4)	6	(9.4)
16–60 min	2	(1.6)	4	(6.3)
1–24 hr	5	(4.0)	17	(26.6)
1–7 days	28	(22.2)	9	(14.1)
8–30 days	45	(35.7)	18	(28.1)
Greater than 30 days	43	(34.1)	10	(15.6)

Note. Demographic variables presented were based on available data. Some data were not available for all participants.

Measures

Index scores of specific memory processes

Seven indexes of short- and long-term memory processes were operationally defined using CVLT and WMS–R Digit Span subtest scores. These scores were: working memory span and central executive functions, and long-term memory encoding, consolidation, retention, retrieval, control abilities. Participants were randomly assigned to receive either the original CVLT or an alternate form (Delis et al., 1991). CVLT protocols were scored using the software developed by Fridlund and Delis (1987). Because of the differing nature of the VA and DoD samples, analyses were conducted separately within each sample. Each index score was standardized to have a mean of zero and a standard deviation of 1 within each sample. Table 2 lists the seven index scores along with their operational (computational) definitions.

Span was conceptualized in accordance with Baddeley (1976) as the ability to hold an adequate amount of information in working memory. The *Central Executive* score is a residual score and measures the ability to manipulate information in working memory, regardless of span capacity (Baddeley, 1976; see Table 2). *Consolidation* was operationally defined as consistent (percent recall consistency) and effective learning over five learning trials (learning slope and total words reported on learning trials). *Encoding* was defined as the ability to impose and use an effective semantic strategy to encode information during learning (see Table 2). *Retention* reflects the ability to maintain learned information over time, that is, long delayed cued recall compared to Learning Trial 5. For this retention measure, long delayed cued recall was used rather than long delayed free recall to minimize the adverse impact of any retrieval problems on this retention index. *Retrieval* measures the ability to retrieve learned information from long-term memory stores. This was computed by averaging across differences in relative performance between free *versus* cued or between free *versus* recognition scores at similar time points. Finally, the *Control* index was based on previously published performance characteristics of TBI survivors (Crosson et al., 1988; Wiegner & Donders, 1999) where problems with intrusive or perseverative memory responses differentiated TBI from controls. *Control* was therefore defined as the ability to keep track of list items *versus* non-list items (intrusions or false positives), as well as keeping track of whether or not an item had been reported previously (perseverations).

Table 2. Derivations of short- and long-term memory indexes

Short-term memory indices	
Span[1] = (CVLT List A Trial 1 + CVLT List B + WMS–R Digit Span Forward)/3	
Central Executive[2] = Residual of (WMS–R Digit Span Backward − Forward)	
Long-term memory indices	
Encoding[3] = Semantic Cluster Ratio	
Consolidation[4] = (Percent Recall Consistency Trials 1–5 + Learning Slope + Sum of Trials 1–5)/3	
Retention[5] = Long-Delay Cued Recall/List A Trial 5	
Retrieval[6] = [(Short-Delay Free Recall/Short-Delay Cued Recall) + (Long-Delay Free Recall/Long-Delay Cued Recall) + (Long-Delay Cued Recall/Recognition Hits)]/3	
Control[7] = (Free Recall Intrusions + Cued Recall Intrusions + False Positives)/3	

Note. All index scores are calculated *z* scores derived within each sample.
[1]CVLT List A Trial 1, List B, and WMS–R Digit Span Forward were converted from raw scores to *z* scores for this calculation. The calculated Span index score was the average *z* score for these three measures.
[2]Residual is the residual score obtained from multiple regression analysis predicting Backward span from Forward span.
[3]The CVLT Semantic Cluster Ratio was converted from a raw score to *z* score.
[4]CVLT variables of Percent Recall Consistency, Learning Slope, and sum of Trials 1–5 were individually converted to *z* scores. The calculated Consolidation index score was the average *z* score for these three measures.
[5]The Retention index was the proportion of items recalled at long-delay divided by the proportion of items recalled at the end of acquisition. The following equation was used: [(Long-Delay Cued Recall/16)/(List A Trial 5/16)]. The resulting ratio was then converted to a *z* score.
[6]CVLT raw scores were used to calculate the component proportions of the Retrieval index. For example, [(Short-Delay Free Recall/16)/(Short-Delay Cued Recall/16)]. The three component proportions were averaged and the average was then converted to a *z* score.
[7]The CVLT intrusions and false positive scores were first converted to *z* scores. The calculated Control index score was the average *z* score of these three CVLT measures.

External correlates

To examine the validity of any derived clusters, external correlates were examined. Demographic external correlates included: gender, race, age, education, length of coma plus post-traumatic amnesia, and weeks since injury. Selected neuropsychological external correlates included the Controlled Oral Word Association subtest (COWA) from the Multilingual Aphasia Exam (Benton & Hamsher, 1989), Boston Naming Test (BNT) and Animal Naming from the Boston Diagnostic Aphasia Exam (Goodglass & Kaplan, 1983), Supermarket Item Naming (Randolph et al., 1993), the Logical Memory I and II and Visual Reproduction I and II subtests of the WMS–R (Wechsler, 1987), the Trail Making Test Parts A and B (Reitan, 1958), Stroop Color and Word Test (Golden, 1978), the Block Design and Digit Symbol subtests of the Wechsler Adult Intelligence Scale-Revised (WAIS–R; Wechsler, 1981), and the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948; Heaton et al., 1993). The WCST was administered and scored using the computerized version developed by Heaton (1993). Table 3 lists the specific scores used in the current study.

A number of scores from the above instruments were used to derive additional external correlate scores measuring different neuropsychological constructs. For example, *percent of information retained* scores for the WMS–R Logical Memory and Visual Reproduction subtests served as measures of retention independent of the CVLT. These were defined as performance on delayed recall divided by performance on immediate recall multiplied by 100. Also, measures of overall memory and of overall cognitive abilities were created. Overall memory ability (*Global Memory Index*) was defined as the age adjusted mean scores of WMS–R Logical Memory II and Visual Reproduction II performance. Overall cognitive ability (*Cognitive Ability Index*) was comprised of performance on the BNT, COWA, WCST, Trails B, and WAIS–R Block Design and Digit Symbol subtests and served as an independent assessment of the severity of cognitive deficit at the time of testing. The residual score of Trails B Time to Completion predicted from Trails A Time to Completion obtained through regression analysis constituted a measure of cognitive flexibility and tracking ability (*Executive Trails*) with psychomotor speed removed. Table 3 also presents the external correlates and the computational formulae for these derived scores.

Table 3. External correlates

Gender
Race
Educational level
Age at time of testing
Weeks since injury
Length of coma plus post traumatic amnesia
Cognitive Ability Index[1] = (BNT Total + COWA Total + WCST Perseverative Responses + Trails B Time + WAIS–R Block Design Age-corrected Scale Score + WAIS–R Digit Symbol Age-corrected Scale Score)/6
Global Memory Index = (Logical Memory II deviation IQ equivalent + Visual Reproduction II deviation IQ equivalent)/2
Logical Memory Percent Retained = (Logical Memory II raw score/ Logical Memory I raw score) × 100
Visual Reproduction Percent Retained = (Visual Reproduction II raw score/Visual Reproduction I raw score) × 100
Executive Trails[2] = Residual of (Trails B − Trails A)
Stroop Color-Word *T* score = Age-adjusted *T* score

[1]Scores were converted to *z* scores prior to averaging.
[2]Residual is the residual score obtained from multiple regression analysis predicting performance on Trails B from Trails A.

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Statistical analyses

The seven memory process index scores were subjected to cluster-analytic procedures to determine the existence of homogeneous subgroups of performance patterns. Because of the differing nature of the VA and DoD samples, analyses were conducted separately within each sample. Each index score was standardized to have a mean of zero and a standard deviation of 1 within each sample prior to analysis to reduce the impact of widely differing variances on the cluster analysis results.

Following the recommendations of Aldenderfer and Blashfield (1984), Ward's method of hierarchical cluster analysis was used to evaluate the number of clusters present in each data set. Squared Euclidean distance was the similarity measure analyzed. Convergence of the cubic clustering criterion (Sarle, 1983), pseudo-*F* statistic (Calinski & Harabasz, 1974), and pseudo-t^2 statistic (Duda & Hart, 1973) were the criteria used for determining the number of groups present in each data set. Solutions with one more and one less group were also examined to determine whether other solutions appeared more viable. Cluster group membership was then determined by a *k*-means iterative partitioning procedure. Following group assignment, a one-way multivariate analysis of variance (MANOVA) was conducted on the seven memory process scores using cluster group membership as the independent variable as another check of the viability of the cluster solution.

Cattell's profile similarity coefficient (r_p) was used to evaluate the similarity of profiles across the two samples (Cattell, 1949). This coefficient takes into account both profile shape and mean level of performance. Values near 1.00 indicate highly similar profiles, while negative values and values near 0.00 indicate different profiles.

Differences among cluster groups with respect to external validity correlates were evaluated by contingency table analysis and analysis of variance (ANOVA) procedures depending on the level of measurement of the external correlate. Type I error rate was set at .05. Tukey's method of pairwise comparison was used as follow-up testing in the case of a significant *F*-ratio.

RESULTS

Cluster Analyses

VA sample

Examination of the number-of-clusters statistics for the VA sample indicated that a five-group solution best represented the data. Follow-up analysis of the index scores verified that differences in patterns of verbal learning and memory performance existed among the derived cluster groups [Wilks's Lambda = 0.04; $F(28, 506.20) = 25.27$, $p < .0001$]. Table 4 presents the mean index scores for each group. To assist in evaluating the characteristic learning and memory pattern of each group, raw scores on the WMS–R Digit Span subtests and CVLT scales comprising the seven index scores were plotted in Figure 1.

Table 4. Mean memory process index scores by cluster group and sample

	Cluster				
Sample	I	II	III	IV	V
VA sample					
n	26	40	9	45	31
Span	0.64	0.34	−0.49	−0.32	−0.36
Central Executive	0.19	0.32	−0.42	−0.21	−0.13
Encoding	*1.64*	−0.19	−0.49	−0.42	−0.37
Consolidation	0.99	0.43	*−1.02*	−0.29	−0.68
Retention	0.42	0.52	*1.88*	*−0.71*	−0.54
Retrieval	0.94	0.57	−0.20	0.02	*−1.57*
Control	0.40	0.38	0.06	0.04	*−0.90*
DoD sample					
n	39	63	3	25	20
Span	0.53	0.02	0.67	−0.57	−0.48
Central Executive	0.12	0.07	0.41	−0.53	0.16
Encoding	*1.21*	−0.41	*1.20*	−0.39	−0.73
Consolidation	0.56	0.09	0.16	−0.36	*−0.97*
Retention	0.55	0.30	−0.57	*−1.47*	0.00
Retrieval	0.63	0.23	0.08	−0.32	*−1.68*
Control	0.37	0.29	*−2.14*	−0.40	*−0.82*

As seen in Table 4, Cluster I ($n = 26$) was characterized by all index scores being above the TBI standardized mean of zero and by a particularly high score on Encoding. This profile appears to represent a normal or no memory impairment subtype. The data presented in Figure 1 indicate intact memory abilities in this subgroup as evidenced by adequate working memory capacity (List A Trial 1 = 6.54, List B = 6.15), intact consolidation, retrieval, and retention abilities (List A Trial 5 = 12.42, Short-Delay Free Recall = 10.77, Long-Delay Free Recall = 11.31), and demonstrable use of an efficient encoding strategy (Semantic Cluster Ratio = 2.45).

Cluster II ($n = 40$) also was characterized by index scores above the TBI standardized mean of zero with the exception of Encoding, which was slightly below the mean (see Table 4). As seen in Figure 1, working memory capacity appears adequate (List A Trial 1 = 5.78, List B = 5.20) along with consolidation, retrieval, and retention abilities (List A Trial 5 = 9.95, Short-Delay Free Recall = 8.35, Long-Delay Free Recall = 8.53). However, when compared with Cluster I, Cluster II had significantly lower Semantic Cluster Ratio scores [$M_{\text{Cluster I}} = 2.45$, $M_{\text{Cluster II}} = 1.20$; $t(64) = 11.37$, $p < .0005$] and significantly higher Serial Cluster Ratio scores [$M_{\text{Cluster I}} = 1.95$; $M_{\text{Cluster II}} = 3.11$, $t(64) = -2.65$, $p < .01$]. Thus, Cluster II also appears to represent a normal or no memory impairment subtype but one characterized by the use of a serial position strategy, rather than semantic, for encoding information.

Cluster III was comprised of a small group of participants ($n = 9$) whose performance was below the mean on

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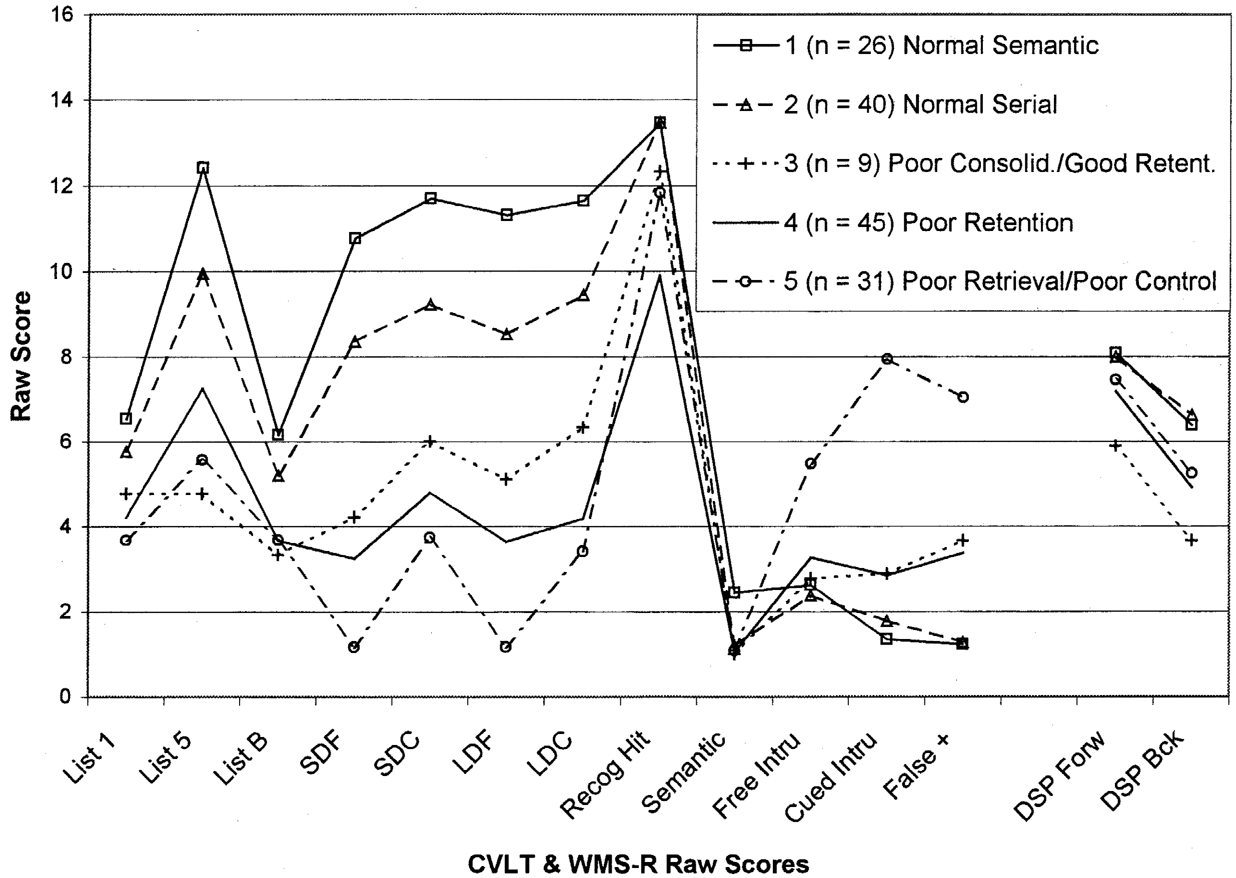

Fig. 1. CVLT and WMS–R raw score profiles for VA sample cluster groups.

all but two index scores and with notably low scores on Consolidation and high scores on Retention (see Table 4). As seen in Figure 1, Cluster III shows relatively poor working memory capacity (List A Trial 1 = 4.78, List B = 3.33). Additionally, there was virtually no increase with rehearsal (List A Trial 5 = 4.78) and recall scores were low (Short-Delay and Long-Delay Free Recall = 4.22 and 5.11, respectively). Memory performance, however, was relatively stable over time compared with Trial 5 on both free-recall and cued-recall tasks (List A Trial 5 = 4.78, Short-Delay Free Recall = 4.22, Short-Delay Cued Recall = 6.00, Long-Delay Free Recall = 5.11, and Long-Delay Cued Recall = 6.33). This profile appears to represent a subtype with impairment in consolidating information into long-term memory but with the ability to retain the limited amount of information that was acquired.

Cluster IV (n = 45) also performed below the mean on all but two index scores but achieved the lowest mean score on Retention of any cluster group (see Table 4). Examination of the raw scores (see Figure 1) shows relatively poor working memory capacity (List A Trial 1 = 4.22 and List B = 3.67) but the ability to acquire information with rehearsal (List A Trial 5 = 7.24). However, mean recall scores were impaired relative to Trial 5 regardless of time of recall or use of semantic cues (Short-Delay Free Recall = 3.24, Short-Delay Cued Recall = 4.80, Long-Delay Free Recall = 3.64, and Long-Delay Cued Recall = 4.18). These data represent a pattern indicative of retention deficits.

Mean index score values were all below the TBI standardized mean of zero for Cluster V (n = 31). Notably, this group obtained the lowest mean of all the groups in this sample on Retrieval and Control scores (see Table 4). The profile of raw scores presented in Figure 1 shows poor working memory capacity (List A Trial 1 = 3.67 and List B = 3.67) but some ability to acquire additional information (List A Trial 5 = 5.58). Difficulty in retrieval ability is seen in the "sawtooth" pattern of lower free recall performance compared with cued recall performance (Short-Delay Free Recall = 1.16, Short-Delay Cued Recall = 3.74, Long-Delay Free Recall = 1.16, and Long-Delay Cued Recall = 3.42). This group also had more intrusions and false positive responses than any other (Free Recall Intrusions = 5.48, Cued Recall Intrusions = 7.94, False Positives = 7.03). As seen in Figure 1, this group performed poorly on almost all measures. Thus, this pattern represents retrieval and control deficits, as well as deficiencies in all memory processes.

DoD sample

A parallel set of analyses was conducted within the DoD sample. Examination of the number-of-clusters statistics also indicated that a five-group solution best represented the

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data. Follow-up analysis of the index scores verified that differences in patterns of performance existed among the cluster groups [Wilks's Lambda = 0.06; $F(28, 502.59) = 20.56$, $p < .0001$]. Table 4 presents the mean index scores for each of these groups. As before, raw scores on the CVLT scales and WMS–R Digit Span subtests comprising the index scores were plotted. Figure 2 presents these data.

Cluster I ($n = 39$) was characterized by all index scores being above the TBI standardized mean of zero and by a particularly high score on Encoding. This profile appears to represent a normal or no memory impairment subtype. The data presented in Figure 2 indicate intact memory abilities in this subgroup as evidenced by adequate working memory capacity (List A Trial 1 = 7.41, List B = 7.00), intact consolidation, retrieval, and retention abilities (List A Trial 5 = 12.41, Short-Delay Free Recall = 11.80, and Long-Delay Free Recall = 12.08), and demonstrable use of an efficient encoding strategy (Semantic Cluster Ratio = 2.38).

Cluster II ($n = 63$) also obtained index scores above the TBI standardized mean of zero with the exception of Encoding (see Table 4). As seen in Figure 2, working memory capacity is adequate (List A Trial 1 = 6.00, List B = 5.29) along with adequate consolidation, retrieval, and retention abilities (List A Trial 5 = 11.00, Short-Delay Free Recall = 9.51, Long-Delay Free Recall = 9.89). Comparing Cluster I with Cluster II, Cluster II had significantly lower Semantic Cluster Ratio scores [$M_{\text{Cluster I}} = 2.34$, $M_{\text{Cluster II}} = 1.24$; $t(100) = 11.51$, $p < .0005$] and significantly higher Serial Cluster Ratio scores [$M_{\text{Cluster I}} = 1.40$, $M_{\text{Cluster II}} = 3.41$; $t(99) = -4.38$, $p < .0005$]. In this sample, Cluster II also appears to represent a normal or no memory impairment subtype but one that is characterized by the use of a serial position, rather than semantic, strategy for encoding information.

Cluster III was comprised of a very small number of participants ($n = 3$) whose performance was above the mean on all but two index scores, Retention and Control, with Control being exceptionally low. Encoding was exceptionally high. Despite being comprised of only 3 individuals, this cluster was also found in the four- and six-group solutions so it was deemed stable and reliable. Examination of the raw CVLT record booklets, however, revealed very high numbers of repeated responses, that is, perseverations which appeared to be self-cues rather than intended memory responses. Given the small size of this cluster and the suspect nature of the data, this group was eliminated from subsequent analyses.

Cluster IV ($n = 25$) performed below the mean on all index scores and obtained the lowest mean Retention score of any cluster group in this sample (see Table 4). Examina-

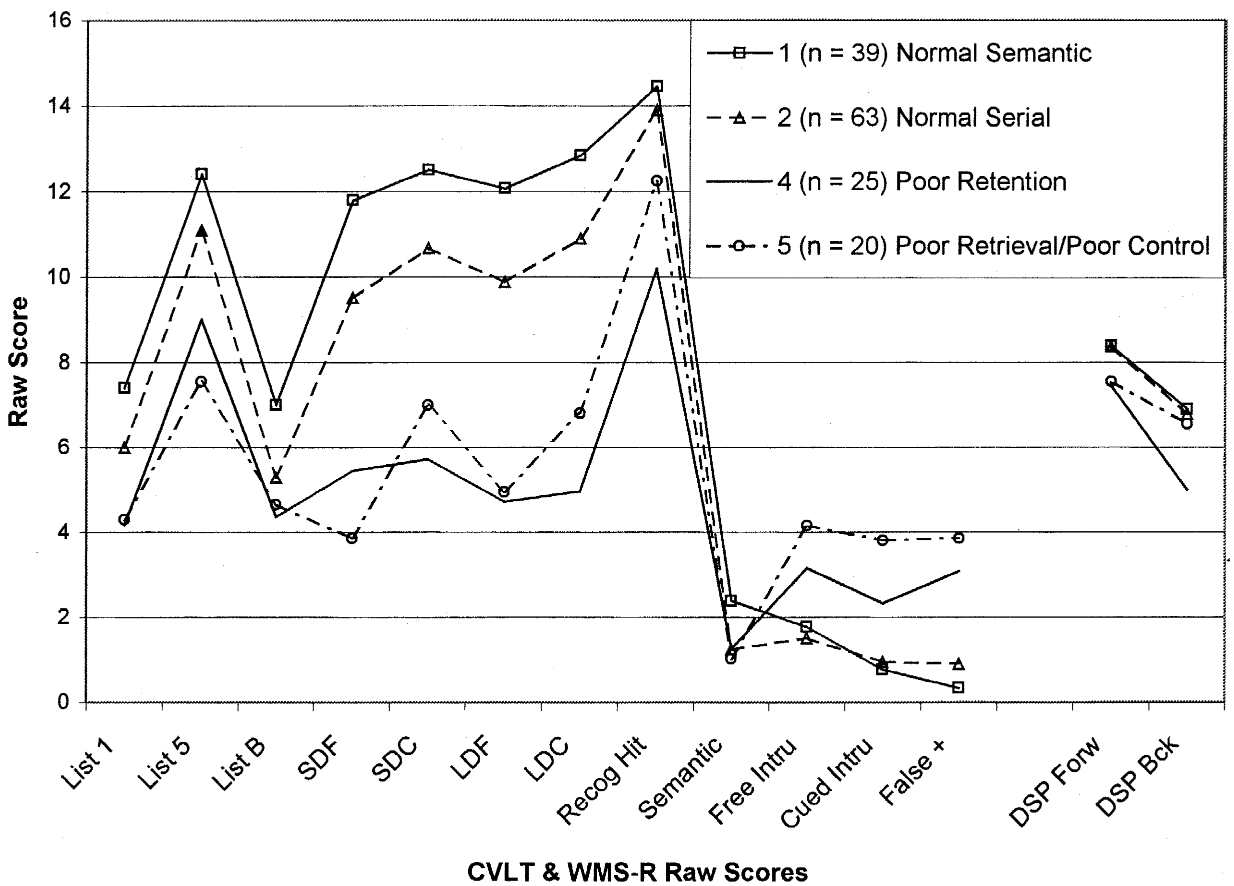

Fig. 2. CVLT and WMS–R raw score profiles for DoD sample cluster groups.

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Table 5. Cattell's profile similarity coefficients (r_p) comparing VA and Department of Defense cluster groups

	Department of Defense cluster group			
VA cluster group	I Normal Semantic	II Normal Serial	IV Poor Retention	V Poor Retrieval/ Poor Control
I Normal Semantic	*.925*	.364	−.040	−.204
II Normal Serial	.720	*.924*	.251	.131
III Poor Consolidation/Good Retention	.156	.478	.031	.296
IV Poor Retention	.337	.792	*.847*	.448
V Poor Retrieval/Poor Control	.005	.346	.619	*.906*

tion of the profile in Figure 2 shows relatively poor working memory capacity (List A Trial 1 = 4.16 and List B = 4.36) but the ability to acquire additional information with rehearsal (List A Trial 5 = 9.00). However, mean recall scores were impaired relative to Trial 5, regardless of time of recall or provision of semantic cues (Short-Delay Free Recall = 5.44, Short-Delay Cued Recall = 5.72, Long-Delay Free Recall = 4.72, and Long-Delay Cued Recall = 4.96). This pattern is consistent with retention deficits.

With two exceptions, mean index score values were all below the TBI standardized mean of zero for Cluster V (n = 20) with the lowest being Retrieval (see Table 4). The profile of raw scores presented in Figure 2 shows relatively poor working memory capacity (List A Trial 1 = 4.30 and List B = 4.65) but the ability to acquire additional information (List A Trial 5 = 7.55). Retrieval difficulty is seen in the sawtooth pattern of lower free recall performance compared with cued recall performance (Short-Delay Free Recall = 3.85, Short-Delay Cued Recall = 7.00, Long-Delay Free Recall = 4.95, and Long-Delay Cued Recall = 6.80). This group also had a high number of intrusions and false positive responses (Free Recall Intrusions = 4.15, Cued Recall Intrusions = 3.80, False Positives = 3.85). This pattern is indicative of retrieval and control deficits.

Replicability of profiles across samples

To answer the question of whether the memory patterns found were unique to the particular setting or set of data, r_p was calculated comparing VA and DoD sample profiles. Table 5 presents these data. The VA Normal Semantic and Normal Serial profiles were most similar with the Normal Semantic and Normal Serial profiles in the DoD sample (r_p = .925 and .924, respectively). The Poor Retention profile in the VA sample was also most similar to the Poor Retention profile in the DoD sample (r_p = .847), but also somewhat similar to the DoD Normal Serial profile (r_p = .792). The VA Poor Retrieval/Poor Control profile was very similar to the Poor Retrieval/Poor Control profile in the DoD sample. The only profile that was not obtained in both samples was the pattern of Poor Consolidation/Good Retention found in the VA sample.

External Validation of Cluster Profiles

VA sample

Differences among the cluster profiles on data not subjected to the cluster analysis procedure were examined to provide external support for these memory patterns. No differences among the five profile groups were found with respect to gender, race, educational level, length of coma plus post-traumatic amnesia period, and length of time since injury. However, the Poor Consolidation/Good Retention group (Cluster III) was comprised of significantly older individuals (M = 44.8, $p < .05$), with mean age differences ranging from 11.1 to 14.7 years. The Normal Semantic (Cluster I) and Normal Serial (Cluster II) groups had significantly higher Cognitive Ability Index scores than either the Poor Consolidation/Good Retention or Poor Retrieval/Poor Control (Cluster V) groups (ps < .05). The Normal Semantic and Normal Serial groups (Clusters I and II, respectively) also obtained significantly higher scores on the Global Memory Index compared with the other three groups (ps < .05). The Poor Consolidation/Good Retention group (Cluster III) also had significantly higher scores on the Global Memory Index scale compared with the Poor Retrieval/Poor Control group (Cluster V). Table 6 presents the mean scores on these measures.

Only cluster groups that showed a profile of memory difficulties (i.e., Clusters III, IV, and V) were selected for closer examination of more specific memory and cognitive ability differences. Analysis of WMS–R scores found significantly lower performance of the Poor Retrieval/Poor Control group (Cluster V) compared with the Poor Consolidation/Good Retention group (Cluster III) on both Logical Memory and Visual Reproduction Percent Retained scores (see Table 6). The Poor Retrieval/Poor Control group (Cluster V) also obtained significantly lower scores than the Poor Retention group (Cluster IV) on Visual Reproduction Percent Retained (see Table 6). The Poor Retrieval/Poor Control group (Cluster V) had the lowest Executive Trails performance while the Poor Consolidation/Good Retention group (Cluster III) had the lowest Stroop Color-Word performance. Table 6 summarizes these group differences.

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Table 6. Mean scores on external validity measures by cluster group and sample

Sample	Cluster								
	I Normal Semantic		II Normal Serial		III Poor Consolidation/ Good Retention		IV Poor Retention		V Poor Retrieval/ Poor Control
VA sample									
Cognitive Ability Index	−0.65	=	−0.82	>	−1.34	=	−1.71	=	−1.98
Global Memory Index	103.75	=	98.01	>	87.22	>	83.33	=	74.67
WMS–R Logical Memory % Retained	—		—		72.15	=	57.60	≥	40.85
WMS–R Visual Reproduction % Retained	—		—		73.99	=	73.12	>	40.63
Executive Trails	—		—		−0.06	=	0.07	>	−0.90
Stroop Color-Word *T* score	—		—		20.57	<	31.45	≤	27.89
DoD sample									
Cognitive Ability Index	0.19	=	−0.17		—	>	−0.66	=	−0.76
Global Memory Index	109.67	=	102.94		—	>	87.81	=	92.00
WMS–R Logical Memory % Retained	—		—		—		65.55	>	51.71
WMS–R Visual Reproduction % Retained	—		—		—		72.02	>	54.70
Executive Trails	—		—		—		−0.16	>	−0.79
Stroop Color-Word *T* score	—		—		—		32.08	=	31.60

Note. Statistics presented were based on available data. Some data were not available for all participants. The symbols ≥ or ≤ indicate that adjacent columns are statistically equivalent, while the non-adjacent columns statistically differ. The symbol = indicates that adjacent columns are statistically equivalent.

DoD sample

In contrast to the findings within the VA sample, no differences among the four DoD profile groups were found on any of the demographic variables. However, the Normal Semantic group (Cluster I) and the Normal Serial group (Cluster II) in the DoD sample obtained significantly higher Cognitive Ability Index and Global Memory Index scores than either the Poor Retention group (Cluster IV) or the Poor Retrieval/Poor Control group (Cluster V; *p*s $< .05$; see Table 6). Comparison of the Poor Retention group (Cluster IV) with the Poor Retrieval/Poor Control group (Cluster V) found significantly lower performance of the Poor Retrieval/Poor Control group on WMS–R Logical Memory Percent Retained, WMS–R Visual Reproduction Percent Retained, and Executive Trails, $p < .05$ in all cases. No difference was found in Stroop Color-Word scores. Table 6 summarizes these group differences.

DISCUSSION

The present study used CVLT and WMS–R Digit Span scores to construct theoretically derived indexes of seven specific short- and long-term memory processes. Scores on these indexes were then cluster analyzed to determine whether groups of TBI individuals exist that demonstrate patterns of memory performance which correspond to deficits in one or more of these theoretical constructs. Using this methodology and in contrast to previous studies, patterns of memory dysfunction were found that correspond to deficits in one or more theoretically meaningful memory constructs. Specifically, clusters were found with deficits in consolidation, retention, and retrieval. The poor retrieval cluster also had accompanying problems with increased intrusions and perseverations (i.e., memory control deficits). Similar to previous studies, subgroups of TBI individuals were also found with intact memory functioning. Strengths of the current study are the replicability of the memory clusters across samples and clinical settings, and the incorporation of external measures to help validate the uniqueness of the memory clusters.

In both the VA and DoD samples, a profile of intact memory performance and use of a semantic encoding strategy (Cluster I: Normal Semantic) was found. This profile is similar to the Active group identified by Millis and Ricker (1994) and Deshpande et al. (1996) in the use of a semantic strategy to encode the information. The Cluster II profile (Normal Serial) was the largest group ($n = 40$ and $n = 63$ within the VA and DoD samples, respectively) and was characterized by intact memory performance and the use of a serial position encoding strategy. This pattern appears to be most similar to the Passive group of Millis and Ricker and Deshpande et al., which also was characterized by use of a serial position strategy. What is clear from the present study is that, despite being a less active organizational cognitive style, use of a serial position encoding strategy can be associated with intact verbal memory performance and appears to be a very common learning strategy within TBI samples. Regardless of encoding strategy, both these profiles are associated with relatively good overall cognitive and general memory abilities. For example, Clusters I and II in both VA and DoD samples performed well within the

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average range on WMS–R Global Memory Index (mean Memory Quotients scores greater than 98 in all cases). Surprisingly, severity of injury (length of coma plus PTA) and length of time since injury did not differ among the memory clusters indicating that intact memory is independent of these variables.

Three clusters indicative of specific memory deficits, rather than simply overall level of memory functioning, also were found. In the VA sample one small subgroup was characterized by deficits in consolidation ability but with preserved ability to retain the information, albeit low with respect to the absolute amount of information (Cluster III: Poor Consolidation/Good Retention). Supporting the validity of relatively preserved retention ability, this group had the highest percent retained scores on WMS–R Logical Memory and Visual Reproduction of the three memory impaired clusters in the VA sample. This group also was comprised of older individuals. Thus, it may be that age-related biological responses to brain trauma increase the risk for disruption of consolidation processes in older adults.

A pattern of retention difficulties (Cluster IV: Poor Retention) was identified in both the VA and DoD samples, characterized by a dramatic drop in performance on all short- and long-delay measures compared to Trial 5 performance, in a manner that differentiated them from all other clusters. This group had the best performance on executive functioning (Executive Trails) of the memory impaired clusters. These findings suggest that this profile may be associated with relative strength in other cognitive ability areas (e.g., executive functions) in comparison with the other patterns of learning and memory deficits.

Results also supported the existence of a pattern of retrieval deficits accompanied by control difficulties (Cluster V: Poor Retrieval/Poor Control group in both samples). This profile was characterized by a sawtoothed pattern on free *versus* cued recall performance that differentiated them from other clusters. This cluster was associated with the poorest performance of all the memory deficit profile patterns in both samples on the other neuropsychological measures, including other measures of memory. This profile represents not only deficit memory processes but also the manifestation of impaired higher-order executive abilities (Executive Trails), perhaps because such executive functioning is involved in the retrieval of stored information. These findings are consistent with recent positron emission tomography research that suggests that successful retrieval is dependent on both a prefrontally mediated memory searching process (retrieval attempt) and successful reactivation of memory information from posterior cortical long-term memory stores (retrieval success; Kapur et al., 1995). Medial temporal activity is associated with retrieval success, rather than retrieval attempt, likely reflecting a role in reactivation of previously stored information (Nyberg et al., 1996). In contrast, the prefrontally mediated memory search reflects an attempt to retrieve information from long-term memory stores. This frontally mediated memory retrieval attempt may be somewhat lateralized: (1) right prefrontal for episodic information, and (2) left prefrontal for semantic information (Buckner et al., 1995; Tulving et al., 1994).

While results of the current investigation provide support for the existence of several theoretically-derived patterns of learning and memory processes and disorders, not all possible patterns of short- and long-term memory deficits were found. For example, contrary to the findings of Wiegner and Donders (1999), the present study did not find a group characterized specifically by deficits in immediate memory span in either sample. However, the absence of this pattern is consistent with the findings of Levin et al. (1982) who suggest that immediate memory span is relatively intact in TBI. Within our data, examination of Digit Span Forward scores reveals that all clusters in both VA and DoD samples except one obtained span scores of 7 or 8. The VA Cluster III (Poor Consolidation/Good Retention) had a significantly lower span score (5.89) compared to all other VA cluster groups ($p < .05$), but even this cluster's span was within the range generally considered normal (i.e., 7 ± 2; Miller, 1956). It appears that the working memory concepts of Span and Central Executive do not play a significant role in the type of memory disorders associated with TBI. In contrast, long-term memory concepts of Consolidation, Retention, Retrieval, and Control are reflected in the types of learning and memory disorders associated with TBI.

It should also be noted that, similar to Haut and Shutty (1992), no relationship was found between brain injury severity and pattern of verbal memory performance. The possibility does exist, however, that specific patterns of memory performance may be associated with the location and/or the extent of brain lesions. For example, it would be reasonable to expect greater involvement of the prefrontal cortical area in TBI patients demonstrating the Poor Retrieval/Poor Control profile than in other memory deficit patterns (Kapur et al., 1995). Unfortunately, neuroimaging data were not available for the current study. Future research is necessary to adequately address this possibility.

There are several limitations to the present study. First, the calculation of the various memory process indices is somewhat complicated and there is no direct way to translate memory process index scores into unique memory deficit patterns outside of the cluster analytical techniques used in this study. Future studies will be necessary to develop clinically useful indices that can operationally define underlying memory process deficits. In this regard, a further limitation is the difficulty in operationally defining consolidation at all using CVLT scores. Although we operationally defined consolidation as consistent and effective learning over five learning trials (mean performance on percent recall consistency, learning slope, and total words reported on learning trials), this is certainly not a universally accepted definition. For example, one might predict that problems with consolidation would be manifested in rapid forgetting, and that these two abilities (consolidation and retention) would be related concepts. For the purposes of this study we attempted to differentiate them, and found support for this separation. However, we acknowledge that no direct measure of consolidation exists within the CVLT variables. The concepts and methods of quantifying semantic encoding, retention, retrieval, and control are more widely accepted.

In summary, this study demonstrated that TBI results in patterns of memory disorders with specific deficits in consolidation, retention, and retrieval processes. Control problems (keeping track of list *vs.* nonlist items) does not appear as an independent deficit pattern; rather it occurs in conjunction with retrieval deficits. These findings partially replicate, but also extend previous studies of memory disorder subtypes associated with TBI. By using indexes that represent specific memory processes such as consolidation, retention, retrieval, and control in research investigations, a richer understanding of memory functions and the manifestations of memory disorders can be gained. In addition, identifying patterns of intact and impaired memory abilities may aid rehabilitation personnel in the treatment and management of memory problems in TBI. For example, environmental retrieval cues would be expected to aid TBI individuals whose memory difficulties were primarily retrieval in nature. Alternatively, spaced repetitive learning sessions may be necessary to compensate for consolidation problems. Finally, the use of ongoing memory notebooks may be essential to assist individuals with retention problems. Future research will be necessary to determine the stability/recovery of these subtypes of memory disorders in TBI and to investigate the utility of alternative rehabilitation memory techniques.

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