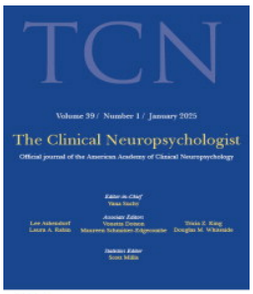

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The processing of verbal memories after traumatic brain injury

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ABSTRACT

Objective: Memory dysfunction is a persistent cognitive symptom following traumatic brain injury (TBI), negatively impacting capacity for independent living and productivity. Traditional scoring of neuropsychological memory tests does not allow for differentiation of specific impairments of encoding, consolidation and/or retrieval, or the potential impact of strategy deficits. **Method:** The current study examined performance of 142 moderate-to-severe TBI participants and 68 demographically matched healthy controls on the Rey Auditory Verbal Learning Test (RAVLT) using Item Specific Data Analysis (ISDA) and strategy use analyses. **Results:** Results revealed significantly greater impairments in encoding, consolidation, and retrieval in TBI participants, compared to controls. Encoding deficits significantly explained the most variance in the long-delayed recall of TBI participants, followed by consolidation, and then retrieval. Participants with TBI showed a reduced ability to spontaneously apply strategies during learning, evident in decreased subjective clusters and increased word omissions, compared to controls. No difference was found between groups in passive learning strategy application, shown through serial clustering. Spontaneous strategy measures both uniquely accounted for variance in the encoding ability of TBI participants. **Conclusions:** These findings highlight the potential value in using ISDA and strategy use measures to assess RAVLT results to better characterize individual memory profiles and inform rehabilitative interventions.

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Introduction

Traumatic Brain Injury (TBI) is a leading cause of disability worldwide (Dewan et al., 2018). Prominent among the cognitive impairments that contribute to this disability are disorders of memory (Grauwmeijer et al., 2018; Ponsford et al., 2014), which begin immediately after injury when patients experience post-traumatic amnesia (PTA)

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(Ponsford et al., 2014). Following emergence from PTA, memory dysfunction, manifested as difficulty creating and storing new verbal and/or non-verbal memories, may continue. It tends to resolve to some degree over time, but can persistent over years following injury (Ponsford et al., 2008) impacting educational and employment outcomes, social relationships, and leisure activities (Gormley et al., 2019; O'Neil-Pirozzi et al., 2021).

Theories of memory function have identified a three-step memory process (encoding, consolidation and retrieval), where information attended to by the senses, flows from short term memory (STM) to long-term memory (LTM) and back again (Baddeley, 1999). These processes work together to support the memory system; however, damage that impacts one process may result in qualitatively different impairments from damage to another. Impairments in encoding impede acquisition of information, manifested as a decreased learning rate or dysfunction in application of learning strategies (Blachstein et al., 1993; Bruce & Echemendia, 2003; Wright et al., 2010). Consolidation impairments result in loss of novel information due to ineffective storage or maintenance in LTM and may present as accelerated forgetting of new information (Hanoğlu et al., 2019; Vanderploeg et al., 2014). Impaired retrieval, defined by inability to recall previously learned information, presents as inconsistent recall of information and/or recall that is improved by prompting or cues (Fandakova et al., 2018; Han et al., 2021; Wright et al., 2009).

Various factors may impact memory performance, including age (Grady & Craik, 2000; Park & Festini, 2017), education, thought to be associated with increased cognitive reserve (Pliatsikas et al., 2019), and gender (Herlitz & Rehnman, 2008). As such, these factors should be controlled for in memory studies (Corrigan et al., 2018; Haring et al., 2015).

The heterogeneity of TBI site and severity results in variable memory impairments, ranging from visual or verbal memory deficits to amnesic syndromes (Ariza et al., 2006; Reddy et al., 2017; Serra-Grabulosa et al., 2005) (for review see Vakil, 2005). These memory impairments may be influenced by attentional impairments (e.g., abnormal dorsal attention network activation) (Mallas et al., 2021), executive dysfunction (Vakil, 2005) and by depression or anxiety (Goverover & Chiaravalloti, 2014). Verbal memory impairments appear most commonly following TBI and persist longer than other memory impairments (Dunning et al., 2016; Vakil et al., 2019). Implicit memory systems are relatively preserved following TBI in adults (Korman et al., 2018). In contrast, explicit memories, often referred to as declarative or event related memories, require conscious effort to be recalled and are more significantly impacted by TBI (Vakil, 2005).

Research examining the processing of explicit memories following TBI has been sparse and yielded mixed results. Some researchers have identified primary deficits in encoding (DeLuca et al., 2000), while others identify consolidation (Douglas, 2010; Vanderploeg et al., 2001; 2014) and retrieval as the most commonly reported impairments (Curtiss et al., 2001). These discrepancies in research findings may reflect limited sample sizes, incongruencies between memory tests (Stallings et al., 1995), and/or potential limitations in scoring of memory measures (Delis et al., 1988; Wright et al., 2009). The resultant limitations in understanding of the precise nature of memory

deficits following TBI makes it challenging to tailor rehabilitation treatment to individual needs (Velikonja et al., 2023).

One of the most frequently used memory tests is the Rey Auditory Verbal Learning Test (RAVLT) (Schmidt, 1996). Traditional scoring of the RAVLT involves recording the number of words recalled on each trial. Encoding is measured through comparison of performance on the first and last learning trial, while consolidation is measured by words forgotten from learning trials to long-delayed recall. Retrieval is measured through comparison of recall and recognition trials (Strauss et al., 2006). Issues have been raised, however, regarding the extent to which traditional RAVLT scoring captures aspects of memory. Firstly, there is no measure to account for difference in initial acquisition level of healthy controls and TBI participants in studies. This may in turn impact measurement of consolidation and retrieval (DeLuca et al., 2000). The original scoring method for encoding relies heavily on performance on the first learning trial, which may be impacted by TBI-related attentional difficulties (Wiegner & Donders, 1999; Wright et al., 2009). The use of summation scores for each trial results in loss of valuable information regarding specific word recall, highlighted by Blachstein et al. (1993) as providing insight into learning patterns and strategies used.

Building on this work by Blachstein et al. (1993), Wright et al. (2009) developed Item Specific Data Analysis (ISDA) for experimental use to better characterise encoding, consolidation, and retrieval processes after TBI. The ISDA was initially applied to the California Verbal Learning Test (CVLT) (Delis et al., 1987), which differs from the RAVLT by including semantically related word lists. The ISDA provides encoding, consolidation, and retrieval deficit indices based on item level performance in list-learning trials, with poorer performance indicated by higher indices. The ISDA indices allow assessment of deficit patterns across learning and delayed recall trials and provide solutions to identified limitations in memory test scoring. Limitations in scoring of encoding are overcome as impairments in word recall are assessed across all learning trials, removing the focus from first trial performance and potential impacts of inattention. The ISDA also removes the confounding nature of traditional consolidation measurement by assessing words forgotten from learning trials to short and long-delayed recall trials. The ISDA also provides a clearer picture of retrieval performance by controlling for initial acquisition level.

The ISDA has only been applied to the RAVLT in one small study involving 23 TBI participants and 25 controls assessed up to three months post PTA emergence (Wright & Schmitter-Edgecombe, 2011). This study suggested memory dysfunction following TBI was explained by deficits in encoding and consolidation, rather than retrieval. This, alongside studies using the CVLT, has supported ISDA as a reliable and valid measure of memory processes after TBI (Wright et al., 2009; 2020).

The finding of a primary impairment in encoding following TBI aligns with other studies, which have also taken an item level approach to memory test analysis. Blachstein et al. (1993) compared words added during RAVLT learning trials, to words omitted, and found that omissions better characterised differences in learning rates of TBI and control groups. Specifically, increased omissions of words previously recalled during learning reflected impairment in strategy application, that in turn impacted encoding.

Only one study has investigated the impacts of active or passive strategy deficits on encoding performance. Wright et al. (2010) applied the ISDA to the CVLT data of 61 severe TBI participants and 63 controls. Participants with TBI exhibited primary encoding and consolidation deficits and were less likely than controls to use spontaneous semantic clusters as an active learning strategy, which was seen to account for their encoding deficits. There were no group differences in application of the passive learning strategy of serial clustering. This study was limited by its small TBI sample assessed up to 28 years post-injury, and by its use of CVLT, which utilizes semantically related word lists. Arguably, measures with unrelated word lists such as the RAVLT provide more accurate measures of spontaneous clustering, and are thereby more sensitive to impairments of strategic encoding.

More recently, Blachstein and Vakil (2022), analysed strategy use on the RAVLT across the lifespan of healthy participants, through measurement of serial clusters (recall of words in order of presentation), as a passive learning strategy, and subjective clusters (words repeatedly recalled together through assignment of meaning) as an active learning strategy. There have, however, been no studies examining strategy use on the RAVLT in individuals with TBI.

The current study expanded upon previous research by applying the ISDA, strategic cluster, and word omission analyses to the RAVLT (a non-clustered learning task), in order to better characterise memory performance following TBI, assessed early after injury. The study incorporated a large sample of moderate-to-severe TBI patients (as classified by days in PTA), compared with healthy controls of similar age, education, and gender.

Aims and hypotheses

The first study aim was to examine impairments in encoding, consolidation and retrieval following TBI, in comparison with healthy controls. The second aim was to compare use of strategies during learning across groups, and determine whether deficits in strategy application accounted for encoding impairments. In accordance with previous research, there were four hypotheses: (1) TBI participants would show deficits in encoding, followed by consolidation, but show no differences in retrieval ability, relative to controls; (2) encoding deficits would have the largest impact on TBI participants' delayed recall performance; (3) TBI participants would exhibit less spontaneous strategy use during learning compared to controls, measured by increased word omissions and decreased subjective clusters across learning trials of the RAVLT, but there would be no difference in serial cluster performance (Wright et al., 2010); and, (4) deficits in encoding performance by participants with TBI would be explained by a lack of strategic encoding, measured by subjective cluster use and word omissions across learning trials of the RAVLT, accounting for variance in the ISDA encoding deficit indices of individuals with TBI.

Methods

Participants

Patients with TBI were recruited from an inpatient TBI rehabilitation program at Epworth Healthcare in Melbourne where patients received rehabilitation in the context

of a no-fault accident compensation system and consented to a Longitudinal Head Injury study. Those eligible had sustained a medically verified moderate to severe TBI with either a Glasgow Coma Scale Score (GCS) <13 and if GCS was 13-15, PTA > 1 day and/or positive CT findings, were English speaking adults aged >17 years, had no previous diagnoses of neurological or psychiatric disorders, and had sufficient cognitive capability to complete the RAVLT within six weeks since injury (and approximately three weeks since emerging from PTA).

Complete RAVLT data could be retrieved for 142 eligible participants who had consented to partake in research. Participants completed memory testing during their inpatient stay after sustaining a TBI between 2014 and 2021, on average 42.8 days ($SD = 24.9$; median = 37 days; range 8-156 days) post-injury. Participants comprised 104 males and 38 females, aged a mean of 40.42 years at injury ($SD = 16.08$, range = 19-86), with an average 11.83 years of education ($SD = 2.64$, range = 7-19, $n = 124$). Most TBIs resulted from motor vehicle accidents (66.9%), followed by pedestrians struck by vehicles (10.6%), bicycle incidents (7%) and falls (6.3%). Regarding injury severity, PTA duration was recorded for 131 participants using the Westmead PTA Scale (Shores et al., 1986). The mean PTA duration was 24.2 days ($SD = 24.71$, range = 1-180). No participants spent less than 24 h in PTA, 23.7% recorded 1-7 days in PTA, 48.1% 1-4 wk, and 28.2% > 4 wk. The mean GCS score was 8.78 ($SD = 4.59$, range = 3-15, $n = 132$): mild (36.4%), moderate (13.6%) and severe TBI (50%). There were 92.9% of participants with TBI who had abnormal computed tomography (CT) findings. Individuals with normal CT and GCS 13-15 had PTA> 1 day, and on this basis injury severity for the TBI sample was deemed moderate to severe.

A demographically similar control group of 68 healthy individuals (41 males, 27 females) with no history of TBI, neurological or serious psychiatric disorder was recruited from the general community. The control group had a mean age of 43.91 years ($SD = 9.86$, range = 28-59), and mean education of 12.47 years ($SD = 2.4$, range = 8-21). Independent t-tests, with Bonferroni correction for multiple analyses, indicated no significant differences between TBI and control groups on gender $t(120.60) = -1.838$, $p > .016$, age $t(195.57) = -1.935$, $p > .016$ and education $t(188) = -1.65$, $p > .016$. Cases were excluded from analysis if data were missing for the variable tested.

Measures

Rey auditory verbal learning test (RAVLT)

The RAVLT (Schmidt, 1996) is a verbal memory test which provides measures of overall performance, encoding, consolidation and retrieval. The RAVLT has shown high sensitivity and reliability in assessing verbal learning following TBI (Draper & Ponsford, 2008; Strauss et al., 2006). Participants were read 15 unrelated words (list A) over 5 trials and recall was assessed after each trial. A second list of 15 unrelated words (list B) was then presented and recall of that list was recorded. Delayed recall of list A was then reassessed immediately and again after a 20-minute delay. A recognition trial requiring selection of list A words from a story, 30-item word list or 50-item word list was then presented, but this was not utilised in the current study. Scoring of RAVLT performance was performed in three separate ways to provide measures of

memory processing (encoding, consolidation, and retrieval), and measures of strategic clustering and words omitted across learning trials.

Memory processes were measured in accordance with ISDA (Wright et al., 2009), with impairments in encoding, consolidation and retrieval calculated from performance across the RAVLT learning and delayed recall trials. The *encoding* deficit index was produced from the sum of all words recalled on less than half (two or less since there were 5 learning trials) of the RAVLT. The *consolidation* deficit index represented the sum of all words not recalled on the immediate recall trial (trial 6) or delayed recall trial (trial 7), which were recalled during learning trials. The *retrieval* deficit index measured all words recalled inconsistently on immediate or delayed recall trials (i.e., recalled on one but not the other), which were recalled during any of the learning trials. The ISDA measure of acquisition level represents number of words recalled on at least one learning trial, out of 15. To account for effects of acquisition on consolidation and retrieval ability, we divided the deficit index by the acquisition level of the participant.

Application of *strategic clusters* was measured from learning trial performance on the RAVLT following Blachstein and Vakil (2022). However, clusters were only measured in sequences of twos rather than the additional three-and four-word clusters, as in previous cluster research (Sternberg & Tulving, 1977), due to the study focus on existence of strategic cluster application following TBI, rather than quality of clusters applied. Clusters were said to occur if two words were recalled together in adjacent trials, and were measured from trial 1-2, trial 2-3, trial 3-4 and trial 4-5. *Serial clustering* was measured as any group of two words recalled in two adjacent trials in the exact sequential order that they were presented (e.g., "drum" "curtain"). *Subjective clustering* was measured as any group of two words recalled in two adjacent trials regardless of presentation order (e.g., "school" "bell"). Subjective clusters are believed to provide a measure of semantic learning, in which the words although unrelated, are recalled together as the participant has applied meaning to them. A score of 1 was given for each cluster, and summed to provide a total for trials 1-2, 2-3, 3-4 and 4-5. Serial and subjective clusters were mutually exclusive in their measurement. Words recalled in incorrect sequential order (e.g., "curtain" "drum") were not counted as either serial or subjective clusters.

Words omitted per RAVLT learning trial was measured as by Blachstein et al. (1993) in a cumulative manner, such that each word not recalled on a learning trial, that had been recalled on any previous trial, was counted as an omission, beginning from trial 2. The number of omissions for each trial was summed to create a measure of total omissions across all learning trials.

Procedures

Ethics approval was obtained from the Monash Health Human Research Ethics Committee (MHHREC # RES-19-0000099E). All participants provided written informed consent to participate and completed the RAVLT as part of their initial neuropsychological assessment within six weeks following PTA emergence. Controls were screened by telephone and assessed by a psychologist at hospital or home. Medical records were also accessed with permission to gather demographic and injury details.

Data analysis

All analyses were conducted using Statistical Package for the Social Sciences (SPSS) version 28. Relevant assumptions were checked prior to analyses, and all sufficiently accepted as described in results. Significance level of $p < .05$ was applied to all analyses unless otherwise stated. As cases were only included if they had complete RAVLT data, there were no missing data.

In a preliminary analysis, independent samples t-tests were conducted to compare TBI and control groups in overall RAVLT performances in terms of total words recalled across learning trials and long delayed recall performance (trial 7). Mixed Analysis of Variance (ANOVA) was also conducted with group (TBI, Controls) and learning trials (Trial 1, Trial 2, Trial 3, Trial 4, Trial 5), followed by paired t-tests as a significant interaction was observed. Following this, independent samples t-tests were conducted, for the first hypothesis to compare TBI and control groups for the ISDA encoding, consolidation and retrieval deficit indices. For the second hypothesis, a three-stage hierarchical multiple regression was conducted with TBI participants' ISDA deficit indices as predictors and RAVLT long delay recall performance (trial 7) as the dependent variable. The first model contained only ISDA encoding deficit index as a predictor, the second added ISDA consolidation deficit index, and the last also included ISDA retrieval deficit index. For the third hypothesis to compare strategy application, independent samples t-tests were used to compare the two groups on strategic and serial clusters applied during learning trials and total words omitted per learning trial, compared to all previous trials. Mixed ANOVA was also conducted with group (TBI, Controls) and omission trial (Trial 2, Trial 3, Trial 4, Trial 5), followed by paired t-tests as a significant interaction was observed. For the final hypothesis, a hierarchical multiple regression was conducted to determine the variance in the encoding deficit index of TBI participants accounted for by use of subjective clustering, included in the first model, and omitted words, added in the second model, as omissions are believed to be a by-product of a lack of subjective clustering. For all analyses, assumption testing was completed and where necessary, alternative statistics were reported. In addition, embedded performance validity testing was conducted where recognition scores <6 were considered non-credible (Binder et al., 2003).

Results

Preliminary analysis: overall RAVLT performance of TBI and control groups

The Independent samples t-test, applied with equal variances assumed, indicated controls learned significantly more words overall ($M = 55.91$, $SD = 7.51$) than TBI participants ($M = 42.65$, $SD = 10.17$), $t(208) = -9.57$, $p < .001$. Controls also recalled significantly more words after a delay ($M = 11.76$, SD = 2.60), compared to TBI participants ($M = 7.02$, $SD = 3.79$), $t(182.66) = -10.58$, $p < .001$.

Visual representation of the performance of TBI participants and healthy controls on each RAVLT learning trial is shown in Figure 1. Mixed ANOVA between group and learning trials indicated a significant main effect of learning trials, $F(3.53, 832)=491.66$, $p<.001$, where significantly more words were recalled with each subsequent trial. There was also a main effect of group, where controls recalled significantly more

words than individuals with TBI, $F(1,208)=91.58$, $p<.001$. There was a significant interaction between group and learning trial, $F(3.53, 832)=10.55$, $p<.001$. Follow-up paired samples t-tests indicated that for individuals with TBI, there was a significant increase in the number of words recalled from T1 to T2 [$t(141)=-14.1$, $p<.001$], T2 to T3 [$t(141)=-8.38$, $p<.001$], T3 to T4 [$t(141)=-5.40$, $p<.001$], and T4 to T5 [$t(141)=-3.04$, $p=.001$]. Similar results were observed for controls, where there was a significant difference in the number of words recalled from T1 to T2 [$t(67)=-15.85$, $p<.001$], T2 to T3 [$t(67)=-7.72$, $p<.001$], T3 to T4 [$t(67)=-4.73$, $p<.001$], and T4 to T5 [$t(67)=-2.91$, $p=.002$].

ISDA encoding, consolidation and retrieval deficits (Hypothesis 1)

Descriptive statistics and t-test results for all ISDA deficit indices are reported in Table 1. Bonferroni correction for multiple analysis was applied and level of statistical significance was set to $p < .016$ (Chen et al., 2017).

The ISDA encoding deficit index was significantly higher in participants with TBI, than controls. TBI participants also showed a significantly higher deficit on both consolidation and retrieval deficit indices. Analysis of effect sizes revealed a large effect of group membership on encoding and consolidation deficit indices and medium effect size for the retrieval deficit indices.

Impact of ISDA deficit indices on delayed recall (Hypothesis 2)

Multicollinearity was not present in the variables; all correlations were below .80, tolerance measurement was below 1, and VIF was below 10 (Kumari, 2008).

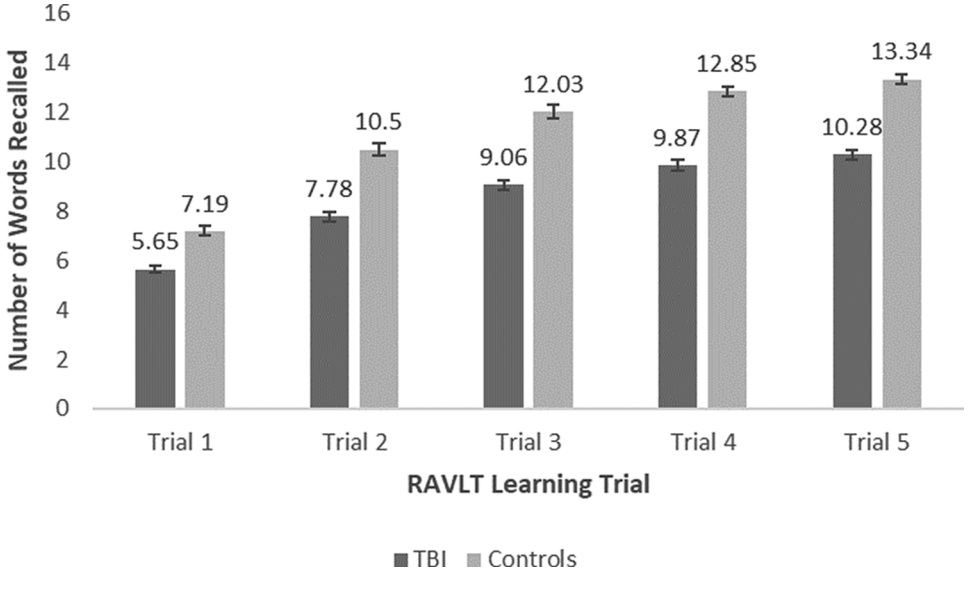

Figure 1. Means and standard errors of TBI and control groups on RAVLT learning trials. *Note*. This figure demonstrates the average performance by each group of participants on trial 1-5 of the RAVLT. Means are displayed at the top of the data bars and standard errors are presented as overhead bars.

Model 1, containing only the ISDA encoding deficit index significantly explained 55.1% of variance in the RAVLT delayed recall performance of TBI participants $F(1, 140) = 171.88$, $p < .001$ (see Table 2).

Model 2, including the addition of the ISDA consolidation deficit index significantly explained 86.6% of total variance in RAVLT delayed recall performance $F(2, 139) = 449.18$, $p < .001$. The ISDA consolidation deficit index accounted for an additional 31.5% of variance in delayed recall, and this was a significant change from the first model $F(1, 139) = 326.66$, $p < .001$ (see Table 2).

Model 3, with the ISDA retrieval deficit index added, significantly explained 89.2% of the total variance in RAVLT delayed recall performance $F(3, 138) = 381.86$, $p < .001$. This was also a significant change $F(1, 138) = 33.99$, $p < .001$, and when other ISDA variables were accounted for, the ISDA retrieval deficit index explained 2.6% of the variance in delayed recall (see Table 2).

Strategy application during learning for TBI and control groups (Hypothesis 3)

Applying Bonferroni correction, the level of statistical significance for all analyses was set to $p < .016$ (Chen et al., 2017). Descriptive statistics and t-test results for all measures of strategy use during learning are presented in Table 3.

Participants with TBI omitted significantly more words, with large effect, and made significantly less use of subjective clusters across learning trials, with medium effect, compared to controls (see Table 3). There was no significant group difference in number of serial clusters applied during learning trials. Trial by trial

Table 1. Means, standard deviations and T-test results for TBI and control groups on ISDA deficit indices (Hypothesis 1).

	TBI M (SD)	Control M (SD)	*df*	*t*	*p*	*Cohen's d*
ISDA encoding deficit index	6.06 (2.9)	2.38 (2.19)	169.85	10.21	< .001***	1.36
ISDA consolidation deficit index	0.39 (0.24)	0.14 (0.13)	206.17	9.77	< .001***	1.18
ISDA retrieval deficit index	0.19 (0.13)	0.13 (0.14)	208	3.17	.002**	0.47

Note. $p < .016$*, $p < .003$**, $p < .001$***, $n = 142$ for each TBI measure and $n = 68$ for each control measure.

Table 2. Summary of hierarchical regression analysis for variables predicting delayed recall (Hypothesis 2)

	R	R^2	R^2 *Change*	*B*	*SE*	*β*	*t*
Model 1	.74	.55***					
ISDA encoding deficit index				−.97	.07	−.74***	−13.11
Model 2	.93	.87***	.32***				
ISDA encoding deficit index				−.35	.05	−.27***	−6.52
ISDA consolidation deficit index				−11.71	.65	−.74***	−18.07
Model 3	.95	.89***	.03***				
ISDA encoding deficit index				−.21	.05	−.16***	−3.98
ISDA consolidation deficit index				−13.40	.65	−.84***	−20.6
ISDA retrieval deficit index				−5.61	.96	−.19***	−5.83

Note. $p < .05$*, $p < .01$**, $p < .001$***, $N = 142$ for all ISDA indices.

visualisation of cumulative words omitted in each RAVLT learning trial by participants with TBI and controls is presented in Figure 2. Mixed ANOVA between group and omission trials indicated a significant main effect of omission trials, $F(2.83, 624)=27.55$, $p<.001$, where significantly more words were omitted with each subsequent trial. There was also a main effect of group, where individuals with TBI omitted significantly more words than controls $F(1,208)=32.67$, $p<.001$. There was a significant interaction between group and omission trial, $F(2.85, 624)=10.85$, $p<.001$. Follow-up paired samples t-tests indicated that for individuals with TBI, there was a significant difference in the number of omissions from T2 to T3 [$t(141)=-6.95$, $p<.001$], T3 to T4 [$t(141)=-3.20$, $p=.002$], but not T4 to T5 [$t(141)=-1.87$, $p=.063$]. For controls, there was a significant difference in number of omissions from T2 to T3 [$t(67)=-3.5$, $p=.001$], but not T3 to T4 [$t(67)=.41$, $p=.67$], or T4 to T5 [$t(67)=1.81$, $p=.07$].

Table 3. Means, standard deviations and t-test results for TBI and control groups on measures of strategy (Hypothesis 3).

	TBI *M* (*SD*)	Control *M* (*SD*)	*df*	*t*	*p*	*Cohen's d*
Total omissions	9.44 (4.6)	5.84 (3.49)	169.12	6.30	< .001***	0.84
Total serial clusters	3.16 (4.45)	4.88 (6.73)	95.98	1.92	.058	−0.33
Total subjective clusters	3.04 (2.26)	4.75 (3.1)	102.24	4.06	< .001***	−0.67

Note. $p < .016$*, $p < .003$**, $p < .001$***. $N = 142$ for each TBI measure and $N = 68$ for each control measure.

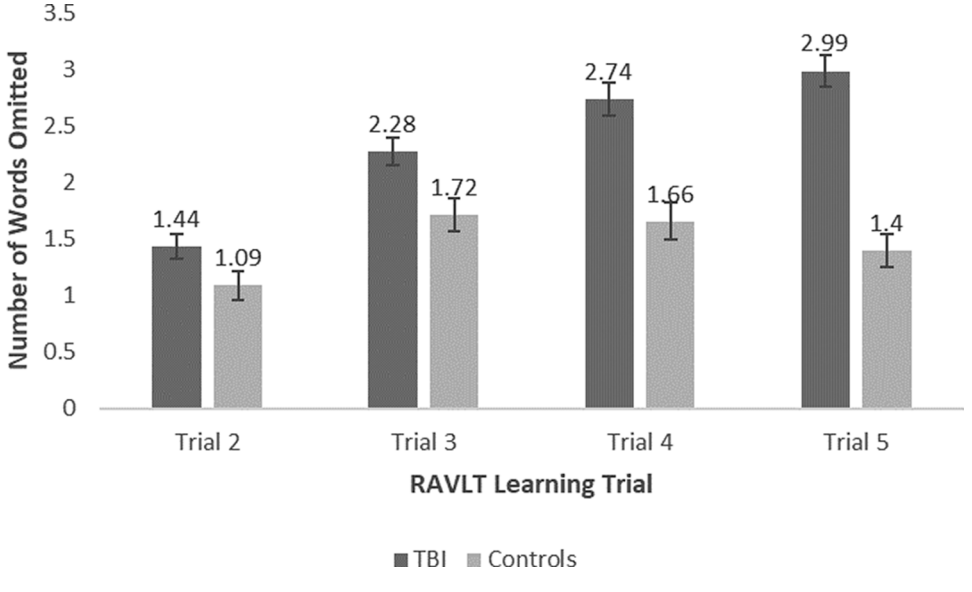

Figure 2. Means and standard errors of words omitted per learning trial of the RAVLT for TBI and control groups. *Note*. This figure demonstrates the average performance by each group on measures of total words omitted per RAVLT learning trial, relative to all previous trials. Means are displayed in the centre of the data bars and standard errors are presented as overhead bars.

Table 4. Summary of hierarchical regression analysis for variables predicting encoding deficits (Hypothesis 4).

	R	R^2	R^2 *Change*	*B*	*SE*	*β*	*t*
Model 1	.34	.11***					
Total subjective clusters across all learning trials				−.44	.10	−.34***	−4.25
Model 2	.46	.21***	.97***				
Total subjective clusters across all learning trials				−.30	.10	−.23**	−2.95
Total words omitted across all learning trials				−.21	.05	.33***	−4.13

Note. $p < .05$*, $p < .01$**, $p < .001$***, $N = 142$ for all measures of strategy.

Impact of strategy on ISDA encoding deficit (Hypothesis 4)

Multicollinearity was not present in the variables, all correlations were below .80, tolerance measurement was below 1 and VIF was below 10 (Kumari, 2008). Regression statistics are displayed in Table 4.

Model 1, containing the predictor of total subjective clusters applied during RAVLT learning trials significantly explained 11.4% of variance in the ISDA encoding deficit index of TBI participants $F(1, 140) = 18.05$, $p < .001$.

Model 2, including the addition of total words omitted per RAVLT learning trial significantly explained 21.1% of total variance in ISDA encoding deficit index $F(2, 139) = 18.62$, $p < .001$. The measure of total words omitted per learning trial accounted for an additional 9.7% of variance in the ISDA encoding deficit index, and this was a significant change from the first model $F(1, 139) = 17.07$, $p < .001$.

Performance validity testing

Of the 142 individuals with TBI in the current study, recognition scores could not be computed for 4 individuals as they had not completed the Recognition test. Of the remaining 138 participants, there were 7 who scored <6 (4.9%).

Discussion

This study confirmed the presence of memory dysfunction following TBI, but more importantly elucidated which aspects of memory processing were most impaired relative to controls. The finding of impairments in encoding following TBI is consistent with existing item level analysis research of memory performance (Blachstein et al., 1993; Wright et al., 2010; 2020; Wright & Schmitter-Edgecombe, 2011). This contrasts with studies that focus on summary scores from memory tests, and identify encoding as being unaffected; however, these studies have used the CVLT rather than the RAVLT (Vanderploeg et al., 2001; 2014), or examined memory performance with the CVLT in *mild* TBI rather than moderate to severe TBI (Tayim et al., 2016). Summary scoring may be impacted by inattention and task switching difficulties (Wright et al., 2009), and does not control for inequities in the initial level of acquisition of material to be learned (DeLuca et al., 2000). Therefore, results of these previous studies are somewhat misleading.

In addition to the impairment in encoding, deficits in consolidation emerged as a significant predictor of memory performance following TBI. This further aligns with previous item analysis research (Wright et al., 2010; Wright & Schmitter-Edgecombe, 2011). Consolidation deficits are theorised to result from hippocampal damage (Schapiro et al., 2019; Wright et al., 2020), and may present as a rapid forgetting of information (Hanoğlu et al., 2019; Vanderploeg et al., 2014).

The finding of a small, but significant, deficit in the retrieval ability of TBI participants was not hypothesized, and does not align with the previous RAVLT study utilizing ISDA (Wright & Schmitter-Edgecombe, 2011). However, impairments in retrieval were found in a study applying ISDA to the CVLT in a severe TBI sample (Wright et al., 2010). Over 75% of participants in the present study were classified as severe according to PTA duration. Memory performance was assessed within 3-4 wk of PTA clearance, while the previous RAVLT study measured participants up to three months post-PTA (Wright & Schmitter-Edgecombe, 2011). Memory function following TBI may show significant improvement between one- and three-months post-PTA (McCrea et al., 2021). Retrieval deficits may resolve more rapidly than aspects of encoding and consolidation, but longitudinal studies are required to confirm this.

The findings of the current study also provide further insight into the impact of executive dysfunction on encoding following TBI, through its demonstration of impaired strategy use, manifested as impaired subjective clustering in individuals with TBI on the RAVLT as opposed to the CVLT, which incorporates semantically related words (Delis et al., 1987; Wright et al., 2010). These results align with previous research and provide credibility to the theory that following TBI, individuals have a reduced ability to spontaneously apply strategies during learning (Alexander et al., 2003; Delis et al., 1988; Stallings et al., 1995; Wright et al., 2010).

The present study also assessed learning strategies through measurement of words omitted and, consistent with the previous work of Vakil and Blachstein and (1993), found increased words omitted in the TBI group relative to controls. These increased omissions have been theorised by Blachstein et al. (1993) to result from a lack of strategy application during learning, and the present study provided confirmation of this for the first time by demonstrating an association between word omissions and encoding deficits in TBI participants that accounted for variance above that of subjective clusters. This suggests that omissions may be underpinned by more than impaired spontaneous strategy application; potentially also by attentional difficulties or reduced self-monitoring, also commonly observed following TBI (Pettemeridou & Constantinidou, 2022; Spikman & van der Naalt, 2010). Further research is needed to investigate these underlying mechanisms.

The findings of the current study have implications for understanding of memory impairments following TBI, but also for rehabilitation. Individuals with impaired strategy application may benefit from explicit memory strategy instruction and/or use of external memory aids (Velikonja et al., 2023). Given the heterogeneity of TBI, decisions regarding suitable interventions are likely to be more effective when based on analysis of specific deficits at an individual level. The deficits identified in the current study would not be evident through assessment of summary scores alone. Application of ISDA and strategy analyses to the RAVLT in the current study took approximately

15 min per participant and required only use of a calculator. Although, this is longer than traditional summary scoring, the use of item level analyses provides an opportunity to assess individual memory impairments; which from a clinical perspective, could provide more comprehensive and informative memory profiles. Future research is recommended to develop of norms for clinical use of the ISDA on the RAVLT (Wright et al., 2009), and for measures of strategic learning (Blachstein et al., 1993; Blachstein & Vakil, 2022).

Assessments of memory were conducted relatively close to the time of injury to maximise likelihood of identifying all injury related impairments. Longitudinal research, featuring application of the RAVLT to the ISDA is also highly recommended, to assess the evolution of memory process deficits over time. Examination of the association of these memory processes with injury severity and with neuroimaging correlates may also be informative, the latter potentially further elucidating the anatomical underpinnings of encoding and consolidation impairments, and their recovery or degeneration overtime.

This study had some limitations. It focused solely on explicit verbal memory impairments and results may not be applicable to visual or implicit memory (Ariza et al., 2006; Vakil, 2005). It did not include individuals with milder injuries where PTA was less than 24 h so the findings cannot be applied to this mild TBI group. Whilst GCS was documented, the duration of loss of consciousness was not specified. Moreover, it also excluded individuals who did not speak English and therefore results may not be applicable to those from a culturally and linguistically diverse (CALD) background. As the RAVLT is available in several languages, this study could be replicated using the translated versions for these CALD individuals. The current study did not collect information regarding race/ethnicity as a vast majority of our patient population are Caucasian, born in English speaking countries. Therefore, our findings may not be generalizable to the wider population. This study also excluded individuals who had such severe cognitive impairments that they could not complete the measures; therefore, the results of the current study may not be applicable to these individuals. While performance validity testing identified a small proportion of individuals with TBI who failed a performance validity measure, this needs to be considered alongside the timing of assessments so early after emergence of PTA and thus may not be reflective of non-credible performance but rather the impact of the brain injury itself.

In conclusion, individuals in the current study, with moderate-to-severe TBI, experienced significant impairments in encoding, consolidation, and retrieval in the early period after injury, as well as deficits in strategy formation as compared with healthy controls of similar age, gender and education. This finding extends and addresses limitations in previous research. Although not meant to replace traditional scoring the importance of documenting RAVLT test performance at an item level, rather than focusing on summary scores only, is highlighted. These methods of scoring are not only informative in research but could become a routine part of clinical assessments. This may in turn inform the selection of rehabilitative strategies to enhance memory function following TBI and improve individuals' overall quality of life.

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

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