Journal of Clinical and Experimental Neuropsychology
2003, Vol. 25, No. 1, pp. 49–58
1380-3395/03/2501-049$16.00

Spacing of Repetitions Improves Learning and Memory After Moderate and Severe TBI

F.G. Hillary[1,2], M.T. Schultheis[1,2], B.H. Challis[3], S.R. Millis[1], G.J. Carnevale[4], T. Galshi[2,4], and J. DeLuca[1,2]
[1]Kessler Medical Rehabilitation Research and Education Corporation, West Orange, NJ, USA, [2]New Jersey Medical School, University of Medicine and Dentistry at New Jersey, NJ, USA, [3]Johnson & Johnson Pharmaceutical Research & Development, L.L.C., NJ, USA, and [4]Kessler Institute for Rehabilitation, West Orange, NJ, USA

ABSTRACT

Extensive research has determined that new learning in healthy individuals is significantly improved when trials are distributed over time (spaced presentation) compared to consecutive learning trials (massed presentation). This phenomenon known as the "spacing effect" (SE) has been shown to enhance verbal and nonverbal learning in healthy adults of different ages and in different memory paradigms (e.g., recognition, recall, etc.). The purpose of this study was to examine whether learning in adults with moderate and severe traumatic brain injury (TBI) is improved using a spacing-of-repetitions procedure. Using a within-groups design, participants with TBI ($n = 20$) were presented a list of 115 words that were presented either once (single condition), twice consecutively (massed condition), or twice with 11 words between presentations (spaced condition). Participants were required to rank each word from 1 to 10 according to their familiarity with the word; they were not asked to "memorize" words for a later test. Word list learning was measured with a free recall test immediately following list presentation and with free recall and recognition tests after a 30-min delay. Participants recalled and recognized significantly more spaced words than massed words during this word list learning task. These results strongly indicate that the spacing of repetitions improves learning and memory in individuals who have sustained moderate to severe TBI. Implications for rehabilitation are discussed.

Memory dysfunction following traumatic brain injury (TBI) is the most common cognitive symptom reported by patients (Goldstein & Levin, 1995; Rosenthal & Ricker, 1999) and is a primary predictor of vocational instability (Drake, Gray, Yoder, Pramuka, & Llewelly, 2000). Investigators examining the nature of memory dysfunction following TBI have focused on deficits in retrieving newly learned information (Brooks, 1976; Kear-Caldwell & Heller, 1980). Based on early observations of learning deficits following TBI (Blachstein, Vakil, & Hoofien, 1993; Crosson, Novack, Trenerry, & Craig, 1988), more recent work has emphasized the acquisition of information, or new learning, as the primary source of memory deficit following TBI (DeLuca, Schultheis, Madigan, Christodoulou, & Averill, 2000). These authors determined that when the amount of information acquired during the learning trials is controlled (i.e., both individuals with TBI and healthy adults reach a predetermined criterion), individuals with TBI recall and recognize information at a level comparable to healthy adults. These findings imply that the primary memory deficit following TBI involves acquiring, or learning, new information. In line with this

Address correspondence to: John DeLuca, Ph.D., Director of Neuroscience Research, Kessler Medical Rehabilitation Research and Education Corporation, 1199 Pleasant Valley Way, West Orange, NJ 07052, USA. Tel.: +1-973-243-6974. E-mail: jdeluca@kmrrec.org
Accepted for publication: August 8, 2002.

conclusion, clinical interventions with patients with TBI should be geared toward enhancing their ability to acquire, or learn, new information.

Past clinical interventions designed to ''retrain'' or improve memory through mnemonic strategies have been received with caution (Prigatano, 1999), if not with controversy (Ben-Yisay, 1993; Wilson, 1997). There has been little data to suggest that beyond the improvement observed during the natural recovery course, memory retraining permanently enhances memory functioning following TBI (Prigatano, 1999; Wilson, 1997). The ineffectiveness of strategies designed to improve memory functioning following TBI has forced clinical approaches away from interventions designed to address the underlying memory deficits and toward interventions focused on the behavioral compensation strategies. In other words, recent cognitive rehabilitation has not focused on cognition but on methods to circumvent cognitive dysfunction (Prigatano, 1999; Wilson, 1997). Research that integrates the study of cognitive deficits and functional outcomes allows for a better understanding of the underlying cognitive deficits associated with TBI. Ultimately, an understanding of the mechanisms underlying memory dysfunction following TBI should directly inform the development of rehabilitation interventions. The challenge for researchers and rehabilitation specialists alike is to bridge the gap between the theoretical and empirical models that have successfully explained cognition in healthy adults and clinical populations and the functional interventions designed to help those with memory impairment.

THE SPACING EFFECT

In his classic 1885 publication on human memory, Ebbinghaus provided convincing empirical evidence that learning and memory are significantly improved when repeated trials are distributed over time (spaced repetitions) compared to consecutive learning trials (massed repetitions; Ebbinghaus, 1885/1994). More recently, this phenomenon known as the spacing effect (SE) has been shown to enhance learning and memory with verbal and nonverbal materials across different age groups and in different memory paradigms (e.g., recognition, recall, etc.). Research shows that the SE occurs with list learning (Challis, 1993; Kahana & Greene, 1993) paragraph reading (Krug, Davis, & Glover, 1990), picture learning (Hintzman & Rogers, 1973) and the learning of faces (Goldstein, Chance, & Otto, 1987). The SE has become one of the most widely studied phenomenon in psychology with many researchers impressed by the ubiquity and robustness of the SE (Braun & Rubin, 1998; Challis, 1993).

There have been various explanations for the SE. One common explanation postulates an ''encoding deficit'' on repeated items during massed trials. For example, when one receives consecutive (i.e., massed) exposures to a stimulus, the initial presentation of the stimulus remains within the working memory buffer (the memory system's ''on-line'' information processing system) during the onset of the second presentation. Because the initial presentation remains within working memory at the time of the second exposure, the second exposure does not require separate encoding. Therefore, consecutive exposures are encoded only once, thus diminishing the benefit of repeated exposure to a stimulus (Braun & Rubin, 1998; Greene, 1989).

Another potential explanation for the SE is referred to as the ''deficient processing hypothesis.'' This hypothesis maintains that individuals are much less likely to fully encode or process consecutive exposures due to factors such as habituation (i.e., taking the stimulus for granted), which minimizes the efficacy of the immediate repetition (Challis, 1993; Hintzman, 1974). Still another potential explanation for the SE attributes the phenomenon to an increase in the number of retrieval cues with spaced repetitions. During distributed learning trials, the retrieval cues associated with each repetition are much more likely to be diversified if they are separated in time, and, ideally, context (Glenberg, 1979). These various explanations for the SE are not mutually exclusive and any one of them, or all of them, may be operating during any given memory paradigm (Greene, 1989). Moreover, the explanations must accommodate the fact that the SE is a natural phenomenon of the human memory system that does not, necessarily, require conscious effort, training, or additional mental operations by the individual (Challis, 1993; Russo, Parkin, Taylor, & Wilks, 1998).

STUDY PURPOSE

The purpose of the present study was to examine whether persons with moderate and severe TBI would benefit from the SE. The study was designed to determine whether spacing of repetitions improves learning and memory after moderate and severe TBI compared to nonspaced presentations. Based on the assumption that the cognitive processes underlying the spacing effect are not dramatically impacted by memory disturbance (Cermak, Verfaellie, Mather, & Chase, 1996), we hypothesized that participants with TBI would recall and recognize a significantly greater number of words in the spaced condition compared to the massed condition. It was further hypothesized that, after controlling for the variance accounted for by neuropsychological status, the SE would continue to significantly facilitate performance on tests of recall and recognition.

METHODOLOGY

Study Participants

The study included 20 participants aged 18–55 years who were diagnosed with moderate or severe TBI. It was often the case that a 24 h Glasgow Coma Scale (GCS) score could not be ascertained ($n = 15$). Because of this, participants were included in the study only if there was documentation of positive CT or MRI neuroimaging results or if there was a definitive period of loss of consciousness (LOC) of 24 h or greater. In this sample, 18 participants experienced a period of LOC of greater than 24 h and the remainder showed single or multiple positive CT findings (e.g., brain contusion, subarachnoid hemorrhage; see Table 1). All participants were recruited through flyers at the New Jersey Medical School, University of Medicine and Dentistry at New Jersey and from within the Kessler Institute for Rehabilitation. Participants were at least 1-year post injury and resided at home alone or with a significant other or family member. Participants were excluded from the study if they had a previous admission to an alcohol/drug treatment program or if they sustained a prior TBI. In addition, potential participants were excluded if they were previously diagnosed with a neurological disorder (e.g., stroke, longstanding seizure disorder), significant neurodevelopmental disorder (e.g., autism), or schizophrenia or bipolar disorder. All study participants signed an IRB approved consent form on the day of testing. Table 1 provides demographic and injury severity variables for study participants as well as their performance on neuropsychological measures.

Materials and Procedure

The critical target words included 80 words selected from the set of words used by Challis (1993) in studies of the SE. These low-to-medium frequency words contained 6–11 letters with a mean of 7.6 letters (e.g., woodchuck, ridicule). The words were printed in upper case letters on index cards for the administration of the list learning task. The 80 target words were randomly divided into 4 groups of 20 words for assignment to one of the 4 presentation conditions (i.e., once-presented, massed, spaced, and nonpresented). The massed condition consisted of a word being repeated twice consecutively, whereas the spaced condition consisted of a word being repeated twice with 11 words between repetitions. One group of words was presented only once (once-presented) and another group of words was not presented but appeared on the recognition test (nonpresented). Therefore, from the original 4 groups of 20 words, 4 separate word lists were constructed and, for each word list, words were presented in one of three study conditions (once-presented, massed, spaced) or they were not presented (and served as foils during the recognition task). Each list contained 115 index cards, with 20 once-presented words (20 cards), 20 massed-repeated words (40 cards), 20 spaced-repeated words (40 cards), 8 nontarget words at the beginning of the list to eliminate primacy effects (8 cards), and 7 nontarget words at the end of the list to eliminate recency effects (7 cards).

The study and test procedure was modelled after procedures used in other studies of the SE (e.g., Challis, 1993). Five participants were randomly assigned to each of the 4 study lists constructed for counterbalancing purposes. Participants were told individual words would be presented on index cards for 3 s, during which time they should read the word and rank it from "1" to "10" according to how familiar they were with the word, with "10" being the most familiar. There was a short practice session and then the list of 115 words was presented to participants. Following list presentation, participants were given an immediate free recall test. Participants were provided a blank piece of paper and asked to: "Write down all the words that you remember from the deck of cards." There was no time limit during this recall period.

Nonverbal neuropsychological tests (described below) were administered during a 30-min delay that

Table 1. Demographic, Injury Severity, and Neuropsychological Data for Entire Sample.

	Mean/percentage	*SE*	
Demographic information			
Age ($n=20$)	41.5	2.4	
Education ($n=20$)	14.1	.47	
Handedness ($n=20$)	95% (r)	–	
Gender ($n=20$)	80% (m)	–	
Years post injury ($n=20$)	4.1	.92	
Employment (% yes, $n=20$)			
Competitive	40%	–	
Protected Non-Comp.	10%	–	
Volunteer	15%	–	
Unemployed	25%	–	
Unknown	10%	–	
Injury severity information			
Duration of acute care ($n=15$)*	23.0	5.1	
Loss of consciousness at scene ($n=20$)*	100%	–	
LOC > 24 hr (% yes, $n=20$)	90%	–	
CT scan positive (% yes, $n=15$)*	93%	–	
Surgical intervention (% yes, $n=13$)*	61%	–	
Neuropsychological data			
Working memory and processing speed			
PASAT (1st two trials, $n=16$)	58.35	5.4	$n=16$**
Digit Span (total, $n=20$)	15.5	1.0	$n=20$
CFL ($n=20$)	36.6	3.4	$n=20$
Learning and memory			
HVLT			
Total ($n=20$)	21.3	1.58	$n=20$
Rey Complex Figure			
Delay ($n=20$)	15.5	1.6	$n=20$
Problem solving and mental flexibility			
Matrix Reasoning ($n=20$)	17.0	0.81	$n=20$
Trails B ($n=19$)	104.0	12.3	$n=19$**

Note. *Could not be determined for entire sample, **Could not be completed by entire sample (the composite *z* score for neuropsychological functioning included only the five tests administered to all participants).

followed the immediate free recall period. After the 30-min delay, a second free recall test and a recognition test for the word list were administered. The delayed free recall test was administered in the same manner as the immediate free recall test. Following the delayed free recall test, participants were administered a recognition test. During the recognition task, participants were provided a list of 80 words containing 60 target (or studied) words that were presented during the learning trial (i.e., 20 massed words, 20 spaced words, and 20 once-presented words) and 20 words that were not presented. Participants were required to read each word and indicate whether the word had been previously presented during the learning trial.

Neuropsychological Assessment Measures

Following moderate and severe TBI, the cognitive deficits most likely observed are in the areas of attention, information processing speed (Madigan, DeLuca, Diamond, Tramontano, & Averill, 2000), problem solving (Hanks, Rapport, Millis, & Deshpande, 1999), and learning and memory (DeLuca et al., 2000; Vanderploeg, Crowell, & Curtiss, 2001). Therefore, the battery of neuropsychological tests administered was geared toward measuring these cognitive functions. The Paced Auditory Serial Addition Test (PASAT), the Control Oral Word Association Test (i.e., CFL), and the Digit Span test were used to assess working memory and processing speed (Lezak, 1998). The Hopkins

Verbal Learning Test (HVLT) and the Rey Complex Figure were used to assess learning and memory (Lezak, 1998). The Trail Making Test (Lezak, 1998) and Matrix Reasoning subtest of the Wechsler Adult Intelligence Scale, Third Edition (Lezak, 1998) were used to assess problem solving and mental flexibility. An index of global cognitive functioning (GCF) was determined by averaging standardized z scores for the neuropsychological tests administered. Table 1 provides the average z scores achieved in this sample for the battery of neuropsychological tests. Not all participants were able to complete two subtests, the PASAT and Trails B, and for this reason, these two subtests were not included in the calculation of the GCF.

Data Analyses

The total number of studied words correctly recalled on the immediate and delayed recall tests and the number of studied words correctly identified on the delayed recognition test served as the dependent variables in this study. Repeated measures analyses for the three study conditions (i.e., once presented, massed, and spaced) for immediate and delayed recall and recognition were conducted with analysis of variance. In addition, paired sample t tests were used to examine the hypothesized direction of the differences between word conditions (spaced > massed > once presented) for the immediate and delayed recall and recognition trials. Finally, a one-way analysis of covariance (ANCOVA), with the GCF score as a covariate, was used to determine if the effect of study condition (i.e., massed, spaced, or once-presented) on learning and memory remained after controlling for the variance accounted for by neuropsychological status.

RESULTS

Immediate Recall

The mean number of correct responses for each learning condition are presented in Figure 1 and Table 2. To examine whether there was an effect of study condition (i.e., spaced, massed, and once-presented) on the list learning task, a repeated measures ANOVA revealed a significant main effect of learning condition on immediate recall, $F(2, 19) = 10.3$, $p < .001$, partial $\eta^2 = .365$. This is a large effect size qualitatively. Based upon the study hypotheses, paired sample t tests were used to determine the relationship between learning conditions. Spaced words were significantly more

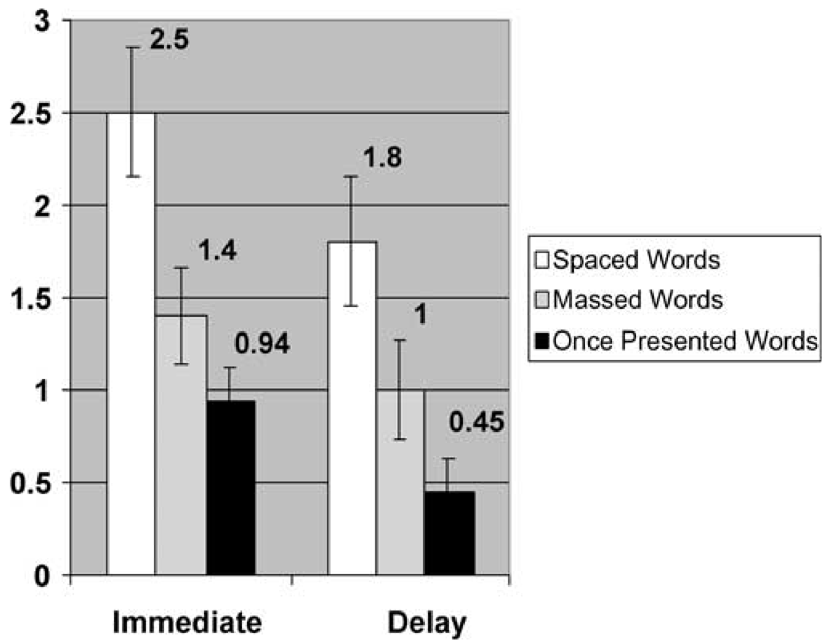

Fig. 1. Mean (standard error of the mean) number of words recalled for spaced, massed, and once presented learning conditions for immediate and delay recall trials.

Table 2. Performance Scores Across Once-Presented, Massed, and Spaced Learning Conditions for the Immediate and Delay Recall and Delay Recognition Trials.

	Sample (n)	Mean words	*SD*	*SE*
Immediate Recall				
Once	19	0.94	0.91	0.21
Massed	19	1.4	1.2	0.28
Spaced	19	2.5	1.7	0.39
Delayed Recall				
Once	20	0.45	0.75	0.17
Massed	20	1.0	1.1	0.24
Spaced	20	1.8	1.4	0.33
Recognition				
Once	19	13.7	3.2	0.74
Massed	19	13.6	4.3	0.99
Spaced	19	15.4	3.7	0.86

likely than massed words to be recalled during the immediate recall [$t(18) = 2.6$, $p = .018$, medium effect size, delta = 0.602] and significantly more likely than once-presented words to be recalled during the immediate recall trial recall [$t(18) = 4.4$, $p < .001$, large effect size, delta = 1.2]. However, massed words showed a nonsignificant effect in improving recall relative to once presented words during the immediate recall period [$t(18) = 1.6$, $p = .086$, small effect size, delta = 0.449].

Delayed Recall

A repeated measures ANOVA was conducted to examine the effect of study condition (i.e., spaced, massed, and once-presented) on delayed recall performance. The mean number of target words recalled in the three study conditions on the immediate and delayed recall tests are presented in Figure 1 and Table 2. This analysis revealed a significant main effect of learning condition on delayed recall performance, $F(2, 20) = 10.73$, $p = .001$, partial $\eta^2 = .36$. This is a large effect size qualitatively. For the delayed recall, paired sample t tests revealed that spaced words were significantly more likely than massed words [$t(19) = 2.77$, $p = .012$, medium effect size, delta = 0.625] and once-presented words [$t(19) = 3.8$, $p = .001$, large effect size, delta = 1.22] to be correctly recalled during delay recall performance. Massed words were also significantly more likely to be recalled than once-presented words during delayed recall performance [$t(19) = 2.4$, $p < .02$, medium effect size, delta = 0.652].

Recognition Performance

Examination of study condition (i.e., spaced, massed, and once-presented) on delayed recognition memory performance was analyzed by a repeated measures ANOVA. Mean number of correct responses for each learning conditions are listed in Table 2. This analysis revealed a significant main effect of learning condition on delayed recognition performance, $F(2, 19) = 8.28$, $p = .01$, partial $\eta^2 = .225$. This is a medium effect size qualitatively (see Fig. 2). Paired t tests revealed that spaced words were significantly more likely than massed words [$t(18) = 3.7$, $p = .001$, small effect size, delta = 0.450] and once-presented words [$t(18) = 2.6$, $p = .017$, small effect size, delta = 0.492] to be correctly recognized during delay recognition trial. In contrast, massed words were no more likely to be recognized than once-presented words during delayed recognition trial [$t(18) = -.075$, $p < .941$, effect size, delta = -0.02]. The mean number of studied words correctly recognized (hits) in the three study conditions, along with incorrectly identified nonstudied words (false alarms), are presented in Figure 2.

Neuropsychological Performance

In order to determine if neuropsychological functioning influenced the effect of study condition on recall and recognition, ANCOVA was used with the GCF as the covariate. This analysis revealed a significant main effect for study condition on immediate recall, $F(2, 19) = 13.0$, $p < .001$, partial $\eta^2 = .43$ (large effect size), delayed recall, $F(2, 20) = 21.6$, $p < .001$, partial $\eta^2 = .546$ (large effect size), and recognition, $F(2, 19) = 4.6$, $p = .017$, partial $\eta^2 = .213$ (medium effect size). Based on these results, when controlling for the variance accounted for by the GCF, word condition remained a significant determinant of recall and recognition performance.

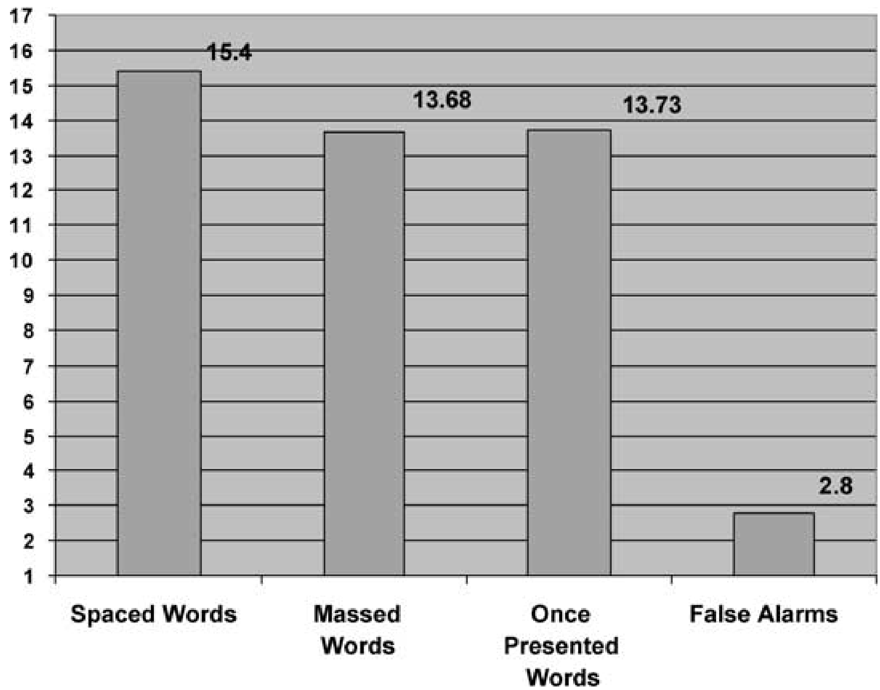

Fig. 2. Mean number of words correctly recognized for the three learning conditions and the number of words endorsed that were not seen (false alarms) during the recognition trial.

DISCUSSION

The results of the present investigation clearly illustrate that persons with moderate to severe TBI can significantly improve their memory performance by altering the manner in which learning takes place. Employing a phenomenon well known from the cognitive psychology literature, the spacing effect (SE), during learning can significantly improve subsequent recall and recognition performance in persons with TBI. Immediate and delayed recall as well as delayed recognition memory performance was significantly superior when words were presented in a spaced learning condition compared to when they were presented in a massed fashion or simply presented once. These findings in individuals with moderate and severe TBI are consistent with decades of work with healthy individuals in facilitating learning and memory across memory paradigms (Braun & Rubin, 1998; Russo et al., 1998).

Recent research in persons with TBI have shown that difficulties in the acquisition (or learning) of information may lie at the root of subsequently impaired memory (i.e., recall and recognition) performance (DeLuca et al., 2000; Vanderploeg et al., 2001). That is, impairments in recall, recognition and rates of forgetting following TBI are more likely a result of insufficient acquisition rather than deficient retrieval from long-term storage. This phenomenon has also recently been demonstrated in persons with TBI up to 10 years post injury (Zec et al., 2001). These data suggest strongly that interventions geared toward improving the quality of learning should result in improved performance on recall and recognition.

In the present study, the absolute increase in performance in the spaced condition compared to the massed condition was relatively modest (1.6–2.6 words for immediate recall and from 1.2 to 2.0 words for delayed recall). In addition, the total number of words recalled, particularly on the immediate test, was rather low compared to the performance of healthy adults in other similar SE studies (Challis, 1993). However, this level of memory performance was expected given the general memory impairment associated with moderate to severe TBI (DeLuca et al., 2000; Zec et al., 2001). Even so, the percentage increase in information recalled from the massed to the spaced condition was substantial (59 and 58% for immediate and delayed recall). As with recall, recognition performance benefited from the spacing of repetition compared to a massed condition and the rate of false positive errors during this task were comparable to undergraduate students participating in other studies of the SE (Challis, 1993). The percentage increase in performance provided by the spaced condition over the massed condition during the recognition trial (13%) was not as dramatic as in the recall trial. Nonetheless, the SE was shown to enhance performance, and further studies examining how the SE can be used to improve subsequent memory performance following TBI are needed.

The results of the present study also revealed that, when controlling for the variance accounted for by neuropsychological status, there remained a significant influence of the SE on recall and recognition performance. This finding is consistent with other studies reporting that the SE was equally effective in facilitating learning in persons with severe episodic memory impairment compared to healthy adults (Cermak, 1999). The implications are that the efficacy of the SE may not be mediated by the individual's general level of cognitive functioning and therefore may represent a more basic effect on learning itself. Consequently, the benefits offered by spaced learning may be employable across neurologic populations with varying degrees of cognitive impairment.

Functional Application of the SE

Prior research has indicated that deficient learning is a primary deficit in persons with TBI and, because of this, methods to improve learning should be a critical focus in cognitive rehabilitation (DeLuca et al., 2000). The SE provides rehabilitation specialists with a potential tool that addresses deficits in new learning. While the efficacy of the SE in enhancing memory performance is promising, its clinical utility in the rehabilitation of memory requires further investigation. Future studies should be geared toward investigating the timing and nature of repetitions in order to maximize the SE. The optimal conditions for the SE have yet to be investigated for functional tasks with clinical populations and, ultimately, these parameters may vary depending upon factors such as the amount of information to be learned or the specific task(s) or skills which are targeted for improvement. The SE has a history of successful application in the classroom of primary school children (for review, see Dempster, 1990) and this prior success may provide a good starting point for the development of new learning strategies in the area of cognitive rehabilitation. For instance, in cases of moderate and severe TBI, the SE may be used to improve new learning for individuals returning to school, to facilitate learning one's medication regimen, or to expedite the learning of new work schedules or daily routines.

An important advantage of the SE is that it is not a memory retraining strategy and it is not skill dependent. Moreover, the effectiveness of the SE does not require one to actively engage in any learning intervention, it simply requires alteration of the timing and context of learning trials. Thus, the challenge for rehabilitation specialists will be to examine how to harness the effect of the SE in their development of programs designed to ameliorate memory impairment following TBI.

Finally, memory rehabilitation strategies emphasizing repetition of information have gained little empirical support (Aldenkamp & Vermeulen, 1991; Berg, Koning-Haanstra & Deelman, 1991; Bergman, 1998; Doornhein & De Haan, 1998) and investigators have concluded that simple repetition does not necessarily facilitate memory (i.e., recall and recognition; Chiaravalotti, Demaree, Gaudino, & DeLuca, in press). The findings of the present study, in fact, indicate that repetition may facilitate memory within a spaced paradigm. The SE may be capturing the effect of repetition that is otherwise concealed during repeated, massed exposures to a stimulus (Challis & Sidhu, 1993). Because of this, it will be important in further investigations of learning and memory to better describe the timing and context of learning trials. Ultimately, the efficacy of the SE in facilitating functional memory will be dependent upon a host of factors related to how the information is repeated (e.g., duration of time between presentations, frequency of distributed presentations), and how memory for the information is measured (Challis, 1993; Dempster, 1988; Roediger & Challis, 1992). For instance, the importance of encoding conditions in a clinical population has been shown with amnesic patients; the SE disappeared when the instructions were manipulated to affect the quality of encoding during the distributed learning trials (Cermak et al., 1996).

In summary, the results of the present study showed that the SE is a naturally occurring learning phenomenon that can be employed to improve recall and recognition in individuals who have sustained moderate or severe TBI. Further application of the SE to cognitive rehabilitation strategies holds the promise of maximizing the residual memory skills of TBI patients. The next step is to develop interventions that make use of the SE to improve learning and memory in day-to-day functioning.

ACKNOWLEDGMENTS

This research was supported in part by NIH grant HD07522, NIDRR grant H133P970011, and a grant from the Henry H. Kessler Foundation, West Orange, New Jersey 07052, USA.

REFERENCES

Aldenkamp, A.P., & Vermeulen, J. (1991). Neuropsychological rehabilitation of memory function in epilepsy. *Journal of Neuropsychological Rehabilitation*, *1*, 199–214.

Ben-Yisay, Y., & Diller, L. (1993). Cognitive remediation in traumatic brain injury: Update and issues. *Archives of Physical Medicine and Rehabilitation*, *74*, 204–213.

Berg, I.J., Koning-Haanstra, M., & Deelman, B.G. (1991). Long-term effects of memory rehabilitation: A controlled study. *Neuropsychological Rehabilitation*, *1*, 97–111.

Bergman, M.M. (1998). A proposed resolution of the remediation-compensation controversy in brain injury rehabilitation. *International Journal of Cognitive Technology*, *3*, 45–51.

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

Braun, K., & Rubin, D.C. (1998). The spacing effect depends on an encoding deficit, retrieval, and time in working memory: Evidence from once-presented words. *Memory*, *6*, 37–65.

Brooks, D.N. (1976). Wechsler Memory Scale performance and its relationship to brain damage after severe closed head injury. *Journal of Neurology, Neurosurgery, and Psychiatry*, *39*, 593–601.

Cermak, L.S., Verfaellie, L.S., Mather, M., & Chase, K. (1996). Effect of spaced repetitions on amnesia patients' recall and recognition performance. *Neuropsychology*, *10*, 219–227.

Challis, B.H. (1993). Spacing effect on cued-memory tests depend upon level of processing. *Journal of Experimental Psychology, Learning, Memory, and Cognition*, *19*, 389–396.

Challis, B.H., & Sidhu, R. (1993). Dissociative effects of massed repetition on implicit and explicit measures of memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*, 115–127.

Chiaravalotti, N.D., Demaree, H., Gaudino, E.A., & DeLuca J. (in press). Is the repetition effect applicable to clinical populations? *Clinical Rehabilitation.*

Crosson, B., Novack, T., Trenerry, M.S., & Craig, P.L. (1988). California Verbal Learning Test (CVLT) performance in severely head-injured and neurologically normal adult males. *Journal of Clinical and Experimental Neuropsychology*, *10*, 754–768.

DeLuca, J., Schultheis, M.T., Madigan, N.K., Christodoulou, C., & Averill, A. (2000). Acquisition versus retrieval deficits in traumatic brain injury: Implications for memory rehabilitation. *Archives of Physical Medicine and Rehabilitation*, *81*, 1327–1333.

Dempster, F.N. (1988). The spacing effect: A case study in failure to apply the results of psychological research. *American Psychologist*, *43*, 627–634.

Dempster, F.N. (1990). The spacing effect: Research and practice. *Journal of Research and Development in Education*, *23*, 97–101.

Doornhein, K., & De Haan, E.H.F. (1998). Cognitive training for memory deficits in stroke patients. *Neuropsychological Rehabilitation*, *8*, 393–400.

Drake, A.I., Gray, N., Yoder, S., Pramuka, M., & Llewellyn, M. (2000). Factors predicting return to work following mild traumatic brain injury: A discriminant analysis. *Journal of Head Trauma Rehabilitation*, *15*, 1103–1112.

Ebbinghaus, H. (1964). *Memory: A contribution to experimental psychology*. New York: Dover. (Originally in 1885).

Gay, L.R. (1973). Temporal position of reviews and its effect on retention of mathematical rules. *Journal of Educational Psychology*, *64*, 171–182.

Glenberg, A.M. (1979). Component levels theory of the effects of spacing of repetitions on recall and recognition. *Memory and Cognition*, *7*, 95–112.

Greene, R.L. (1989). Spacing effects in memory: Evidence for a two-process account. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 371–377.

Hanks, R.A., Rapport, L.J., Millis, S.R., Deshpande, S.A. (1999). *Archives of Physical Medicine and Rehabilitation*, *80*, 103–107.

Hintzman, D.L. (1974). *Theories in cognitive psychology: The Loyola Symposium* (Solso, R.L., Ed.). Potomac, MD: Lawrence Erlbaum.

Kear-Caldwell, J.J., & Heller, M. (1980). The Wechsler Memory Scale and closed head injury. *Journal of Clinical Psychology*, *36*, 782–787.

Krug, D., Davis, T.B., & Glover, J. (1990). Massed versus distributed repeated reading: A case of forgetting helping recall? *Journal of Educational Psychology*, *82*, 366–371.

Lezak, M.D. (1998). *Neuropsychological assessment* (4th ed.). New York: Oxford University Press.

Madigan, N.K., DeLuca, J., Diamond, B.J., Tramontano, G., & Averill, A. (2000). Speed of information processing in traumatic brain injury: Modality-specific factors. *Journal of Head Trauma Rehabilitation*, *15*, 943–956.

Prigatano, G.P. (1999). The outcome of neuropsychological rehabilitation programs. In *Principles of neuropsychological rehabilitation* (pp. 256–257). New York: Oxford University Press.

Roediger, H.L., & Challis, B.H. (1992). Effects of exact repetition and conceptual repetition on free recall and primed word fragment completion. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*, 3–14.

Rosenthal, M., & Ricker, J.H. (2000). Traumatic brain injury. In R. Frank & T. Eliott (Eds.), *Handbook of rehabilitation psychology* (pp. 49–74). Washington, DC: American Psychological Association Press.

Russo, R., Parkin, A.J., Taylor, S.R., & Wilks, J. (1998). Revising current two-process accounts of spacing effects in memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 161–172.

Vanderploeg, R.D., Crowell, T.A., & Curtiss, G. (2001). Verbal learning and memory deficits in traumatic brain injury: Encoding, consolidation, and retrieval. *Journal of Clinical and Experimental Neuropsychology*, *23*, 185–195.

Wilson, B.A. (1997). Cognitive rehabilitation: How it is and how it might be. *Journal of International Neuropsychological Society*, *3*, 487–496.

Zec, R.F., Zellers, D., Belman, J., Miller, J., Matthews, J., Ferneau-Belman, D., & Robbs, R. (2001). Long-term consequences of severe closed head injury on episodic memory. *Journal of Clinical and Experimental Neuropsychology*, *23*, 671–691.