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Baseline performance and learning rate of conceptual and perceptual skill-learning tasks: The effect of moderate to severe traumatic brain injury

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Existing literature presents a complex and inconsistent picture of the specific deficiencies involved in skill learning following traumatic brain injury (TBI). In an attempt to address this difficulty, individuals with moderate to severe TBI (n = 29) and a control group (n = 29) were tested with two different skill-learning tasks: conceptual (i.e., Tower of Hanoi Puzzle, TOHP) and perceptual (i.e., mirror reading, MR). Based on previous studies of the effect of divided attention on these tasks and findings regarding the effect of TBI on conceptual and perceptual priming tasks, it was predicted that the group with TBI would show impaired baseline performance compared to controls in the TOHP task though their learning rate would be maintained, while both baseline performance and learning rate on the MR task would be maintained. Consistent with our predictions, overall baseline performance of the group with TBI was impaired in the TOHP test, while the learning rate was not. The learning rate on the MR task was preserved but, contrary to our prediction, response time of the group with TBI was slower than that of controls. The pattern of results observed in the present study was interpreted to possibly reflect an impairment of both the frontal lobes as well as that of diffuse axonal injury, which is well documented as being affected by TBI. The former impairment affects baseline performance of the conceptual learning skill, while the latter affects the overall slower performance of the perceptual learning skill.

Keywords: Skill learning; Traumatic brain injury; Tower of Hanoi Puzzle; Mirror reading; Conceptual; Perceptual.

Traumatic brain injury (TBI) is highly prevalent in industrialized countries. According to the Centers for Disease Control and Prevention, 3.5 million people in the US suffer from TBI annually (Coronado et al., 2012). TBI frequently leads to widespread diffuse axonal injury in which the frontal lobes were found to be the most vulnerable cortical areas, though not exclusively (for review see Bigler & Maxwell, 2011). Magnetic resonance imaging (MRI) abnormalities have been frequently found in the mesial temporal and lateral frontal lobes in addition to ventricular enlargement (Crosson, Sartor, Jenny, Nabors, & Moberg, 1993).

TBI has many cognitive implications that prevent patients from fully recovering their previous abilities, though memory impairment is one of the most (if not the single most) common and disabling impairments caused by TBI (for review see Vakil, 2005). Patients with TBI and their relatives voice more complaints about memory deficiencies than any other cognitive domain (Arcia & Gualtieri, 1993). Some improvement is observed six months to one year after the injury (Kersel, Marsh, Havill, & Sleigh, 2001) and six months to two years later (Lannoo, Colardyns, Jannes, & DeSoete, 2001). Nevertheless, deficient learning and memory skills were detected in patients with severe TBI even 10 years post injury (Zec et al., 2001). The above observations may explain why memory impairment is the cognitive deficiency most widely investigated in patients who have sustained TBI (Vakil, 2005).

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Literature on memory clearly demonstrates that memory is not a unitary system, but rather a series of systems composed of different cognitive subprocesses (Squire & Zola-Morgan, 1991). Over the last three decades it has become clearer that memory can be assessed both explicitly and implicitly. In explicit memory tasks, such as recall and recognition, the person is explicitly asked to retrieve specific information. On the other hand, the facilitatory (or inhibitory) effect of performance due to previous exposure to the particular information is considered an implicit memory measure (Schacter, 1987). Implicit memory tests are frequently divided into two major subtypes: priming or item-specific tests, and skill or procedural learning tasks (Moscovitch, Goshen-Gottstein, & Vierzen, 1994; Squire & Zola-Morgan, 1991).

Despite the extensive research that has been conducted to investigate the effect of TBI on a wide range of memory processes, the focus is most commonly placed on explicit memory processes (Vakil, 2005). Significantly fewer studies have been conducted on the effect of TBI on implicit memory tasks, particularly skill learning.

TBI is known to have minimal effect on the patients' ability to perform skills acquired before their injury (Schmitter-Edgecombe & Nissley, 2000; Vakil, Biederman, Liran, Groswasser, & Aberbuch, 1994). Studies were conducted using the serial reaction time (SRT) task (Nissen & Bullemer, 1987)—a commonly used skill-learning task that generates indirect and direct measures of sequence learning. Mutter, Howard, and Howard (1994) reported that the indirect measure of sequence learning indicated impaired performance among patients suffering from moderate to severe TBI, though the participants demonstrated normal performance on the direct measure of sequence learning. McDowall and Martin (1996) tested patients with TBI using the SRT task and reached contradictory results: Patients with severe TBI performed normally on the implicit sequence learning measure of the SRT task. Vakil, Kraus, Bor, and Groswasser (2002) used the SRT task to test explicit and implicit measures of sequence learning in patients who sustained TBI. Their findings suggest that this patient group shows a unique pattern of results—impairment on both the explicit and implicit measures of sequence learning. These findings do not correspond with performance in amnesia patients whose implicit sequence learning is preserved, but performance is shown to be impaired when skill learning is measured explicitly (Nissen & Bullemer, 1987). Patients with Parkinson's disease, on the other hand, show the opposite pattern (Ferraro, Balota, & Connor, 1993).

The Tower of Hanoi Puzzle (TOHP) is another task commonly used to evaluate cognitive skill learning. When used as a single-trial task, it is considered a measure of executive functions (Lezak, Howieson, Loring, Hannay, & Fischer, 2004), whereas repeated administration over multiple learning trials primarily assesses cognitive skill learning as expressed by reduced number of moves and time per move as a function of training. Similarly to other skill-learning tasks, the performance of patients with amnesia was preserved (Beaunieux et al., 2006; Cohen, Eichenbaum, Deacedo, & Corkin, 1985) while that of patients with lesions to the basal ganglia was impaired (Vakil & Herishanu-Naaman, 1998).

In an attempt to resolve these contradictory findings on TBI patients' ability to learn new skills, researchers proposed differentiating between different types of skill-learning tasks. Types of skills are most commonly divided into three groups—sensorimotor, perception, and cognitive skills (Gabrieli, 1998; Moscovitch et al., 1994). Vakil and Hoffman (2004) proposed dividing skill-learning types into perceptual and conceptual groups based on the attention resources required to acquire the skill. This strategy was based on previous studies that used divided attention to distinguish between conceptual and perceptual priming, in which the former but not the latter was affected by divided attention (see Mulligan, 1998, for review). Vakil and Hoffman used the same divided attention task as that used by Russo and Parkin (1993)—namely, the tone-monitoring task. In this task, participants listened to three tones (high, medium, and low pitch) presented in random order at a quasi-random rate. Participants were asked to call out each tone (i.e., high, medium, or low) upon presentation, while simultaneously performing either the TOHP or the mirror reading (MR) task. Their study showed that performance in the TOHP task was affected when the divided attention condition was applied, though performance was not affected in the MR task. Accordingly, the contradictory findings might be reconciled by distinguishing between conceptual tasks known to be sensitive to frontal lobe function (e.g., TOHP and SRT), and perceptual tasks (e.g., search detection and MR tasks) that are less mediated by the frontal lobes. However, the circuits connecting premotor planning areas and the frontal eye-fields are obviously involved in search-detection tasks and in the MR task.

This study specifically focuses on skill-learning abilities in patients with moderate to severe TBI by examining their performance in the two tasks used by Vakil and Hoffman (2004)—TOHP and

MR—to test conceptual and perceptual skill learning, respectively. In addition, the patient group performed two tests known to be sensitive to frontal lobe functioning (Lezak et al., 2004). One is independent of time performance—the Wisconsin Card Sorting test (WCST; Heaton, Chelune, Talley, Kay, & Curtiss, 1993)—and the other is time dependent—the semantic fluency and phonemic fluency tests (Hebrew version, Kave, 2005).

Several studies have demonstrated that divided attention simulates frontal lobe dysfunction (Moscovitch, 1994; Troyer & Craik, 2000; Troyer, Winocur, Craik, & Moscovitch, 1999). Accordingly, it has been predicted that performance of patients with TBI, who typically suffer frontal lobe dysfunction (Bigler & Maxwell, 2011), would show a similar pattern of performance as that under the divided attention condition. Thus it is predicted that, as shown by Vakil and Hoffman (2004), baseline performance on the conceptual skill-learning task (i.e., TOHP) would be impaired, and learning rate would not be affected, while baseline as well as learning rate on the perceptual task (i.e., MR) would be preserved compared to the controls. This would also be consistent with a previous study that showed that patients with TBI exhibited impaired performance on the conceptual priming task (i.e., category production) and preserved performance on the perceptual priming task (i.e., partial word identification; Vakil & Sigal, 1997). Furthermore, it is predicted that the accuracy aspects of the tasks would be associated with performance on the WCST, while the time measures would show an association with the verbal fluency task. This would support the assumption that patients' performance on skill-learning tasks is associated with the functioning of the frontal lobes.

METHOD

Participants

Two groups participated in the experiment: a group of 29 patients with moderate to severe TBI (3 women and 26 men), average age 29.14 years (SD = 5.75), and an average of 13.31 years of education (SD = 1.89); and a control group of 29 healthy participants (3 women and 26 men) with no history of cerebral injury, average age 27.17 years (SD = 4.88), and an average 14.07 years of education (SD = 2.38). Age, $t(56) = 1.40$, $p = .17$, and education, $t(56) = -1.34$, $p = .19$, did not significantly vary between the groups.

The patients suffering from TBI who participated in the study were recruited from various rehabilitation centers in Israel and participated in the study on a voluntary basis. All had sustained their injuries at least six months prior to the study and were classified as suffering from moderate to severe TBI. The severity of their injury was classified according to the three accepted measures: a score of 3–12 on the Glasgow Coma Scale (GCS); posttraumatic amnesia (PTA) lasting over 24 hours; and loss of consciousness for more than 20 minutes. The control group was composed of college students. All participants were native Hebrew speakers, with no history of mental illness, central nervous system trauma, cognitive impairment (i.e., learning disabilities, attention disorders, etc.), alcoholism, or drug abuse. Written informed consent was obtained from all participants. The study was approved as required by the Helsinki committee at each institute in which it was conducted.

Tasks and procedure

Skill-learning tasks

Tower of Hanoi Puzzle (TOHP). A computerized version of the TOHP was used. Three pegs appeared on the screen, numbered 1–3. Four disks were arranged according to size with the largest disk at the bottom of the peg on the far left (#1). Participants were instructed that their goal was to move the disks from the leftmost peg (#1) to the rightmost peg (#3) using a minimum number of moves, while adhering to the following rules: Only one disk may be moved at a time, no disk may be placed on a smaller one, and the middle peg must be used. The optimal solution for four disks requires 15 moves. The computer automatically measures the time and the number of moves required to solve the puzzle. Each participant was instructed to perform the task 10 times using the fewest possible number of moves. The number of moves and average time per move were recorded for each repetition of the task.

Mirror reading (MR). Words are shown on the computer screen in mirror image, using the SuperLab software (Cedrus, Inc.), and participants are instructed to decide, as quickly as possible, whether the word that appears is concrete or abstract. The task is composed of six blocks, with 24 words per block. Half of the words in each block are concrete, and half are abstract. Half of the blocks consist of new words, and the other half are repeated words. Response time was automatically recorded by the program.

Tests sensitive to frontal lobe functioning

The Wisconsin Card Sorting Test (WCST; Heaton et al., 1993) indexed with total number of categories completed. The Hebrew version of the semantic fluency and phonemic fluency tests (Kave, 2005) indexed with semantic and phonemic sum scores. Although these two tests are known to be sensitive to frontal lobe functioning, the WCST is independent of time performance while the fluency tests are time dependent.

RESULTS

Tower of Hanoi Puzzle

The TOHP was used to examine the difference between the ability of patients with TBI and that of the control group to acquire conceptual skills. A 2 × 10 mixed-design analysis of variance (ANOVA) with repeated measures was performed in order to compare the learning rate (10 trials; within-subject factor) for the TOHP in the two groups (between-subject factor): TBI and controls. Two dependent measures of skill learning were analyzed: total number of moves and average time per move. Total number of moves reflects accuracy, while average time per move reflects speed of performance—that is, the overall response time corrected by the number of moves.

Total number of moves

Both main effects [group, $F(1, 56) = 15.02$, $p < .001$, $\eta^2 = .21$; learning, $F(9, 504) = 2.99$, $p < .005$], reached significance. The group by learning interaction did not reach significance, $F(9, 504) = 1.13$, $p = .34$, $\eta^2 = .02$, indicating that the learning rate of the two groups was not significantly different. As can be seen in Figure 1, the controls required much fewer moves to solve the TOHP from as early as the first trial, and this advantage remained constant throughout the learning trials.

Average time per move

The same analysis as that described above (i.e., a 2 × 10 mixed design ANOVA with repeated measures) revealed that both main effects [group, $F(1, 56) = 15.71$, $p < .001$, $\eta^2 = .22$; learning, $F(9, 504) = 49.57$, $p < .001$, $\eta^2 = .47$], as well as the interaction, $F(9, 504) = 2.60$, $p < .01$, $\eta^2 = .04$, reached significance. As can be seen in Figure 2, the interaction is due to the fact that although the group with TBI started off very slowly, their learning rate was steeper than that of the control group, most likely because the controls reached a floor effect as they approached the advanced learning trials.

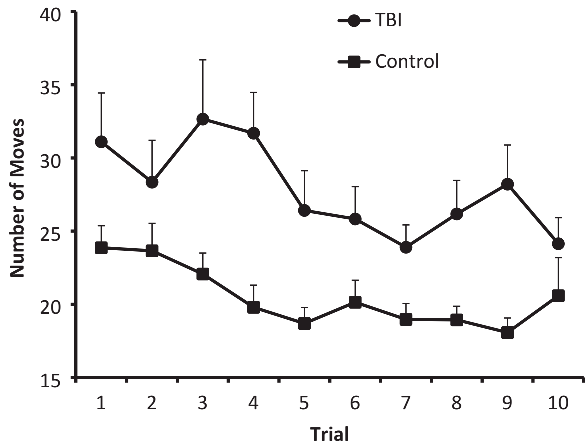

Figure 1. Mean number of moves and standard deviations for the 10 repetitions of the Tower of Hanoi Puzzle (TOHP): traumatic brain injury (TBI) groups compared to the control group.

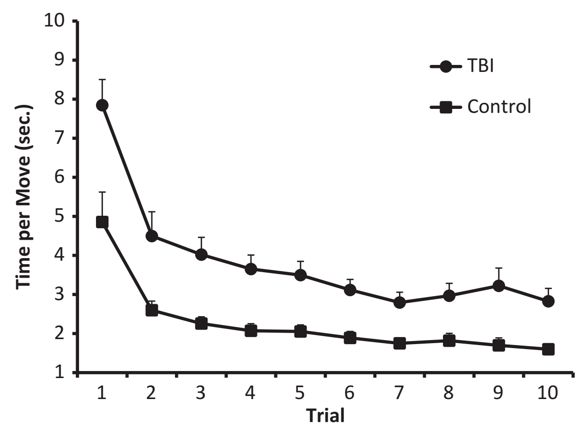

Figure 2. Mean time per move and standard deviations for the 10 repetitions of the Tower of Hanoi Puzzle (TOHP): traumatic brain injury (TBI) groups compared to the control group.

Mirror reading

A 2 × 6 × 2 mixed-design ANOVA with repeated measures was applied using the group as the between-subject variable (TBI and control). The within-subject variables were learning (six blocks) and repetition (new vs. repeated words). All main effects and interactions reached significance ($p < .01$). In order to understand the source of the triple interaction, $F(5, 280) = 5.23$, $p < .001$, $\eta^2 = .09$, follow-up, simple analyses were conducted. More specifically, the groups' learning rates for repeated and new words were analyzed separately.

New words

Both main effects, group and learning, reached significance, $F(1, 56) = 37.50$, $p < .001$, $\eta^2 = .40$; $F(5, 280) = 13.01$, $p < .001$, $\eta^2 = .19$, respectively. The interpretation of these main effects should be done cautiously because of the significant interaction, $F(5, 280) = 4.07$, $p < .005$, $\eta^2 = .07$. As can be seen in Figure 3, the overall reading time of the control group was faster than that of the group with TBI, although the learning rate of the group with TBI was steeper than that of the control group.

Repeated words

As with new words, both main effects [group, $F(1, 56) = 59.26$, $p < .001$, $\eta^2 = .51$; learning, $F(5, 280) = 57.63$, $p < .001$, $\eta^2 = .51$] and the interaction, $F(5, 280) = 10.74$, $p < .001$, $\eta^2 = .16$, reached significance. As can be seen in Figure 4, the overall reading time of the control group was faster than that of the group with TBI, although the learning rate of the group with TBI was steeper than that of the control group.

Thus, the analyses revealed similar result patterns for new and repeated words. In terms of response time, the control group was faster than the group with TBI. As can be seen in Figures 3 and 4, the interaction is due to the fact that the learning rate of the group with TBI was steeper than that of the control group, most likely because the controls reached a floor effect as they approached the advanced learning trials. Although the result patterns were similar for the new and repeated words, the overall learning rate for the latter was steeper than that of the former, as reflected by the triple interaction.

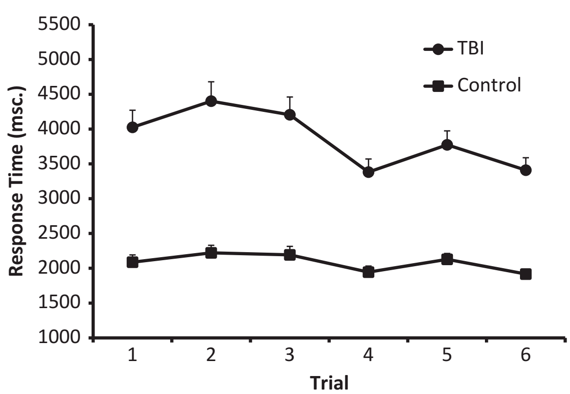

Figure 3. Mean response time and standard deviations for the six repetitions of the mirror reading (MR) task with new words: traumatic brain injury (TBI) groups compared to the control group.

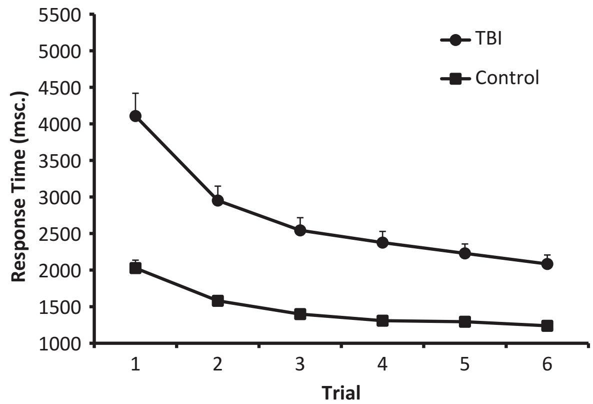

Figure 4. Mean response time and standard deviations for the six repetitions of the mirror reading (MR) task with repeated words: traumatic brain injury (TBI) groups compared to the control group.

Correlations between performance on the frontal lobe tests and the skill-learning tasks in the group with TBI

Pearson product moment correlations were conducted between performance on the two frontal lobe tests and performance on the skill-learning tasks. Two measures of each one of the skill-learning tasks were generated: one reflecting baseline performance (Trial 1) and the second reflecting learning rate (first trial minus last trial rates—10th trial for the TOHP and 6th for the MR). As can be seen in Table 1, performance on the WCST was significantly associated only with baseline and learning rate measures of the TOHP but not with

TABLE 1
Correlations between performance on the frontal lobe tests and the skill-learning tasks in the group with TBI

Procedural tasks	*Measures*	*WCST*	*Verbal fluency test*
TOHP	Trial 1 number of moves	–.39*	–.21
	Learning (Trials 1–10) number of moves	–.43*	–.26
	Trial 1 time per move	.14	–.21
	Learning (Trials 1–10) time per move	.37**	–.04
MR	Trial 1 new words	–.03	–.36*
	Trial learning (Trials 1–6) new words	–.10	–.02
	Trial 1 repeated words	–.18	–.47**
	Trial learning (Trials 1–6) repeated words	–.15	–.33

Notes. TBI = traumatic brain injury; WCST = Wisconsin Card Sorting Test; MR = mirror reading task; TOHP = Tower of Hanoi Puzzle.
*$p < .05$. **$p < .01$.

measures of the MR task. However, the verbal fluency measure was significantly associated with baseline but not with the learning rate measures of the MR task.

DISCUSSION

This research studied the ability to acquire new skills following TBI. Existing literature presents a complex and inconsistent picture of the specific deficiencies involved in skill learning after head injuries of this kind. TBI causes widespread, diffuse damage, which MRI studies have found to affect primarily the frontal lobes. It is also possible that pathways that connect with the frontal region are disrupted due to the diffuse axonal injury associated with TBI (Bigler & Maxwell, 2011).

Based on prior classification of skill-learning tasks as being conceptual and perceptual according to their sensitivity to divided attention, TOHP (i.e., conceptual) and MR (i.e., perceptual; Vakil & Hoffman, 2004), it was predicted that the performance of patients with TBI would be inferior to that of controls on the conceptual (i.e., baseline performance) but not on the perceptual task. These hypotheses were further based on previous findings that showed that performance among patients with TBI was impaired compared to controls on the conceptual priming task and preserved on the perceptual priming task (Vakil & Sigal, 1997).

Consistent with our predictions, overall baseline performance of the groups with TBI was impaired compared to the control group while performing the TOHP, while the learning rate was not. This was true whether accuracy (number of moves) or speed (time per move) was measured. A similar pattern of results was found when healthy individuals solved the TOHP under the divided attention condition (Vakil & Hoffman, 2004), which is assumed to simulate frontal lobe impairment (Moscovitch, 1994; Troyer & Craik, 2000; Troyer et al., 1999). Elderly individuals who were tested using the TOHP also displayed a similar pattern of results (Vakil & Agmon-Ashkenazi, 1997) in which the learning rate was maintained, and baseline performance was impaired compared to young participants. The vulnerability of the frontal lobe as a function of aging has been well documented (Raz et al., 2005).

Although the vulnerability of the frontal lobes following TBI has been well documented, as this paper does not present brain-imaging data for the patients who participated in this study, conclusions regarding the brain structures involved in these tasks must be drawn cautiously. Nevertheless, the claims noted above indicate that there is converging evidence of involvement of the frontal lobes primarily in baseline performance of the TOHP (i.e., a similar pattern of results under divided attention and the effect of age). The fact that the WCST was significantly correlated with TOHP baseline performance as well as learning rate might indicate that the frontal lobes are involved to a certain degree in the learning process of the TOHP as well.

Consistent with our prediction, the learning rate in the MR task for the group with TBI did not significantly differ from that of the control group. In fact, TBI patients showed a faster learning rate, as reflected by a significant interaction between group and learning variables (as well as in the time per move measure of the TOHP). As we explained in the Results section, the interaction is most likely due to the fact that the controls reached a floor effect as they approached the advanced learning trials (see Figures 2, 3, and 4). Thus, the present results did replicate findings on the effect of divided attention on the TOHP but not on MR (Vakil & Hoffman, 2004). However, the fact that, contrary to the effect of divided attention, the patient group's performance was overall slower than the controls on the MR task might suggest that in addition to the frontal lobes there is yet another mechanism that fails to function adequately following TBI. The diffuse axonal injury associated with TBI (Bigler & Maxwell, 2011) could explain the overall slowness observed in the MR task. It could also explain the overall increased time-per-move observed in the patient group in the TOHP, but does not explain the need for more moves to solution, which is not time dependent. Previous studies have already reported that processing speed is a very sensitive measure of TBI (Martin, Donders, & Thompson, 2000). Furthermore, processing speed was associated with diffuse axonal injury in patients with TBI (Meythaler, Peduzzi, Eleftheriou, & Novack, 2001). This conclusion is further supported by the significant correlation of all measures of the MR task (which are all time dependent) to the verbal fluency task. Thus, the pattern of results observed in the present study reflects an impairment of the frontal lobes as well as the result of diffuse axonal injury, the former affecting baseline performance of the conceptual learning skill and the latter the overall slower performance in the perceptual learning skill.

These findings further strengthen the dissociation between baseline performance and learning rate in skill learning (Vakil & Agmon-Ashkenazi, 1997; Vakil & Hoffman, 2004), which is presumed to reflect different cognitive processes. Nevertheless, this conclusion is based on an insignificant difference in learning rate (or actually in some cases, steeper learning rate of the patient group) and should be considered cautiously because of the relatively small sample size and low statistical power.

In addition to the theoretical implications of this study, there are implications for rehabilitation as well. The study suggests that, regardless of cognitive impairment, patients with TBI are capable of learning conceptual as well as perceptual skills, despite their impaired baseline performance. As pointed out above, due to the small sample size and low statistical power we cannot claim that the learning rate is similar to that of the controls, but we can certainly conclude that the learning rate is significant even following moderate to severe TBI. Thus, routinizing various daily activities at home or at work (e.g., operating a computer or a machine) by performing tasks in a repeated sequence could be a useful strategy to compensate for impaired explicit memory.

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