Published in final edited form as:

Curr Phys Med Rehabil Rep. 2015 June 1; 3(2): 99–105. doi:10.1007/s40141-015-0081-6.

Training to Optimize Learning after Traumatic Brain Injury

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Abstract

One of the major foci of rehabilitation after traumatic brain injury is the design and implementation of interventions to train individuals to learn new knowledge and skills or new ways to access and execute previously acquired knowledge and skills. To optimize these interventions, rehabilitation professionals require a clear understanding of how traumatic brain injury impacts learning, and how specific approaches may enhance learning after traumatic brain injury. This brief conceptual review provides an overview of learning, the impact of traumatic brain injury on explicit and implicit learning, and the current state of the science examining selected training approaches designed to advance learning after traumatic brain injury. Potential directions for future scientific inquiry are discussed throughout the review.

Keywords

traumatic brain injury; rehabilitation; implicit learning; rehabilitation; training

Introduction

Traumatic brain injury, whether mild, moderate or severe, causes significant changes to everyday life. The ability to care for oneself and others, engage in productive activities, and participate in personal and social roles can be dramatically altered, requiring individuals with traumatic brain injury to learn new knowledge and skills, or to learn new ways to execute previously acquired knowledge and skills. A major focus of rehabilitation is the design and delivery of training approaches that promote this learning. These training approaches vary greatly in conceptualization and implementation, and these variances may influence learning differentially. For example, a priori instruction in the optimal method for executing a particular motor task may yield different results than permitting the client to first attempt the task without a priori instruction. Furthermore, the efficacy of training approaches may also vary based on the type and severity of impairments of the client, the

Conflict of Interest

Elizabeth R. Skidmore reports grants from National Institute of Disability & Rehabilitation Research, grants from National Institutes of Health, during the conduct of the study; grants and salary support from San Bio, Inc., outside the submitted work.

Compliance with Ethics Guidelines

Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

client's goals, the task being trained, and the environment. Therefore, it is incumbent upon the rehabilitation profession to examine and understand factors that shape learning. This understanding may inform guiding principles to optimize training after traumatic brain injury. This brief conceptual review discusses perspectives on learning, the impact of traumatic brain injury on learning gleaned from experimental and clinical studies, and the impact of selected training approaches on learning after traumatic brain injury. Potential directions for future scientific inquiry are discussed throughout the review.

Perspectives on learning

Learning is the process of acquiring a relatively lasting change in knowledge and skills. Learning cannot be measured directly, and assessment may address different criterion indicators of learning. Acquisition is demonstrated through permanent change in knowledge or skill, typically achieved through repeated exposure. Retention is demonstrated through retrieval or execution of acquired knowledge or skill at a time point after acquisition. Transfer is demonstrated when knowledge or skills trained in one set of circumstances improves knowledge or skills executed in a different set of circumstances [1].

Based on a combination of incidental and experimental observations, robust evidence supports the dissociation of learning into explicit (declarative) learning and implicit (non-declarative) learning [2,3]. Explicit (declarative) learning is the process of consciously encoding, consolidating, storing and retrieving factual knowledge [4]. Explicit learning may include learning new words, concepts, and their meaning (semantic learning), or committing details of an event or location to memory (episodic learning) [5]. For example, committing to memory a list of medications, their side effects, and dosing requirements may rely heavily on explicit learning. Impairments in explicit learning have been associated with damage to the temporal and frontal lobes. Specifically, damage to the hippocampus, a grey matter region located within the medial temporal lobe, has been associated with difficulties encoding or forming new declarative memories, a process critical to explicit learning [2,6]. Furthermore, damage to dorsolateral prefrontal cortex has been associated with impairments in working memory (the ability to hold information and concepts in mind), as well as impairments in conceptual organization (planning, sequencing) [7–9].

Implicit (non-declarative) learning is the process of unconsciously acquiring or modifying behavior through experience [10]. Implicit learning may include developing a conditioned response to a specified stimulus (associative learning), developing a sensitization or habituation in response to a specified stimulus (non-associative learning), or learning a new skill (procedural learning). Implicit learning is shaped through sensory and perceptual experiences that alter the function of the neurological system, promoting efficiencies in communication among neuronal networks, and efficiencies in behavioral execution. For example, transferring in and out of a car while maintaining a partial weight-bearing restriction becomes more effective and more efficient with practice. Impairments in implicit learning, particularly impairments in procedural learning, have been associated with lesions to the striatum, as well as ventromedial, premotor, and supplementary motor areas of the frontal lobes; lesions to the cerebellum have been associated with impairments in learning rhythm or timing when executing a motor skill [11–15]. The distribution of these cortical

and subcortical grey matter areas, and the critical white matter pathways that connect these areas, illustrates the complexity of the networks that support implicit learning throughout the brain [16].

Traumatic brain injury: impact on explicit and implicit learning

Given the mechanisms that cause traumatic brain injury, and the anatomical location of structures critical to learning, explicit learning may be more vulnerable to injury than implicit learning, particularly after focal injury [17]. Focal trauma to the head often results in contusions to the anterior and lateral surfaces of the brain – incorporating damage to the dorsolateral prefrontal cortex and the medial temporal lobe (and underlying subcortical structures, in the cases of severe injury). Certainly midline cortical and subcortical structures are vulnerable to traumatic brain injury, and may be damaged as the result of diffuse trauma (e.g., axonal shearing, anoxia), as well as secondary complications of the initial focal trauma (e.g., inflammation, neurotoxicity, bleeding). However, in comparison to anterior and lateral surfaces of the brain – midline cortical and subcortical structures tend to be relatively preserved after focal injury. This is perhaps most evident in experimental animal models of focal traumatic brain injury, such as fluid percussion and controlled cortical impact models, where the location and the severity of contusion is highly controlled [18–21]. For example, Wagner and colleagues have examined cognitive impairments associated with controlled cortical impact injuries that cause contusion in the cortical areas over the hippocampus, a region associated with explicit learning. They have demonstrated that skill acquisition through implicit learning after injury is generally retained, and comparable to non-injured animals. In contrast, explicit skills were severely impaired relative to non-injured animals [22].

Although the location and severity of damage to the brain in clinical traumatic brain injury is much less controlled, the impact of clinical traumatic brain injury on implicit and explicit learning appears to be quite similar. Several studies report that individuals with severe traumatic brain injury demonstrated skill acquisition through implicit learning at the same rate as matched peers who did not experience a traumatic brain injury [23–27]. Although individuals with severe traumatic brain injury may require more time to achieve the same rate of skill acquisition [28,29], long-term retention of skills once acquired appears to be comparable between individuals with and without traumatic brain injury [30]. However, several studies have reported that relative to non-injured controls, individuals with traumatic brain injury demonstrate pronounced impairments in acquisition and retention of new information through explicit learning [31–33].

Although implicit learning may appear to be less affected by traumatic brain injury than explicit learning, the impact of traumatic brain injury on transfer of implicit learning across tasks or environments is unclear. Experimental animal models of traumatic brain injury suggest that, although animals with controlled cortical impact injury demonstrated retention of the implicit learning after injury, transfer from one task (Morris Water Maze hidden platform task) to another related task (hidden platform moved to another quadrant) was limited relative to non-injured animals [22,34]. Because few clinical studies have rigorously examined transfer of implicit learning relative to non-injured controls, it is difficult to

comment on the generalizability of findings from experimental animal studies to clinical rehabilitation. In fact, this seems to be a gap in current clinical studies, and a very important direction for future clinical rehabilitation research.

Explicit and implicit learning: implications for rehabilitation

Given that implicit learning is generally less impaired than explicit learning after traumatic brain injury, some have argued that training approaches that emphasize implicit learning after traumatic brain injury may be preferable to training approaches that emphasize explicit learning [35]. However, as of yet, there is limited robust evidence to support this assertion. One of the primary reasons for this limited evidence is that it is difficult to completely divorce explicit and implicit learning during the training of complex knowledge and skills that are typically the focus of clinical rehabilitation. For example, listening to or reading about the procedure for using a walking aid may emphasize explicit learning, but rehearsal of these procedures, whether through verbalization or action, emphasizes implicit learning. Similarly, “learning by doing” clearly emphasizes implicit learning through procedural learning, allowing experience to shape skill acquisition, retention, and transfer. However, therapist-directed or self-generated analysis of the experience emphasizes explicit learning, and this in turn may also shape skill acquisition, retention, and transfer. The question remains whether optimal training should or should not promote elements of both explicit and implicit learning, and if so, to what degree and in what sequence. To begin to answer these questions, we must first consider factors that promote learning in the context of traumatic brain injury rehabilitation.

Much of what we understand about factors that support optimal learning in rehabilitation has emerged from neuroscience, psychology, and instructional methods studies with healthy participants. For example, it is well-documented that the presence of a clear goal to learning [36], motivation or desire to achieve that goal [37], relevance or salience of the goal to the client [38,39], as well as the novelty and complexity of the skill being learned [39,40] are all factors that promote successful learning. High dose, or high quantity and intensity of exposure or practice, is also critical to successful learning [41]. Less clear are the roles of various types of practice conditions and instructions in promoting optimal learning. Consistency or variability of practice conditions may differentially impact learning, depending on the criterion of interest (i.e., acquisition, retention, transfer). The timing and manner of instructions, feedback, and support for learning may also differentially impact learning. Furthermore, error-based learning may also play a harmful or a beneficial role, depending on the client and the projected outcome. These last few factors, and relevant evidence in traumatic brain injury rehabilitation, are discussed in more detail.

The consistency or variability of practice conditions has been one focus of clinical studies examining optimal training approaches for implicit learning. Consistent or blocked practice can be defined by the practice of the procedures associated with a specific skill, in the same order, with the same timing, and in the same context. Variable or random practice may involve the systematic introduction of variability in the order of content or procedures, the timing, or the context of practice. First described by Shea & Morgan as the contextual interference effect [42], random practice has been associated with comparable rates of

acquisition and retention of implicit learning when compared to blocked practice and superior rates of transfer among healthy children and adults [43]. Similar findings have been reported in brain injury, with some studies reporting comparable rates of acquisition and retention between blocked and random practice of simple, discrete tasks [44], and other studies reporting higher rates of retention attributed to random practice of similar tasks [45]. Neither of these studies examined transfer of learning after brain injury. Furthermore, in healthy participants, the presence of the contextual interference effect is less apparent with complex, continuous tasks that require controlled cognitive processing, compared to simple, discrete tasks that rely more heavily on automatic cognitive processing [43,46,47]. Thus, the comparative value of blocked and random practice would appear to be based on the task and the client's cognitive capacity. Additional research in this area may further illuminate guiding principles for best practices in traumatic brain injury rehabilitation.

Although there has been a strong focus on implicit learning in traumatic brain injury rehabilitation, more recent studies have begun to explore the role of explicit learning. Several studies have examined the use and timing of explicit instructions or cues. Boyd and colleagues have demonstrated that the provision of explicit instructions prior to task performance may actually impede skill acquisition after brain injury (in this case stroke) [14,15,48], and their findings are supported by studies in healthy adults [49–52]. Alternatively, the use of explicit analysis and feedback *after* the performance of a given skill has been associated with efficient acquisition and retention, and in some cases transfer of learning [52]. Evidence from meta-analyses of instructional learning studies suggests that the manner in which post hoc explicit analysis and feedback are generated may matter [53]. Therapist-directed analysis and feedback is informed by the expertise of the therapist and is provided directly based on the therapist's observations of performance. For example, after attempting to come to a stand from the edge of the bed and then sitting back down, the therapist may tell the client that he needs to lift his head higher next time or straighten his knees. Therapist-guided analysis and feedback may come in the form of elicited explanation (specification or explanation of skill to another person after identified through performance) or guided discovery (structured opportunities for clients to “discover” an approach to the skills they are learning or solutions to problems they are facing). For example, using the same activity, the therapist may ask the client what he thinks went wrong during the attempted stance and ask the client to generate a potential plan for the next attempt. Using principles of guided discovery, the therapist may ask guiding questions to help the client generate one particularly useful strategy. The therapist may also provide a scaffolding to guide the learner's thinking. Meta-cognitive strategy instruction approaches teach the learner a broad strategy (e.g. Goal – Plan – Do – Check) [54] that can be applied to a variety of tasks and use this broad strategy to guide the learner to safe and effective learning without emphasizing the therapist's expertise. [It is important to note that therapist-guided analysis differs from unassisted discovery learning which typically involves learning through observation or experience without any structure, support, or guidance] [53, 55] Evidence from meta-analyses on feedback suggest that therapist-guided analysis may be more effective for promoting learning than therapist-directed analysis and feedback, but that both are likely to result in better outcomes than unassisted discovery learning [53, 56–61].

The role of error in learning after traumatic brain injury is another focus of clinical rehabilitation studies. Errorless learning is a training approach that emphasizes implicit learning through repetitive task-specific training without the experience of error [62–64]. The therapist and client identify a specific task for training, and the therapist breaks the task or information down into finite steps or procedures. Therapeutic techniques such as vanishing cues (introducing the target by providing partial cues, and then withdrawing cues following successful recall of the target) [65] and spaced retrieval (prompted recall of the target over successively longer intervals) are used to reinforce implicit learning of each step of the task in sequence [66] and to chain the steps together. Steps are practiced in sequence (blocked practice), and practice is halted immediately to correct errors (thus preventing implicit learning of these errors). In fact, errorless learning ensures acquisition and retention of a given skill [67] and minimizes the need for conscious (explicit) control during skill execution [68,69]. However, training is task specific and therefore is generally associated with limited transfer [64,68,69].

In contrast, errorful learning has been associated with good skill acquisition and retention, as well as good skill transfer, particularly for complex skills where judgment and problem solving may be critical [70–73]. Errorful learning typically incorporates implicit learning through skill execution without a priori instruction and incorporates explicit learning through analysis of performance or behavior after the fact to generate adaptations for future performance. The explicit analysis leverages trial and error to inform learning [74] and frequently employs random practice (i.e., trying more than one strategy for skilled performance). While it may seem that the evidence surrounding errorless and errorful learning is conflicting, a closer look may clarify this apparent controversy. Some have suggested that both errorless learning and errorful learning can be effective training approaches, but that effectiveness is contingent on the client's abilities, the client's goals, and the client's environment [75]. For example, for individuals with severe explicit learning impairments (i.e., severe anterograde amnesia), errorless learning may be more effective than errorful learning, particularly if the client's goal is acquisition and retention of a specific skill (e.g., learning to use a smartphone to plan daily events) and if the environment is supportive (i.e., stable, limited variability) for the specified skill. For individuals without severe explicit learning impairments, errorful learning may be more effective than errorless learning, particularly if the client's goal is transfer of a specific skill (e.g., wheelchair transfers) to a variety of related contexts (e.g., bed, car seat, desk chair).

In an effort to understand conditions that promote optimal learning, scientists have attempted to isolate and contrast elements of explicit and implicit learning. In fact, studies do suggest that explicit and implicit learning processes compete for neurological resources [76]. That is, when developing explicit learning, implicit learning may suffer. The reverse may also be true. Thus, it is tempting to directly compare explicit and implicit learning in the context of training. However, the evidence may suggest that optimal learning is not the over-emphasis of either explicit or implicit learning, but rather a balance of both. For example, over-reliance on explicit learning may blunt implicit learning of new skills ("analysis paralysis"). In contrast, over-reliance on implicit learning may produce a dependency on habits that limit adaptability (inability to alter behavior in response to contextual changes). Rather than focusing on one or the other, studies examining the timing

and sequence of explicit and implicit training approaches, and comparing effectiveness of these approaches based on the client's abilities, the task characteristics, and the environment, may provide more useful information [52]. For example, the preponderance of evidence discussed in this brief review would suggest initial focus on implicit learning of simple, discrete tasks (incorporating elements of random practice), coupled with post-performance analysis (explicit learning), may lead to better learning outcomes for individuals with traumatic brain injury who do not have severe explicit learning impairments. However, this approach may not be beneficial for learning complex, continuous tasks or for individuals with severe anterograde amnesia. Comparative study of these elements, alone and in combination, are likely to shed light on some of the apparently contradictory evidence to date, as well as uncover additional factors that may influence the design of rehabilitation training.

To inform this comparative study, additional attention to the specification of training approaches may be necessary. The development and comparison of carefully specified and contextually-relevant training paradigms in experimental animal models (see [22, 34] for examples) offer unique opportunities for advancing our understanding of biological and behavioral mechanisms that support learning. From these studies, we may also glean some insights into the benefits of experimental manipulation of elements that we could not otherwise glean from clinical studies (i.e., controlled comparisons of type and severity of injuries and environments). That said, significant advances can be made through well-designed comparative studies conducted in the clinical rehabilitation setting, allowing us to test the robustness of training approaches, either alone or in combinations, in the "real world," that is in the presence of the variety of true moderating factors that influence learning and recovery. In both cases (experimental animal studies and comparative clinical studies), greater attention to best practices in specification and implementation of training components is warranted [77–81]. Such improvements are likely to lead to better clarity as to what training components and what sequence of these components is best for specific individuals according to their goals, the tasks they wish to learn, and their environments.

Conclusions

The state of the science raises many questions as to the best practices for promoting learning after traumatic brain injury. Synthesis of concepts across studies suggests that both implicit learning and explicit learning may play an important role in rehabilitation, but that the sequence and the timing of approaches that emphasize learning require additional study. Studies examining optimal implementation of implicit and explicit learning training approaches should address how the characteristics of the client, task, environment, and overall goal (i.e., acquisition, retention, transfer). Much of the science has focused on defining and operationalizing concepts, and testing concepts in tightly controlled conditions. This work is valuable, and provides insights into the mechanisms that influence learning. However, the development of more complex experimental animal training paradigms that more closely resemble clinical rehabilitation paradigms may bring additional insights. Furthermore, elevation of the science to the testing of these concepts in the clinical rehabilitation setting may add additional insights. This could be done by employing best practices for operationalizing and comparing training components, examining the timing and

sequence of training components, and looking for differences in treatment response (i.e., acquisition, retention, and transfer) based on participant abilities, goals, and environments using comparative effectiveness study methods.

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