Consolidation of Implicit Knowledge

by

Leonid Litman

A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, the City University of New York.

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THE CITY UNIVERSITY OF NEW YORK

Abstract

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Consolidation is a fundamental process of memory formation that has traditionally been studied in two ways: retroactive interference (RI) and distributed learning (DL). Currently, however, there is seemingly no coherent theoretical framework within which to understand RI and DL data that have been collected over the last one hundred years. In this paper the argument is made that in order to make sense of the RI and the DL effects, memory cannot be treated as a single unified process. Rather, at least four types of memory systems must be examined separately: declarative implicit, declarative explicit, cognitive procedural, and motor procedural. In the first part of this paper each of these systems is explored, and the RI and DL effects for each of them is reviewed. It is argued that RI disrupts explicit declarative memories but not implicit declarative memories. Further, evidence for a RI time gradient has only been found for procedural memory. These findings are discussed within the framework of a strategic retrieval view of RI effects.

In the second part of the paper the differences in consolidation among cognitive procedural knowledge and motor procedural skill are examined empirically. The DL and the RI effects for both cognitive procedural and motor procedural knowledge are examined using the sequential reaction time task (SRT). It is found that the consolidation of cognitive procedural knowledge and motoric procedural knowledge differ in a number of ways: a) the time course b) their resistance to interference and c) the rate of their improvement. The implications of these findings to the theory of consolidation are discussed from an evolutionary/computational perspective.

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This dissertation is dedicated to Arthur Reber

The road from personal curiosity to scholarly understanding can never be traveled alone. There are countless people over the last few decades who have helped me along the way. Some have been teachers, others have been friends and yet others have been strangers whose off the cuff comments in a random coffee shop might have made something click.

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Introduction

If a typical body organ such as the heart is functioning well it will predictably perform repetitive, mechanical tasks over and over again. The brain is an exception to this rule. Unlike almost any other body system the brain's ability to function effectively depends on its capacity to change with experience. Gradually the brain adapts to new and unpredictable life situations by the constant rewiring of existing cells and the growth of new ones; a process that probably happens after every new learning experience.

Many recent studies show that new experiences rewire the brain. For example, when a monkey is trained to press a button using two of its fingers for two weeks, activity in the part of the motor cortex that controls those fingers increases dramatically (Jenkins, Merzenich, Ochs, Allard, & Guic-Robles, 1990; Jenkins, Merzenich, & Recanzone, 1990). Likewise, changes in the organization of the cortex following learning have been observed in auditory (Weinberger, 1995a, 1995b) and visual (Karni et al., 1995) modalities. Changes in the structure and function of neurons also occur following many forms of learning such as habituation, classical conditioning and operant conditioning as well as tasks that are more cognitive in nature (Kandel, Schwartz, & Jessell, 2000). For example, in a series of experiments Maguire, Frackowiak, and Frith (1997) demonstrated that when taxi drivers learn the spacial outline of a city their hippocampal volume increases (Maguire et al., 2000; Maguire et al., 2003).

Interestingly, most of the biochemical and structural changes in the brain do not take place *during* learning. Rather, cortical reorganization continues its development after the actual process of learning has completed (Kandel et al., 2000). These types of experience-dependent long-term changes are part of a process known as consolidation.

While the notion of memory consolidation has been around for at least one hundred years, it was not until very recently that the neural underpinnings of this process have begun to be elucidated (McGaugh, 2000). At the same time it has been clear for a while now that there are a variety of different learning and memory systems. One possibility that has not been explored in the literature is that the neural processes of consolidation are different for the different memory systems. In this thesis this possibility will be explored. We will focus on a number of systems of learning and memory exploring the various paradigms that have been employed to investigate consolidation, and addressing the possibility that the time course and the nature of the consolidation process in at least some of these memory systems is not the same.

The experiments that are described in this paper focus specifically on the consolidation of procedural memory— a system containing knowledge of *how* to do something. However we wish to view these experiments within a larger framework in which the process of consolidation is central for the formation of all memory, not just procedural. To do that the consolidation of other memory systems will also be considered. The other major cognitive systems that will receive most attention here include the declarative system, the implicit system and the explicit system.

The declarative systems is composed of two parts: semantic and episodic. The semantic system contains factual information such as the ability to recall the name of the Russian capital, or the number of people living in the United States. Episodic memory contains representations of episodes of past experiences where people, places, objects and scenes are bound together in relational fashion

One assumption that is commonly made in the cognitive neurosciences is that all declarative knowledge is, by its very nature, explicit and all procedural knowledge is by its nature implicit (Squire, 2004). This assumption however is probably in need of elaboration since there are many cases where some aspects of procedural knowledge are acquired explicitly. Declarative knowledge is likewise not always explicit (Litman & Reber, 2005). We will come back to examine the best way to differentiate between the systems later on. For now keep in mind that at least three distinctions will be needed in order to make sense of the last 100 years of the consolidation literature: a) implicit vs. explicit b) declarative vs. procedural and c) cognitive procedural (associative relationships that are learned in the process of performing a procedural task) vs. motor procedural (motor skill acquisition). These systems will be explored with regard to the possibility that the consolidation process is not the same for them all. First we turn to the distinction between implicit and explicit processes.

Implicit Processes

Patterns are all around us. From infancy we are surrounded by people who speak, act and interact with the world, and with each other, in highly organized, and often predictable ways. Whether it is grammar, music or social interactions, our ability to function effectively as human beings depends, in large measure, on being able to learn about the orderliness that surrounds us in every day life.

Learning starts in infancy and continues all throughout our lives. As soon as we are born the initial chaos of the sights and sounds surrounding us begins to cohere and form a sensible, structured world. For example, infants as young as three months of age are surprised when they hear a sentence in their native language presented backwards (Dehaene-Lambertz, Ghislaine, & Houston, 1998; Mehler, Jusczyk, Lambertz, & Halsted, 1988), and four-day old infants can distinguish between their native language and a foreign language (Dominey & Ramus, 2000). The ability to differentiate between how different languages sound suggests that even by that young age speech is more than just a collection of random noise. Four-day-old infants have already learned that there are patterns to linguistic sounds. They have a sense of sequential regularity in speech and are surprised when that regularity is violated. The unfamiliar sounds of a foreign language are registered by their brains as being out of place.

What is most surprising is that infants can do this before being able to understand language and before knowing the rules of grammar. An entirely different knowledge system seems to be operating here; one in which knowledge is not developed through the conscious faculty of rule knowledge or through memorizing facts. This knowledge system extracts regularities in complex domains through a fluid interaction with the environment, and where the knowledge itself is hard to characterize, especially by an outside observer, other than through a thorough observation of behavior change over time.

As adults we learn about social norms and personalities of people in our lives in order to act effectively in a complex social environment. Further, we develop aesthetic preferences, learn languages, acquire interpersonal skills, learn complex procedural skills, and learn to rely on our intuitions in many situations. One question that has intrigued psychologists, and continues to puzzle computer scientists and neuroscientists alike, is how we manage to learn so much in such a short period of time. Although very little is known about the actual computational or neurological mechanisms of learning, some insights can be gleaned from thinking about systems of knowledge acquisition and, specifically, the different ways in which knowledge can be acquired. One theory that is increasingly becoming accepted in the cognitive neurosciences is that the brain contains a powerful learning system capable of extracting regularities from complex environments, and that this system operates largely in the absence of conscious awareness (Reber, 1993). This is known as the implicit system.

Recent research demonstrates that knowledge about complex domains such as language grammars (Dehaene-Lambertz et al., 1998; Dominey & Ramus, 2000; Gomez & Gerken, 1999; Gomez & Gerken, 2001; Mehler et al., 1988), socials norms (Haidt, 2001), and personality patterns (Klein, Cosmides, Tooby, & Chance, 2002) as well as the learning of other procedural and cognitive tasks (Reber, 1993) often forms in a bottom-up way, automatically, and largely independently of conscious control. Experimental work in the area of unconscious knowledge acquisition suggests that implicit knowledge forms independently of our intentions to learn or of the awareness that learning has taken place (Reber, 1967, 1993; Stadler & Frensch, 1998). This kind of process, whereby learning takes place in a largely unconscious manner is referred to as implicit learning (Reber, 1993).

Implicit learning describes a process of learning that is different from its opposite, the explicit learning process, in a number of ways. The explicit process is, for the most part, effortful and requires conscious awareness of what is being learned and memorized, while the implicit process is bottom-up and is a product of unconscious computations. Importantly, recent research has shown that the systems mediating implicit and explicit processes have different underlying neurological mechanisms (P. J. Reber, Gitelman, Parrish, & Mesulam, 2003; P. J. Reber, Knowlton, & Squire, 1996; P. J. Reber & Squire, 1994, 1998; Squire & Zola, 1996).

In addition to implicit learning, implicit memory is also a fundamental component of the unconscious system. Simply stated, whereas implicit learning is the process of unconscious *knowledge acquisition*, implicit memory usually refers to knowledge that is *stored* following acquisition, provided that that knowledge is not accessible for conscious inspection. Together, implicit learning and implicit memory make up what is referred to as the implicit system. Understanding the dissociations between the implicit and the explicit systems both psychologically, behaviorally, and neurologically provides many insights into the efficiency of learning and memory and of the complexity of cognition as a whole.

The Implicit/Procedural Explicit/Declarative Distinction

While it is commonly thought, especially in the taxonomy described by Squire (2004), that procedural and implicit always go together, many examples in the literature suggest that the actual picture is more complex than that (see Brauner and Becker, 2001). Experiments demonstrate that procedural knowledge can be acquired both implicitly and explicitly. One example that clearly demonstrated the difference between an implicit and an explicit mode of knowledge acquisition in procedural tasks comes from studies of procedural learning in which a method known as the sequential reaction time task (SRT) is used. The complexity of making easy demarcations between memory systems quickly becomes apparent.

In this task subjects view a computer monitor on which several small boxes are arranged along the bottom of the screen. A light or symbol flashes in one of the boxes and the subject is asked to press the button or key that corresponds spatially with that location as quickly as possible. On each trial a different box lights up and each time the participants must react to it as quickly and accurately as possible.

Two versions of the SRT procedure have been used to investigate learning, one implicit and the other explicit. In the implicit version of the experiment (Nissen & Bullemer, 1987) the sequence of lights follows a repeating pattern but the participant is not told about this. Rather, the participant goes about the task without any intention to learn it. The classic finding is that subjects' reaction times (RT's) get faster over trial blocks as they learn to exploit the structure in the sequence (see Hsiao & Reber, 1998 for a review).

To make sure that subjects are really learning the sequence and not merely learning a simple sensorimotor task, a random block of trials is introduced and any changes in the overall RT's to the new, non-structured series of lights is observed. The standard finding is that RT's slow down dramatically as soon as the sequence is removed and speed up again if it is later restored. Subjects are typically unaware of the existence of the structured sequence let alone having access to reportable knowledge about its structure.

How do we know that the subjects are not consciously learning the sequence? A lack of explicit knowledge can be demonstrated when they are tested again at some point after learning. Subjects perform the standard SRT procedure, except that at certain points they are asked to predict the location of the next stimulus. The vast majority of participants are unable to do this despite having clearly learned the pattern (Litman, Fischman, Waxman, & Reber, in preparation). Interestingly, those subjects who show some level of explicit knowledge about the sequence do not perform better than those who have no explicit knowledge at all.

In the explicit version of this procedure (Walker, in press; Walker, Brakefield, Hobson, & Stickgold, 2003; Walker, Brakefield, Seidman et al., 2003; Walker, 2002) a similar procedure to the one above is used, except that the subjects are told exactly what the sequence is. Subjects can view the sequence order at all times during the experiment, and participants are asked to look at the pattern and to tap out that pattern as many times as they can in thirty seconds. On each consecutive thirty second trial subjects become faster at doing this, presumably by becoming better at the procedural component of the task and by explicitly committing the pattern to memory. In this explicit version of the SRT task the explicit system is more involved than the implicit system.

Procedural tasks can be learned both implicitly and explicitly. The simple idea, then, that procedural skill is always implicit needs to be modified. As we argue below each procedural task can be divided into its cognitive and motor components. While the motor component is always implicit, the cognitive component can be either implicit or explicit, depending on the nature of the task, the extent to which various brain structures, such as the hippocampus and the frontal lobes are functioning, age, the amount of attention that is being allocated to the task, as well as other variables that can affect the ability to develop explicit awareness of complex stimulus environments.

Implicit learning can also be studied in domains other than procedural. Other areas where implicit cognition has been investigated include the learning of artificial grammars (Knowlton & Squire, 1994, 1996; Reber, 1967, 1989), category learning

(Knowlton & Squire, 1993; Squire & Knowlton, 1996), Pavlovian conditioning (Daum & Ackerman, 1994), decision making in social settings (Lewicki, 1986a; Uleman & Bargh, 1989), the hidden covariation task (Lewicki, 1986b), preference formation (Gordon, 1983; Manza, Zizak & Reber, 1998), the production control task (Berry & Broadbent, 1988), and dot pattern classification (P.J. Reber, Stark & Squire, 1998).

Learning, therefore, can be procedural or declarative, and it can take place both implicitly and explicitly. Procedural/explicit and declarative/implicit combinations are possible and, furthermore, every procedural task is probably composed of a combination of both implicit and explicit factors. Declarative knowledge is also composed of a combination of both implicit and explicit factors as has been shown in a number of studies, most notably with amnesic patients (see Litman & Reber, 2005). To complicate things even more, it is not clear how best to characterize the explicit component of a procedural task such as that of Walker's version of the SRT. Is it best to call the ability to verbalize a sequence of on-screen locations as explicit procedural knowledge or should we say that it is declarative knowledge that is acquired during a procedural task?

The problem with calling this type of knowledge declarative is that subjects similarly learn sequential information in the implicit version of the task, and they do so without conscious awareness. Clearly then, one and the same thing, at least in this case, can be known both implicitly and explicitly. Rather then distinguishing between implicit and explicit forms of knowledge based on the type of information in question (i.e. facts and events vs. procedural skill), we prefer to distinguish between them based directly on the way in which knowledge is represented. If the information is being represented in consciousness it is explicit, otherwise it is implicit. Attempts at reducing implicit knowledge to something simpler such as procedural skill, or simple associations will probably not capture their scope and complexity, and such an approach will have a hard time making sense of a large database of findings that paint a different picture (see Litman & Reber, 2005).

The approach adopted below keeps the four terms— implicit, explicit, procedural and declarative—separate, and discusses each in its own right while keeping in mind that the terms overlap often, and interact with each other in complex ways. Consolidation in each of these four types of knowledge systems must be examined separately.

More on Implicit and Explicit Systems

In the last few decades the convergence of a number of different paradigms has led to the acceptance, for the most part, of the view that there are multiple learning and memory systems—one that handles implicit knowledge and one that handles explicit knowledge— and that the distinction between these systems is not just behavioral but also neurological (for reviews see Kandel et al., 2000; Squire & Knowlton, 1995). At least two major lines of research have led to this conclusion: work with amnesiacs, and experiments with normally functioning participants that have employed implicit measures of memory such as priming. The existence of distinct memory systems first came to light when it was discovered that a bilateral excision of the hippocampus and associated areas selectively destroys the ability to form new long term explicit memories, while leaving implicit memory largely intact (Scollville & Milner, 1957; Milner, 1968; Ogden and Corkin, 1991).

For example Warrington & Weiskrantz, (1974) demonstrated that amnesiacs are capable of remembering new semantic information but that the critical factor determining successful retrieval is the manner in which the amnesiacs were tested. In their experiments the performance of normal participants was much better than that of amnesiacs on yes/no recognition tests, while the performance of the two groups was indistinguishable in the cued-recall test—an associative memory test not requiring explicit recollection of previously learned material. As Warrington and Weiskrantz put it

“Amnesiac patients can demonstrate good verbal retention but the method of testing it is of critical importance”. Because amnesiac patients in this experiment were as good as normals on tests of implicit memory while performing poorly on tests of explicit memory, this experiment suggests that implicit memory and explicit memory are handled by separate learning and memory systems.

A second line of research leading to the acceptance of a dual-systems view was initiated by psychologists working with populations of normal i.e. non-brain damaged participants. Interestingly, memory dissociations were found in normals that are similar to those observed in amnesiacs. In these experiments previously presented words which could not be recalled or recognized by participants could nevertheless affect their behavior on a variety of priming experiments that are similar to those employed by Warrington and Wieskrantz (Schacter, 1987).

Implicit techniques, therefore, not only demonstrate the existence of intact long-term memory in amnesiacs but also tap into the unconscious system of normals. Why are the primed responses often unconscious in normals and intact in amnesics? The answers to this question came slowly, but eventually the culmination of the work with both normals and amnesiacs led to the development of a dual-process theory of learning and memory (Reber, 1993; Squire and Zola-Morgan, 1996; Kandel et al., 2000). [See Zaki & Nosofski, (2003) and Zaki & Nosofski, (2001) for an alternative theoretical position.]

This theory proposes the existence of two learning and memory systems –one explicit and the other implicit. The implicit system is instantiated within a neural network that is evolutionarily older, and hence shows less variation in its performance, which explains the resistance of implicit knowledge to neurological trauma. Since the emergence of the dual-process view onto the psychological landscape one important line of investigation within cognitive psychology and the neurosciences has been to understand the ways in which the explicit and the implicit systems might differ from each other functionally, anatomically, and behaviorally. It is the investigation of these dissociations between the implicit and explicit systems, specifically with regard to differences in consolidation, that we turn to next.

Investigating the Dissociations of Implicit and Explicit Systems

An attempt to discover functional dissociations between the implicit and the explicit systems has always been a popular line of research in cognitive psychology. Classic issues abound: Do implicit memories tend to last as long as explicit memories? Is there a similar retention curve for the two memory systems (Brooks & Baddeley, 1976; McAndrews, Glisky, & Schacter, 1987; Schacter & Graf, 1986)? Does explicit memory change over the lifespan when compared to explicit memory (for example Dennis, Howard & Howard, 2003)? Do standard techniques that enhance explicit memory, such as depth of processing, have a similar effect on implicit memory (Challis & Brodbeck, 1992; Hamman & Squire, 1996; Thapar & Greene, 1994)?

Investigations of these and many other differences between implicit and explicit functioning have created a cottage industry in the study of memory and learning. This is because numerous dissociations have been found between the implicit and the explicit systems, most of which point to the idea that implicit knowledge is more robust and less prone to damage than explicit knowledge. However the question of consolidation and the related problem of the impact of interference remain virtually unexplored. Is implicit knowledge as prone to interference as explicit knowledge, and what are the implications of this for consolidation theory? Furthermore, the question of the declarative vs. procedural memory with regard to consolidation is also largely unexplored.

Consolidation

A Brief History

The idea that a memory trace continues to strengthen after the initial learning episode is over has been consolidating in the minds of psychologists for over a century. Consolidation, while a relatively modern concept, has its roots in the work that Georg Müller carried out at the end of the 19th century. Müller's research focused on a question that is perhaps as fundamental to psychology as any other— what causes forgetting? While the work of Hermann Ebbinghaus (1884) initiated a few decades earlier, focused on descriptive characterizations of forgetting, it provided very little insight into the question of why forgetting actually occurs. Ebbinghaus described memory as something that decays over time, suggesting that time somehow causes memory traces to weaken. Müller, however, did not treat time as a variable that necessarily plays a causal role in forgetting. Within Müller's framework time is something that is correlated with forgetting much in the same way as time is correlated with the way that iron rusts. Iron will rust with the passage of time, however time does not cause iron to rust— oxidation does. Without oxygen iron could never rust no matter how much time went by. In a similar way the idea that memory decays, while useful for descriptive purposes, provides little insight into the question of why forgetting actually occurs (Erdelyi, 1996).

In 1900 Müller and Pilzecker proposed one possible explanation as to why some memories are forgotten while others are not. According to their approach neural representations of each memory trace continue to form after they are first created. An important point about their view is that the process of ongoing memory formation is biological in nature and reflects underlying reverberating neural activity that continues to take place after the initial learning is over (McGaugh, 2000). Müller and Pilzecker referred to this process as 'perseveration'. Immediately after learning, and before this biological process has a chance to complete, a memory trace exists in a fragile state and is particularly prone to interference. Perseveration causes a memory trace to consolidate and become more resistant to interference.

One of the reasons that forgetting occurs is that the persevaration process is interfered with, whether by brain trauma or by learning new information, which leads to the disruption of any unconsolidated memory trace. Time is only a factor here to the extent that with time there is a greater likelihood of producing interference for the memory trace that did not get a chance to completely form. In Müller's view forgetting is the product of a disruption in the normal course of neural activity.

A hundred years went by before the neural mechanisms that are involved in consolidation were described. Much like Müller predicted, psychologists found that after the initial learning episode, neural changes continue to take place. In addition some, perhaps surprising, insights were made about the process of consolidation, one of which was that it is not a single, unified phenomenon. Rather, at least three forms of memory consolidation have been described that are relevant for the formation of everyday memory.

Neuronal Consolidation Involves at Least Three Distinct and Possibly Sequential Stages

Neural processes during the formation of short-term memory.

One type of especially short-lived consolidation process involves alterations in the chemical signals at the synapse. For example, after brief exposures to a non-threatening stimulus Aplysia californica habituates to the stimulus and stops retracting its gill (Kandel et al., 2000). This change in behavior is the direct result of a decreased release of the neurotransmitter glutamate. The modification in the release of this neurotransmitter is transient, resulting in behavioral changes that only last for a few minutes at most. Neural activity that is involved in the modification of chemical release at the synapses (Kandel et al., 2000) is least important for our purposes.

Long-term potentiation.

Some new experiences can lead to long-term changes in the structure and function of cells that can last hours to days (Kandel et al., 2000). For example, Weinberger (1999) found that classical conditioning of a 9 kHz tone leads to the tuning of individual neurons in the auditory cortex. Cell recordings from single neurons showed that before conditioning, a particular neuron would fire maximally to a 10 kHz tone, while after conditioning the functioning of that neuron changed so that it now maximally responded to a 9 kHz tone, and these changes were long lasting.

Long-term changes in neural structure and function take place as a result of a cascade of chemical processes in the neuron. The stimulation of neurons provides a signal to the DNA that tells it to start creating specific kinds of proteins. The function of these proteins is to maintain and regulate what happens in the cell chemically and structurally. The new proteins serve to actually change the structure and function of the neuron as, for example, in the creation of new terminal buttons. The structural and chemical changes that take place during this process are responsible for the ability of neurons to respond more efficiently to stimuli that have been presented in the past and for “tuning” the cells to respond in new ways to previously presented stimuli, as in Weinberger’s study.

This long-lasting form of consolidation has been demonstrated to play an important role in the formation of memory during a variety of learning procedures such as habituation (Castellucci, Carew, & Kandel, 1978), sensitization, and classical and operant conditioning (Kandel et al., 1983; Kandel et al., 2000). Long-term potentiation has also been shown to be important for learning in virtually all modalities such as visual, auditory, and motor (Hess, Aizenman, & Donoghue, 1996; Rioult-Pedotti, Friedman, & Donoghue, 2000; Rioult-Pedotti, Friedman, Hess, & Donoghue, 1998) as well as in more complex forms of learning such as fear conditioning and social learning (Ferguson, Aldag, Insel, & Young, 2001; Ferguson et al., 2000; Ferguson, Young, & Insel, 2002). Indeed, evidence is beginning to show that this is a fundamental process of learning.

Concrete evidence that neuronal consolidation is taking place when procedural/implicit tasks are learned is accumulating. A number of paradigms have now been developed with which the biochemical processes of consolidation can be studied more directly than ever before. Two of these techniques are known as repeated transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS). The techniques have been hypothesized to enhance consolidation by accentuating some of the processes that are necessary for it to occur, such as the depolarization of post-synaptic neurons. When rTMS is applied to the motor cortex it changes the excitability of the neurons and these changes can be observed for several hours. Nitsche et al. (2003) showed that implicit learning of an SRT task was enhanced by the application of rTMS to the primary motor cortex of humans during learning. RTs of participants in this task were faster and the learning was better relative to a control group that was trained on a random pattern. Importantly, the stimulation of other brain areas did not result in similar improvements.

Similar evidence was obtained for implicit tasks that are more cognitive and less motoric in nature by Kincses, Antal, Nitsche, Bartfai, and Paulus (2004). They showed that direct electrical stimulation of the prefrontal cortex enhances the ability to learn a probabilistic classification task. In their study participants learned to predict the weather in a probabilistic classification task, while receiving (tDCS). After being exposed to combinations of geometric figures, each of which has a certain probability of predicting either good or bad weather conditions, subjects receiving tDCS performed significantly better than controls.

In a further examination of the effects of tDCS, Leibtanz et al. (2002) administered a selective NDMA blocker dexteromethorphan (DMO) to participants during tDCS of the primary motor cortex of human participants—a procedure that stops a key aspect of the consolidation process. They found that the administration of DMO reduced the long-term evoked motor potentials that are associated with direct cranial stimulation. This suggests that the effects found by Kincses et al. (2004) and by Nitsche et al. (2003), in which the ability to learn implicit tasks was enhanced by rTMS, might have been due to the fact that rTMS enhances the consolidation process. This is likely because blocking NMDA receptors eliminates the enhancing effect of rTMS

Additional support for the idea that post-learning consolidation takes place after people learn an implicit task comes from fMRI research looking at the possibility that consolidation takes place during sleep. Peigneux et al. (2003) showed that the same brain regions that are activated during the learning of the SRT task are also activated when the participants are sleeping. This is not the case however when the sequence of button presses is random. In the random version of the SRT task the brain areas are no longer active during sleep, suggesting that during sleep complex information that is learned implicitly throughout the day is processed and "made sense of". Importantly, this finding suggests that learning in the SRT task is not only unconscious during the acquisition period, but also that unconscious processes continue to take place after the initial learning episode is over while participants are not consciously thinking about this information.

The experiments described above provide the most direct evidence for the idea that a biological consolidation process is involved in the formation of procedural/implicit memory. It seems that by manipulating this process by electrical stimulation and possibly through the use of pharmacological agents the process of consolidation can be enhanced. While the specific mechanisms of rTMS and tDCS are not known, the fact that NMDA blockers disrupt the enhancing effects that these procedures have on the performance of implicit tasks provides some compelling evidence that after the learning episode is complete neural processes continue to strengthen and consolidate the initially acquired memory in implicit learning tasks.

Systems-level consolidation.

So far we have been describing a process of consolidation that takes place within individual neurons and their synapses, and whose time course lasts hours to days. There is also another process of consolidation, one that lasts much longer. In fact some have suggested that this process of consolidation never really ends. This consolidation process takes place on the level of brain systems, and is referred to as systems-level consolidation (see Eichenbaum and Cohen, 2001 for a review). Importantly, unlike neuronal consolidation that is involved in the consolidation of procedural and implicit memory, systems-level consolidation is involved in the consolidation of declarative and explicit memory.

The cortical representation of information during this process undergoes a slow transformation between the hippocampus and the neocortex (McClelland, McNaughton, & O'Reilly, 1995). By far, the most compelling evidence for systems-level consolidation comes from investigations of amnesia. It has been known at least since the late 1800s that traumatic brain injury often results in retrograde amnesia for events that have preceded the trauma (Ribot, 1882) [in Eichenbaum & Cohen, (2001)]. One theory as to why this happens is that brain trauma interferes with the consolidation processes that are necessary for the memory to form.

An examination of amnesic patients such as HM shows that in addition to anterograde amnesia that follows the removal of the hippocampus there is also substantial memory loss for events prior to the operation. Estimates as to the extent of retrograde amnesia in HM range from two years (Scollville & Milner 1957) to eleven years (Sagar, Cohen, Corkin, & Growdon, 1985). In these investigations HM was found to have no memory for the end of World War II or his high school graduation, but had no problem recalling events prior to 1942, which was eleven years prior to the operation. It appears that bilateral hippocampal lesions erase relatively recent declarative memories while sparing ones that have taken place long ago.

Recent memories are more prone to damage because they exist in a less consolidated state. The mere passage of time seems to make a memory less likely to be erased following brain damage. One explanation for this effect is that as the memory consolidates its representation gradually translocated from the hippocampus to the neocortex. Therefore, as time goes by, the earlier memories become resistant to the removal of the hippocampus (McClelland et al., 1995).

Prospective animal research using rats and monkeys has also shown that the removal of the hippocampus disrupts recently acquired memories, and additionally, that a longer time interval between learning and the hippocampal lesion leads to better retention (Zola-Morgan & Squire, 1990). Similar results have been obtained in human and animal studies using electro-convulsive shock (Vakil, 2000; Squire, 1974; Squire, 1983; Duncan, 1948).

An Interim Summary

The studies mentioned above paint an interesting picture of memory formation. Unlike the picture that is suggested by Ebbinghaus's forgetting curve, which suggests that after the initial learning episode is over memory begins to decay, memory formation turns out to be an ongoing process—one that continues long after the initial learning episode is over. The consolidation of memory has two stages –one relatively short-term stage during which procedural and implicit memories consolidate, and a relatively long term processes during which explicit memories are transferred from the hippocampus to the cortex. The changes in brain structure that comprise the consolidation process are critical for memory formation, and when these processes are disrupted, such as by brain trauma, electroconvulsive shock, hippocampal damage, or the administration of pharmacological agents, memory fails to form.

Behavioral Manifestations of Consolidation

Neuroscientists' investigations of the biological mechanisms of consolidation have been informative for our understanding of memory and progress in this area of inquiry continues to be made. But psychologists have always had a problem answering a seemingly simple question: Is there any behavioral evidence for consolidation? This question has been quite elusive and cognitive psychologists who studied memory in normal subjects without brain damage, and without using physiological techniques have concluded on more than one occasion that there is no evidence for consolidation at all.

Historically there have been two experimental paradigms that in theory could provide support for the theory of consolidation. The first is called distributed learning and the second is called the retroactive interference paradigm.

Distributed Learning

The distribution of learning (DL) effect was originally described by Jost in 1897. Distributed learning studies show that practicing a task with long breaks between sessions results in better performance than when the same task is performed with short breaks between sessions. In other words, performance improves between, not just within practice sessions. The original studies carried out by Jost demonstrated that given equivalent amounts of practice, greater retention is seen when a long time interval is inserted between practice trials. For example in one study Jost had subjects learn nonsense syllables for twenty-four trials. Some subjects learned 2 trials a day for 12 days, others learned 4 trials for 6 days, 8 trials for 3 days or all 24 trials on the same day. While in all cases subjects practiced 24 times, Jost's results showed that longer time periods between practice sessions resulted in greater memory improvement.

Interestingly, he measured learning 24 hours after the completion of the last training session in all groups, thereby eliminating the possibility that the results are due to fatigue—a possible confound in all distributed learning experiments and an issue we briefly return to later. Similar findings with the distributed learning effect were obtained in numerous other early studies (see McGeoch & Irion, 1952 for a review). In fact, this finding is so unequivocal that McGeoch and Irion concluded that "so widespread is this phenomenon that it may be stated as a general empirical conclusion for the practical control of learning."

The Retroactive Interference Procedure

In retroactive interference (RI) experiments, after subjects learn something, it can be anything, a second task is introduced at some point after learning. In many situations the second task can be shown to interfere with one's memory for the first. Over one hundred years ago Müller and Pilzecker demonstrated that there is a time gradient in RI effects; as time passes memory develops resistance to interference. This was interpreted by Müller and Pilzecker as evidence of consolidation.

Retroactive interference research like the distributed learning paradigm, is a classic area of psychological inquiry and is probably as old as any other memory phenomenon that has been experimentally investigated (see Münsterberg, 1894; Müller and Pilzecker,1900). A time gradient of RI effects shows that immediately after something is learned the memory trace is weak but that it gets stronger as time goes by. Consolidation of the memory trace should make a memory more resistant to the detrimental effects of interfering tasks.

The first studies that investigated retroactive inhibition date back to Münsterberg and his student Bigham (1894; 1895) who looked at interference effects of such diverse stimuli as colors, geometrical forms, lists of words and lists of nonsense syllables (in Britt 1936). However it wasn't until Müller and Pilzecker (1900) conducted their now classic studies that a new chapter of memory research began. This era, which lasted until around 1970, came to be known as the "classical interference era" (Anderson & Neely, 1996), and generated a wealth of knowledge about the phenomenon of retroactive interference.

In Müller and Pilzecker's typical experiment subjects memorized lists of nonsense syllables (Task A) and after a period of time would be introduced to a second list of nonsense syllables (Task B). The goal was to examine the way in which Task B influenced the retention of Task A. In one study they compared memory after the interpolation of two time intervals: 17 seconds and 6 minutes. Müller and Pilzecker found that the longer time period results in less interference. This result led them to two conclusions: a) the interpolation of a secondary task interferes with the neuronal mechanisms involved in the formation of a memory for Task A and b) as time goes on interpolation of Task B will become less likely to interfere with Task A.

Over the last one hundred years retroactive interference and distributed learning effects provided two separate avenues of study into the investigation of consolidation effects in everyday learning. Several questions about these two paradigms however remains unexplored: Are between-session memory improvement and the development of resistance to interference both manifestations of the same underlying consolidation process? Is it possible that RI and DL effects tap into two separate aspects of the consolidation process? Do improvements in performance and the development of resistance to interference happen in parallel i.e. at the same time, or do they happen sequentially? Are these two processes part of the same underlying aspect of the consolidation process or are there separate and distinct stages to consolidation, as well as separate neurological mechanisms that underlie them? As of now these questions remain unexplored.

A further complication arises when the question of DL and RI is examined within the context of the possibility that consolidation is not the same for various types of memory systems. Is it possible, for example, that some memory systems only consolidate by improving over time, while others consolidate by developing resistance to interference over time? Below the following argument is presented: While evidence for the consolidation of declarative memory using the retroactive interference paradigm has always been woefully lacking, a RI gradient in procedural tasks has received considerable support in the last ten years. Further, because procedural memory is so strongly associated with the implicit system and declarative knowledge with the explicit system, the implication is that implicit knowledge and explicit knowledge do not consolidate in the same way. A further complication is that procedural memory is made of both cognitive and motoric components, and the cognitive components can be either implicit or explicit. Below, we make the case that careful distinctions must be made both between memory systems and between the various consolidation processes in order to understand the contribution of consolidation to the formation of memory in general.

Declarative Memory and Retroactive Interference

Virtually all review articles since the 1930s have concluded that memory does not develop resistance to interference with the passage of time (Wixted, 2005) which, perhaps, is why most psychologists have historically not taken the idea of consolidation seriously. Importantly, however, most of these studies investigated declarative memory. Secondary tasks (i.e. interference tasks) have been shown to disrupt memory at virtually all time intervals equally as much. For example, in one of the first studies of the RI gradient Robinson (1920) had subjects memorize numbers and then using consecutive intervals of five minutes looked at whether the interference had a graded effect depending on the time interval. He found no systematic relationship at all: “Under the conditions of this experiment, at least, the degree of retroactive inhibition is independent of the temporal position of retroactive interpolation.”

Bunch and McTeer (1932) found that retroactive interference can be produced as much as three weeks following learning. McGeoch (1933a, 1933b) also found no consistent relationship between the time interval and the extent of interference. He used

20 minutes, 1 hour, 24 hours, 48 hours and 144 hours. No systematic relationship was found for the time interval when judged by recall recognition or relearning. After conducting a series of a half a dozen studies McGeoch concluded “there is no uniform and consistent variation with time interval in percentage of retroactive inhibition.” (Britt, 1935; McGeoch & Irion, 1952)

Later reviewers (McGeoch & Irion, 1952) have also considered the interpolated time interval to be a non-relevant issue for understanding RI. In their review of all of the known factors that influence retroactive interference, the time interval is not mentioned—a telling factor that suggests that by the 1950’s researchers did not consider the time interval between Task A and Task B to be an important factor with regard to retroactive interference. In fact, since McGeoch and Irion’s review in 1952 things have not changed. There is no recent evidence that would indicate that there is any systematic relationship between the time of the interpolated task and the extent of retroactive inhibition for declarative knowledge.

Retroactive interference experiments testing declarative systems suggest that interfering tasks continue to disrupt performance much after the consolidation process would have theoretically been completed, and present perhaps the greatest challenge to the perseveration hypothesis—at the very least to the perseveration hypothesis of declarative memory. The lack of a relationship between the time of the interpolated task and retroactive inhibition suggests very strongly that consolidation alone cannot account for retroactive inhibition effects in declarative memory.

Additionally, for implicit measures of memory that are more sensitive than recall, such as savings, relearning and priming, retroactive interference effects are absent entirely. Relearning, for example, is not disrupted by secondary tasks in the same way as is recall. These findings were first observed by McGeoch, (1928). Later work (Johnson, 1933; Lester, 1932) supported McGeoch’s findings. A number of other studies (Melton, 1940; McGeoch, 1943; Thune & Underwood, 1943; Underwood,1945) also showed a clear dissociation between recall and relearning. Even in conditions of complete absence of recall after interference, List A is still relearned much faster when compared to a control group that has never seen the list before. In one study Underwood (1945) showed that even when the interpolated word list is overlearned to the extent that Task B was memorized 20 times, relearning effects still persist relative to a control group that had never seen List A before.

Studies that investigated retroactive interference with respect to relearning showed that in all important aspects of retroactive interference including similarity between the original and the interpolated lists and the extent of learning of interpolated lists, the original material is still relearned faster and easier when compared to a control group that did not learn the list to begin with. Based on these finding McGeoch's conclusion with regard to retroactive interference is very similar to Ebbinghaus's explanation of forgetting: "The common experience that although recall of a particular skill may be at or near zero point, a very small amount of practice is necessary to bring it back" (1884, p.427). The implication is that, although secondary tasks disrupt the ability to retrieve information, they do not actually erase the memory trace as the theory of consolidation predicts. Another way of explaining these results is that interfering tasks disrupt explicit declarative memory while implicit memory for declarative information is not affected.

Studies using less explicit measures of retrieval such as recognition have also failed to show the retroactive interference effect and, interestingly, many of these studies came from Müller's own laboratory. In a series of 33 studies Heine, Müller's student, (in Britt, 1935) was not able to find any effect of retroactive inhibition in any of the studies using recognition as a dependent measure as opposed to recall. The combined results of the 33 experiments conducted by Heine suggest that retroactive interference is a more complex process than was thought by Müller. Although subsequent work by some researchers (Gibson, 1934; McKinney, 1935; Zangwill, 1938) did show that retroactive interference disrupts performance in recognition tests, making it difficult to draw firm conclusions here, many recent studies continued to have difficulty finding this effect using recognition as a memory measure (Postman, Stark, & Henschel, 1969). These studies provide strong evidence that the extent to which retroactive interference disrupts memory depends in large measure on the manner in which participants are tested.

The picture that emerges from the more recent studies is mostly consistent with the earlier research. In general, very few recent studies have systematically investigated the effect of retroactive interference on declarative memory using measures other than recall and recognition, but those that did (Graf & Schacter, 1987) found no interference effects when implicit measures were used to asses memory. [However, see (Lustig & Hasher, 2001a, 2001b) who have found retroactive effects in priming tasks when Task A and Task B were highly perceptually similar to each other].

We will therefore consider one piece of the puzzle solved. When investigating memory consolidation a distinction must be made between explicit declarative memory and implicit memory for declarative information. Explicit declarative memory does not develop resistance to interference over time. Interference always effects declarative memory negatively, and it does so independently of the time interval that elapses after learning.

Implicit memory for those items however remains intact after virtually any kind of interference—no matter how intense or how shortly it is administered following learning. Implicit memory for facts and events is mostly immune to interference.

Müller and Pilzecker would probably not have predicted this. Their theory says that RI disrupts the “reverberating neural activity” that continues after learning. The last one hundred years of retroactive interference research, however, shows that it is only explicit memory that is disrupted. The strong implication here is that, at least for declarative memory, RI does not disrupt the neural activity that is involved in laying down the memory. Rather RI disrupts the ability to retrieve information explicitly. We will come back to explore this possibility further.

Procedural Memory and Retroactive Interference

While the evidence for a RI gradient in declarative tasks is mostly lacking, a very different picture emerges when RI is studied using procedural tasks. With regard to procedural learning the effects of interfering tasks have been studied with some attention to the question of the time course of RI. In one experiment (Brashers-Krug, & Bizzi, 1996) subjects were trained to move a lever in a complex pattern of movements. The lever was attached to and controlled by a robot that can be programmed with a variety of force vectors that push and/or pull the lever in particular directions. The subject's Task A is to learn to counteract the mechanical forces of the device and learn to make the required movements smoothly and efficiently. The interpolated, interfering Task B appears identical to the initial task, only the robot arm is reprogrammed so that the original counteractive movements are no longer effective and new ones must be learned.

With this task Brashers-Krug, et al. (1996) found clear RI effects. If the second task was carried out immediately after the first, it virtually wiped out any representation of the original learning. Subjects in this condition showed essentially no savings when retested on the first task 24 hours later. However, the insertion of a time interval between Tasks A and B dramatically improved performance on Task A 24 hours later. Subjects given a short rest period before Task B show a small but reliable savings effect. As the time between the two tasks was lengthened to 4 hours and 24 hours, performance on Task A became increasingly better. The suggestion is that immediately after learning, the implicit memorial representation of the learned domain exists in a rather fragile state and is relatively easy to disrupt. However, as time passes the memory becomes stronger, more robust, and less prone to interference.

In another series of experiments (Walker, 2003) demonstrated a similar retroactive interference effect in an explicit version of the SRT task. Walker, et al. had subjects perform a second sequence after the first and manipulated the time between them. Their findings were very similar to that of Brashers-Krug et al. in that a longer time interval between Task A and B resulted in better Task A performance 24 hours later.

Taken together, the findings of Walker et al. (2003) and Brashers-Krug et al. (1996) are largely consistent with the theoretical arguments made by Müller and Pilzecker's idea that memory becomes resistant to interference over time. The extent of interference in procedural tasks, whether the procedural task is implicit, as in the task used by Walker et al., (2003), or explicit, as in the task used by Brashers-Krug et al., (1996), appears to be time dependent. A longer time interval between learning and the interpolation of the secondary task seems to make the memory more resistant to interference. But implicit memory in experiments examining declarative information does not develop resistance to interference over time.

An Interim Summary

So what is the effect of RI on performance? The answer to this question seems to depend on the type of memory in question. Retroactive interference disrupts explicit representations of declarative memory but the extent to which the performance is disrupted does not follow a time gradient. Explicit representations of procedural memory, however, do seem to develop resistance to interference over time. Further, implicit representations of declarative knowledge do not seem to be affected by interference tasks at all. However, implicit representations of procedural knowledge are affected by interference and do follow a time gradient. The picture that seems to be emerging here is that to understand the effect of RI on performance, and in turn to understand how consolidation unfolds over time, implicit and explicit declarative memory need to be examined separately from procedural memory.

The Distribution of Learning Effect

Nearly a century after Jost performed his classic distribution of learning experiments and following literally hundreds of experimental studies Dempster (1988) described the distributed learning effect as “one of the most remarkable phenomena in experimental psychology”. He provided a number of reasons for this claim:

> First, the spacing effect is one of the most dependable and replicable phenomena in experimental psychology. Second, it is remarkably robust. In many cases, two spaced presentations are about twice as effective as two massed presentations (e.g., Hintzman, 1974; Melton, 1970), and the difference between them increases as the frequency of repetition increases (Underwood, 1970). Moreover, demonstrations of achievement following massed presentations often are slightly higher than that following a single presentation (e.g., Melton 1970). Third, the spacing effect is truly ubiquitous in scope. It has been observed in virtually every standard experimental learning paradigm, with all sorts of traditional research material.

Distributed learning, is indeed a powerful effect and one that provides strong support for consolidation theory. At the heart of the theory of consolidation lies the idea that a memory becomes strengthened during the time interval that follows learning. The spacing effect is therefore a direct consequence of the consolidation process. A second practice session has a greater effect on performance following a time interval then when it immediately follows the first practice session since during the passage of time the memory reorganizes and improves. Indeed, the notion of consolidation is greatly supported by the dependability, reliability, and robustness of the distribution of learning effect.

However, the ubiquity of the effect is not as clear-cut as Dempster concluded. Specifically, while the strongest distributed learning effects have been reported in tasks that have a large procedural component, distributed learning effects for tasks with a heavy declarative component have been less widespread. Underwood, (1961), a pioneer in the area of distributed learning, described the difference in the extent of distributed learning between declarative and procedural tasks as follows:

> When distributed practice (DP) is introduced in the acquisition of a motor task, such as pursuit rotor, enormous facilitative effects on performance are observed. There is no comparison to be made between the magnitude of such effects and those which occur as a consequence of DP in verbal learning. Facilitation by DP in verbal learning occurs only under a highly specific set of conditions, and the magnitude of the effect when it does occur is relatively small.

The distributed learning effect and, as we have seen before, the retroactive interference effect are both found more in procedural paradigms that in declarative learning tasks. This provides another piece of the puzzle. Procedural knowledge seems to consolidate in two respects. It becomes immune to interference with the passage of time and it improves over time. Declarative memory, on the other hand, does not develop resistance to interference and the distributed learning effect for declarative memory, while there, is relatively small.

Procedural Tasks

By carefully paying attention to memory systems in the consolidation literature, we can paint a relatively consistent picture with regard how consolidation works. However, one fundamental complication still needs addressing with regard to procedural memory. It is the issue of the complex composition of procedural tasks. It turns out that any procedural task can be further subdivided into at least two components: A motor component which is purely motoric and cognitive component where patterns within the task are learned.

For example, during the SRT task a person acquires both a motoric skill and also cognitive knowledge of the sequence. Motoric aspects of the task are seen when the targets are presented randomly; subjects still get faster over trial blocks (Nissen & Bullemer, 1987) although the targets do not follow any particular pattern.

In the presence of a sequence subjects speed up even more. This is the result of having acquired sequence knowledge. Overall improvement in the SRT task is the result of both the acquisition of a general motor skill and sequence-specific knowledge. In virtually all experiments that look at the consolidation of procedural knowledge that have been reviewed so far, it isn't clear what exactly is improving over time. For example, in the procedure used by Walker et al. (2003) it isn't clear whether the ability to follow the sequence-specific series of button presses is consolidating, or whether the overall motor ability is getting better.

While it is possible that performance is improving specifically because subjects are consolidating the information about the sequence, something that is assumed in all SRT studies, it is also possible that what is in fact consolidating is a general motor ability. Do the motor and the cognitive aspects of procedural knowledge consolidate in the same way or not? This is the missing piece of the puzzle that we attempt to fill in in this study. Are the cognitive aspects of procedural knowledge more like declarative knowledge which does not seem to develop resistance to interference over time and does not greatly benefit from the passage of time? Or will cognitive knowledge that is acquired during a procedural task follow a time gradient that has been demonstrated for procedural tasks? Further, we will address the question of the relationship between the development of resistance to interference and performance improvement over time. Do they happen at the same time or does one occur after the other?

Also, does it matter whether the cognitive knowledge that is acquired during the performance of procedural tasks is implicit or explicit? The studies that were conducted by Walker et al. and Brashers-Krug et al. seem to show that it does not. In their studies both implicit and explicit procedural tasks consolidate over time. Goedert and Willingham (2002) however found a different effect. Their study substantially complicates the picture and is the basis of the first experiment in this thesis.

Retroactive Interference for Implicit and Explicit Procedural Knowledge

The idea that there is no RI gradient for declarative memory but there is one for both implicit and explicit procedural memory, is complicated by another finding—and here is where the issue of procedural/implicit and procedural/explicit distinction becomes even more important. Goedert and Willingham (2002) failed to find evidence for consolidation of procedural learning (i.e. of a RI time gradient) in an SRT task that was implicit in nature. In their study, subjects were trained on an SRT sequence and then, either 5-minutes, 1-hour, 5-hours or 24-hours later, learned a second (interfering) sequence. Later, 48-hours after the first session, subject's performance on the first sequence was tested.

The second sequence always interfered with performance. Every group was effected by interference by the same amount, whether the interference was presented immediately after the first session or after a time interval— a result commonly found in declarative memory experiments. No RI time gradient was found to suggest that resistance to interference is built up as time passes in the implicit version of the SRT task.

Goedert and Willingham's, and Walker et al.'s findings conflict with each other if we make the assumption that all procedural tasks are the same, regardless of whether they are implicit or explicit. If we take note however of the important fact that in Walker's task the subjects had explicit knowledge of the sequence while in Goedert et al's. task sequence knowledge was implicit, the difficulty is partially resolved. We need only to postulate that while explicit procedural knowledge follows a RI gradient implicit procedural knowledge does not.

Brashers-Krug et al.'s findings still provide support for a RI gradient in implicit procedural tasks under this postulate. However their task is sufficiently different from Goedert and Willingham's, and Walker et al.'s to be considered separately. More on this later.

Additional evidence along the lines that a distinction must be made between implicit and explicit procedural learning with regard to the distribution of learning effect was reported by Robertson (2004). Their study showed a differential involvement of sleep in the consolidation of procedural knowledge using the SRT procedure. While an explicit version of the SRT task required sleep in order for improvement of performance to take place, the procedural knowledge gained in the implicit version of the SRT task did not require sleep.

Robertson's, and Goedert & Willingham's study provide support that for both the spacing effect and the RI gradient explicit memory requires a more thorough consolidation process. These results would seem in theory to agree with what is known about the neuroscience of consolidation, specifically that the hippocampus is a major player in the consolidation process, as is known from amnesic patients. The assumption here is that the explicit cognitive knowledge acquired in the course of procedural tasks is handled by the hippocampus and consolidates differently than implicit cognitive knowledge and motor skill.

According to this position, implicit and explicit procedural tasks do not consolidate in the same way. Explicit procedural tasks slowly acquire resistance to interference over time while implicit procedural tasks do not. Alternatively, it is possible that consolidation did not occur in Goedert and Willingham's study for other reasons.

Prior to concluding concluding that implicit and explicit procedural knowledge does not consolidate in the same way the task and the procedure that was used in their study need to be examined more fully. It is with Goedert and Willingham's task, therefore, that we begin our study. The aim of the first experiment will be to try to understand why they failed to find a RI gradient in the implicit version of the SRT task.

Experiment 1

A number of problems in Goedert and Willingham's study need to be considered before concluding that a distinction needs to be made between the nature of the consolidation process for explicit and implicit procedural knowledge. First, the number of training blocks in the first session was very high, leaving open the possibility of ceiling effects. As Goedert and Willingham's themselves state "It may be that subjects in our sequence-learning experiment had overlearned the SRT task, and therefore, we failed to see a pattern of temporally graded retroactive interference consistent with a long-term consolidation account". A second possible confound in the study is that many structureless, semi-random blocks were used during the first session, and this might have reduced the efficacy of the first training session. These issues require more consideration.

In Goedert and Willingham's study, nine blocks of trials were used in the first learning session. Of those blocks the first was semi- random, as is often done by some researchers in order to familiarize subjects with the task at hand. The sixth and the seventh blocks were also semi-random and so was the ninth. These random blocks were used to assess learning. Four out of nine blocks, almost half of the entire learning procedure, were semi- random. These semi-random blocks might have acted as interference blocks, thereby disrupting subsequent consolidation even before the intended interfering tasks were ever presented. In turn, a lack of a time-depended consolidation gradient might have resulted from the random blocks acting as interference during the first session. The studies conducted by Robertson et al. (2004) share the same confound. The interpretation of Goedert and Willingham's experiment therefore needs to be reconsidered in order to determine whether overlearning or the presence of interfering material could have been responsible for the inability to find a RI gradient in the SRT task.

There are two possibilities regarding the nature of the consolidation process in procedural skills that are implicitly acquired. One possibility, suggested by Brashers-Krug et al. (1999) and Walker et al. (2001, 2003) is that implicitly acquired procedural knowledge follows the same time course as explicitly acquired procedural knowledge. The other possibility, suggested by the results of Goedert and Willingham, and Robertson is that implicit and explicit procedural knowledge does not undergo the same consolidation process as does explicit procedural knowledge. In the experiments described below we attempt to shed some light on this question.

The first experiment is an attempt to replicate Goedert et al.'s results. The SRT task was used to examine both the retroactive interference and the distribution of learning effects with the aim of investigating both aspects of the consolidation process. There were six experimental groups in this experiment. Two of the six groups were employed to examine the distribution of learning effect. The learning sessions for these groups ware separated by one of two time intervals: 5 minutes or 24 hours (see Figure 1). As in the classic distribution of learning experiments we expected that best performance should result when a longer time interval is interposed between the learning sessions because a longer time interval allows the memory to consolidate

In the other four of the six groups the question of whether the mere passage of time makes memory more immune to interference was examined. The same SRT task was used and, once again, the learning trials were distributed over two sessions. In adition to the learning trials, an interference task was interposed between the two learning sessions at three intervals: 5 minutes, 5 hours and 24 hours (see Figure 2). According to consolidation theory a longer time interval between the first session and the interference condition should result in improved performance on the second session.

Method

Participants

One hundred and four Brooklyn College undergraduates participated in this study. Each of the participants signed up for the experiment as part of an introduction to psychology course requirement. All participants were given experimental credit upon completing all sessions of the experiment.

Target Display

The target display consisted of six lines arranged in a row along the center of a computer screen. A target in the form of a plus sign appeared on top of one of the lines and stayed there until the appropriate response was made. All responses were made using the RB-640 Cedrus response box. Six buttons on the response pad were arranged in a row, each corresponding to a location on the screen. Participants were told to place three fingers from each hand on the buttons and to keep them there at all times. When a target appeared in its designated location the subjects' task was to press the corresponding button as quickly as possible without making mistakes.

The Target Sequence

The targets were generated by a sequence consisting of a twelve-step repeated pattern: 263415613254. (Each digit here corresponds to one of the six possible locations on which a target may appear on the screen). A number of aspects about the sequence are important. Each location in the sequence appears exactly twice per cycle. During each of the two presentations the position of the preceding targets is never identical. For example a target appears in Location 6 twice—the first time being preceded by a target in Location 2 and the second time proceeded by a target in Location 5. Each on-screen position therefore can, in principle, be preceded by one of two possible locations.

Having a target preceded by two different locations ensures that simple stimulus/response associative processes cannot account for improvements in performance on this task. To predict which location comes next, in addition to seeing the current locations of a target, one needs to also know where the previous target was. This introduces a short-term memory component into the learning procedure and guarantees that subjects are learning at least the second-order conditional elements of the display. Additional aspects of the pattern are that a target may not appear in the same location twice in a row and that there are no instances of a single alternation (i.e., no clusters such as 232 or 626).

The Learning Sessions

Each block consisted of 120 trials made from 10 repetitions of the twelve-step sequence described above. Each of the two sessions consisted of six blocks. The targets in the first four blocks (1-4) and the last block (6) followed the repeating pattern. The fifth block was semi-random, and its purpose was to test learning. This block was always comprised of a semi-random sequence of on-screen locations. It is the critical testing block where the nature of the sequence to which the participants have been exposed changes. In this block the on-screen locations do not follow the repeating sequence. Instead, the locations are generated in a semi-random fashion, with the only restriction being that the target cannot appear in one location twice in a row. The details of how learning is tested in the SRT task are described further below.

Measuring Learning: Sequence Knowledge

Block 5 is key for measuring both motor learning and sequence knowledge. The critical comparison by which sequence knowledge is measured involves looking at the extent to which RTs on Block 5 (the semi-random block) are slower than those on Blocks 4 and 6. Higher RTs on the fifth block indicate that subjects learned the sequence and that their performance is slowing down because the targets in this block do not contain predictive information. It is expected that on Block 5 RTs will slow down proportionally to the extent to which sequence knowledge is facilitating performance. If the subjects have not learned the sequence at all, taking the sequence away will not affect reaction time. Conversely, when subjects become slower upon the removal of the sequence it is an indication that sequence knowledge was facilitating their performance. Examining the reaction time increase from Block 4 to Block 5 and the reaction time decrease from Block 5 to Block 6 (see Figure 5) provides a measure of sequence knowledge.

Measuring Learning: Motor Skill

As Nissen and Bullemer showed in the original SRT study, subjects become faster on the SRT task even when the targets are presented randomly. We refer to the skill that is acquired in a random SRT task as motor skill. Motor skill reflects the acquisition of coordinated motor ability that is gained as subjects become better at pressing buttons. Motor skill improvement will be measured in this study by taking the difference between the RTs of Block 1 and those of Block 5-the semi-random block (see Figure 5). If motor skill is improving over the course of the SRT task, faster RTs should be observed on the fifth block than on the first block, reflecting the acquisition of coordinated motor ability that is independent of sequence knowledge (see Figure 5).

Measuring Overall Learning

Overall learning is the total RT improvement over the whole experiment. Overall learning is a combination of both motor skill and sequence knowledge. It is measured by subtracting reaction times of Block 6 on the second session from those of Block 1 on the first session.

Design and Procedure

Six groups of subjects were run using two different procedures. Two of the groups were employed to examine the distribution of learning effect. In this procedure the time interval between two SRT sessions was varied but no interference task was interpolated between them. These groups are referred to as the No-Interference Groups (NI). The other four groups will be referred to as the Interference Groups (I). These groups had an interfering task interposed between two SRT sessions. The purpose of the I groups was to examine the retroactive interference gradient.

The No-Interference Groups

The NI groups were run through two SRT sessions, each of which consisted of six blocks. Within each session, the first four blocks consisted of a repeating sequence, the fifth block was semi-random and in the sixth block the repeating sequence was restored. The second session followed the first after one of two time intervals: 5-minutes or 24-hours.

The independent variable for the NI groups was the time interval between Session 1 and Session 2. The temporal relationships between the groups are laid out in Figure 1.

The critical question being asked here is whether the 24-hour NI group will perform better than the 5-minute NI group. A consolidation view of memory formation predicts this result.

The Interference Groups

Like the NI groups, the I groups were all run through six blocks of the SRT procedure during both learning sessions. In addition to the learning session, an interfering task was introduced either 5- minutes, 5- hours or 24- hours following the first session, with the aim of examining the effect of the interfering task on the information that was learned during Session 1. The timing parameters of the I groups are presented in Figure 2. All I groups had a 24-hour delay between the two SRT sessions, and an additional group (described further, below) had a 29-hour delay. The independent variable for the I groups is the time between the first learning session and the interference task.

The Interference Task

The interference task consisted of three 120-trial blocks of semi-random targets. Each of the interference blocks was generated using the same principles as Block 5 of the regular SRT task. The purpose of introducing the interference task after Session 1is to disrupt the memorial representation of what was learned in the 1st session. Consolidation theory predicts that a longer time interval between the first learning session and the interfering condition will result in better performance during the second session on the argument that interference tasks will disrupt consolidation processes if introduced shortly after learning.

The 29-Hour Group

Each I group performed the second session exactly 24 hours after Session 1 with the exception of the 29-hour group—the proactive interference control. One possible problem with interpreting the data from the 24-hour interference group is the effect of proactive interference (PI) on performance during the second session which occurs immediately following the interfering task. To control for possible effects of PI an additional group was used. The difference between the 24-hour group and the 29-Hour group is in the time interval between the first session and the interfering task. While in the 24-hour I condition the second session immediately follows the interference condition, the 29-hour group waits 5 hours between them. The prediction is that participants in this group will perform maximally, since information that was learned during the first session has had twenty-four hours to consolidate and, in addition, unlike in the 24-hour interference condition, the expression of learning during Session 2 is not being compromised by PI.

Measuring Consolidation

To measure consolidation of sequence knowledge and motor skill, performance during the first session will be compared to that in the second session. It is predicted by consolidation theory that learning will be greater in the second session than in the first, and that the difference between the first and the second session will increase as a function of both the time interval between session one and two (for the NI groups), and as a function of the time interval between the first session and the interfering task (for the I groups). However, given the results of Goedert and Willingham we do not expect to find these effects for sequence knowledge. Motor skill consolidation, on the other hand, was not tested in their study and we predicted that motor learning effects will get better from the first to the second session.

Consolidation can also be measured by examining the way in which performance changes from one block to the next. In the standard SRT task performance improves as subjects continue to practice the task. The improvements are mostly linear in that RTs become faster from one block to the next. The phenomenon of distributed learning, however, predicts that the nature of improvements should not be monotonic. Rather the greatest improvements should occur between the blocks that are separated by a break. Importantly, there is no way to tease apart whether RTs improve from one block to the next due to increased sequence knowledge or due to increased motor skill. Rather, block-to-block RT changes reflect the improvement that are due to both motor skill acquisition and improvements in sequence knowledge.

It is expected that a time interval between practice sessions will affect SRT performance in two ways. First, a longer time interval will improve performance of the NI groups. This is predicted by distributed learning theory. An examination of the distributed learning effect will be the basis of the first part of Experiment 1. For the I groups, a longer time interval between the first session and the interfering task should make the knowledge that is gained in the first session less prone to interference effects. The retroactive interference effect will be analyzed in the second part of Experiment 1. It is not clear, however, whether DL and RI affects will be the same for sequence knowledge and motor skill. It is possible that the initial time interval is more beneficial for sequence knowledge than it is for motor skill.

It is also expected that the interfering task will not affect sequence knowledge in the same way as it will affect motor skill. It is expected that motor skill will be less affected by the interpolation of an interfering task than will sequence knowledge.

Results

Data Collection and Analysis

The data.

Superlab software collects reaction time with one millisecond precision. Reaction times for each button press in the experiment were recorded. Erroneous responses were not included in reaction time analysis. Analyses of error rates were carried out separately and include all erroneous responses.

Means of medians analysis.

Each of the six blocks within each session consists of 10 repetitions of the 12-step pattern. In the course of one block 120 data points are collected from each subject. These data were analyzed using the means of medians technique outlined by Rah and Reber, (1999). For this analysis medians are taken of the 12 responses for each of the ten repetitions of the pattern. Ten medians are therefore obtained per each block for each participant. A mean of these medians within each block was used as a measure of performance for that block. Six means were generated using this technique per each subject in each of the two sessions. These means were then analyzed using SPSS software.

Motor Skill and Sequence Knowledge: A Collapsed Analysis of All Groups

Sequence knowledge.

For the following analysis sequence knowledge of all six groups was collapsed together. Since the dependent variables of motor skill and sequence knowledge are the same in all six groups, the four Interference groups and the two No-Interference groups were combined together and their sequence knowledge was averaged.

The average RTs on Block 5 were subtracted from the average of the RTs on Blocks 4 and 5. This was done both for the first and the second session. The purpose of looking at the collapsed performance of all six groups together is to check whether the standard SRT sequence knowledge effect was found in both the first and the second session. It is typically found that the transfer block, in our case Block 5, is slower than the blocks that immediately precede it and the block that immediately follows it. This outcome was expected for both Session 1 and Session 2. The overall pattern of results is presented in Figure 6 for reaction time and Figure 7 for error rates. Significant sequence learning took place both as measured by reaction time in the first $t(103)= 15.4$, $p < .05$, and the second $t(103)= 13.2$, $p < .05$ sessions as expected.

Motor skill.

Motor learning was examined in the same manner as sequence knowledge. All six groups were combined. Motor learning, as measured by RT differences between the first and the fifth blocks, did not take place within the first or the second session (see Graph 7). RTs on Block 5 of Session 1 were slower than RTs of Block 1 of Session 1. The same was true for the second session. Reaction times of Block 5 were slower than those of Block 1.

Motor learning did take place across both sessions however. Comparing Block 5 of Session 2 to the first block of the first session showed that motor learning did take place over the course of both sessions $t(103) = 8.2$, $p < .05$.

Subjects acquire sequence knowledge over the first four blocks of Session 1. Motor skill, however, takes longer to acquire and, importantly, improvements in motor performance take place during the break between sessions rather than within each session while the task is being performed. It is possible that a time interval that follows learning is particularly important for motor skill acquisition. The differences in the way that sequence knowledge and motor skill are affected by the time interval between the learning sessions will be examined in more detail below.

Block-to-block performance improvements.

In the next analysis block-to-block improvements are examined for all groups collapsed together. The RTs of each subject in the study were averaged on each block and the RTs of each block were subtracted from the preceding block. This provides a measure of the extent to which RTs get faster from one block to the next. The data are shown in Figure 8. One striking effect that immediately jumps out of Figure 8 is the dramatic improvement in RTs following a break, especially when that improvement is compared to the RT changes that take place within-sessions. Indeed further analyses show that RT changes between the two sessions (i.e. from the last block of the first session to the first block of the second session) are much greater than any other within-block changes. For this analysis RTs from Block 2 were subtracted from RTs of the first block, Block 3 RTs were subtracted from Block 2 and Block 4 was subtracted from Block 3. This was done in both Session 1 and Session 2, making a total of seven difference scores.

The greatest improvements took place during a break between sessions. A one way ANOVA looking at the difference scores confirmed this result. The ANOVA showed that there are significant differences between the block-to-block RT changes $F(6, 103) = 88$, $p < .001$. Contrast analysis comparing the RT changes between the blocks showed that RT changes between the two sessions (i.e. the last block of Session 1 and the first Block of Session 2) were significantly greater then he block-to-block changes within sessions (all p. values < .001).

As predicted by the distribution of learning effect, a time interval between Session 1 and Session 2 had a beneficial effect on performance. Distribution of learning effect also predicts that a longer time interval should have a greater effect on performance than a shorter time interval. To examine this prediction the between-session RT improvements were examined further. Specifically we examined whether the RT improvements will be higher in the groups with a longer time interval between the two SRT sessions, and between the first SRT session and the interfering task. We hypothesized that the 24 hour NI group will improve more from the last block of the first session to the first block of the second session than the 5-minute NI group. It was also expected that the 29-Hour NI group should improve more than the 5-Hour NI group and that the 5-Hour NI group should improve more than the 5-Minute NI group.

In the following analysis the between-session improvements of the six groups were compared. As expected, a one-way ANOVA showed that the between-session improvements were not the same for all groups F(5, 98) = 5.2, p< .05, as can be seen in Figure 9. The between-session improvement was greatest for the 29-hour group, as predicted by consolidation theory. A series of planned comparisons showed that the improvements in this groups was greater than all other groups except the 5-hour I group (p. < .05).

Furthermore, the performance of the interference groups (excluding the 24-hour group) followed a linear trend F (1, 51) = 9.5, p < .05. This shows that performance improves as the interval between the first session and the interfering task becomes larger.

The 24-hour group was excluded from the linear trend analysis because the proactive interference effect of having just completed the interference task makes this group not strictly comparable with the others.

The time interval between the first session and the interference condition also had an effect on overall learning for the I groups. Overall learning, as described earlier, is measured by subtracting the RTs on the last block of the second session from the first block of the first session. A one-way between-groups ANOVA showed that the time interval that follows the first session affects overall SRT performance F (5, 103) = 4.5, p. < .05 (See figure 10). Here, however, while the 5-minute I group is significantly different from the 5-hour I group (p < .05), the difference between the 29-hour interference group did not reach significance (p > .05). While this result is partially mediated by a ceiling effect, as discussed below, it isn't clear why the 5-hour group was significantly better than the 29-hour group.

The *effect of Interference on Sequence Learning and Motor Skill*

The following analysis examined whether interference affected sequence knowledge in the same way as it affected motor skill. The hallmark of interference research is that interpolating an interfering task between practice sessions has a disruptive affect on performance. But is motor skill disrupted in the same way as is sequence knowledge? To examine this question, the four I groups were compared to the two NI groups, making a total of two omnibus conditions—the interference condition consisting of all the participants in the four interference groups and the No-Interference condition consisting of all the participants of the two No-Interference groups. A MANOVA was run with interference being the dependent variable and sequence knowledge and motor skill being the dependent variables. The MANOVA showed that there are overall differences between the Interference and the No-Interference conditions F (2,101) = 340.5, p. < .001.

The MANOVA further showed that the interference group's motor performance improved significantly more over the course of the study compared to the No-Interference groups F(1,102) = 22.8, p < .01. For sequence knowledge, however, there were no differences between the NI and the I groups F(1, 102) = 1.25, p > .05. (see Figure 11). The three interference blocks did not have a detrimental effect on sequence knowledge, but contributed greatly toward motor performance. The later result is not surprising since during the interference task the subjects have an additional opportunity to learn to coordinate their finger movements and for this reason motor skill improves during the performance of an interference task.

The situation with regard to sequence knowledge is more complex. We expected to find that sequence knowledge for the I groups would be worse than for the NI group. A failure to find this effect suggests two possibilities. The first is that sequence knowledge is not affected by interfering tasks. The second and more likely possibility is that the first and second training sessions were too long, producing a ceiling effect similar to the one in Goedert and Willingham's study. If so, the long training sessions ended up equalizing the performance of all groups. This result led directly to the second experiment where the length of the training sessions were shortened. As will be seen Experiment 2, the length of the blocks in the SRT task is indeed an important variable to consider when studying consolidation.

Sequence Learning: Reaction Time

The following analyses examined how sequence knowledge is affected by both the time interval that was interposed between the two learning sessions and the time interval interposed between Session 1 and the interference task. In this first series of analyses, sequence knowledge during Session 2 was examined. Consolidation theory makes two predictions about the outcome of these analyses. The first is that the 24-hour NI group will perform better than the 5-Minute NI group. The second prediction is that the 29-Hour I group will perform better than the other I groups.

As mentioned above, sequence knowledge was measured by taking the average of the 4th and the 6th blocks and subtracting it from Block 5 in the second session. First we examined whether each of the six groups had demonstrable levels of sequence knowledge on this measure. For each group sequence knowledge was compared the test value of zero. All six groups showed learning on this measure (all t-test values < .001). However, a one-way between-subjects ANOVA showed that there were no differences among the six groups, F (5, 243) = 3.8, p > .05 (see Figure 12). This result was contrary to our hypothesis. We interpret this result in light of the analysis presented above (see Figure 11) which showed that there were no differences in sequence knowledge between the I and the NI groups. It is likely that both of these outcomes are due to a ceiling effect.

In next analysis sequence knowledge in the second session was compared to sequence knowledge in the first session. Although no differences between groups were found in the second session, as described above, perhaps sequence knowledge improved at different rates for the six groups. Consolidation theory predicts that the 24-hour NI group will improve more from the first to the second session and also that among the I groups largest improvements will be observed in the 29 hour I group. A 2 X 6 (session X group) mixed-design ANOVA was run to determine whether sequence knowledge of the six groups improved at a different rate from the first to the second session. While there was a main effect for session F (1, 98) = 12.6 p. < .01, the session X group interaction failed to reach significance F (5, 98) = 1.7. p. > .05 (see Figure 13). The graph does show however that there is a trend in the predicted direction.

The change in error rates however did not improve from the first to the second session at all. The same 2 X 6 ANOVA as above was run for error rates and did not show any main effects or an interaction F(1, 98) = 3.0, p. > 05. As before, we failed to find the expected effect of consolidation in this analysis, both in RTs and in error rates. These analysis further confirm that, assuming that consolidation does take place for the knowledge attained in an SRT task, the design of this study is not optimal for finding these effects. Again, we suggest that ceiling effects are the main problem of this design.

Motor Skill: Reaction Time Measures

As described above, no motor learning took place within either the first F(5,103) = 1, p < .05 or the second session F (5, 103) = .7, p. > .05. Overall motor learning, as measured by subtracting the RTs on the fifth block of the second session from the RTs on the first block of the first session, did take place however F (5, 103) = 6.7, p. < .001. When motor learning was examined for each of the six groups individually it was found that motor learning is not the same for all groups. Planned comparison tests showed that the 29-hour I group improved less than the other Interference groups [p. < .05 (one-tailed)]. This result is predicted by consolidation theory. However, the 29- Hour I group, the, 24-Hour NI group and the 5-Hour I groups were not statistically different from each other. Also, the 24-Hour NI group was not different from the 5-Hour NI group, (see Figure 14). A similar picture emerges for motor learning in these analysis as for sequence knowledge in that the performance of the 5-Minute I group is worse than all other Interference conditions, and the NI groups are not different from each other.

Two predictions were made by consolidation theory with regard to the expected performance improvements of both motor skill and sequence knowledge. For the No-Interference groups it was expected that the group with a longer interval between sessions (i.e. the 24-Hour NI group) will perform better than the group with a short time interval between sessions (i.e. the 5-Minute NI group). With regard to the Interference groups consolidation theory predicts that, when proactive interference is controlled for, groups with a longer time interval between the first session and the interference task (i.e. the 29-Hour I group) should perform better than the other groups with the shorter time intervals. While results for motor skill were partially corroborated in that the 5-Minute I group's performance was worse than the other Interference groups as expected, the results for the other Interference groups and for the No-Interference condition did not follow the predicted trend.

Discussion

The results of the first experiment are both encouraging and at the same time raise some concerns regarding the methodology of this study. A consolidation effect is clearly seen in that the greatest decrease in reaction times takes place between Session 1 and Session 2. While subjects become faster in the first blocks of both sessions their RTs do not seem to improve that much during the latter blocks, suggesting an upper limit to how much can be learned in one session. It is specifically during a break between sessions that performance improves the most. After practice ends memory continues to improve further as predicted by consolidation theory.

Groups that have a longer break between the first session and the interfering task perform better. The between-session improvement of the 29-hour I group is superior to that of the 5-minute I group. The implication of these results is that an interfering task disrupts performance immediately after practice, but not if a sufficient time interval was interposed.

While there are clear indications that consolidation is taking place in this study, the lack of sequence knowledge differences between the I and the NI groups (see Figures 9 and 11) is a major concern. In all groups, sequence knowledge seems to max out at around 80 ms., strongly suggesting a ceiling effect. If the maximal performance on the sequence knowledge task is in the neighborhood of 80 ms. then there would be no way to detect the effect of interference. The effect would not be detectable because enough trials during the second session will bring sequence knowledge back. If so, the problem in both Goedert and Willingham’s and this study is that there were too many practice blocks in both the first and the second sessions.

A second problem might have to do with the first session itself, specifically with the semi-random Block 5 that is used for testing sequence knowledge. Because this semi-random block is exactly the same as the interfering task (except shorter), it itself might be initiating a disruption of the consolidation process from the very beginning. Perhaps memory consolidation in the NI groups does not take place in this experiment because the interfering material is presented in the first session for all groups during Block 5. As mentioned above, Goedert and Willingham's study employed four semi-random blocks during the initial learning session. While this problem is less likely in our study than in Goedert and Willingham's study because in our experiment there was only one semi-random block, in our experiment too this is a viable possibility.

To deal with both of these potential confounds the procedure of the second experiment was changed in three ways. First, the length of both sessions was decreased. Instead of four training blocks the learning phase was reduced to two blocks each. Second, the number of sequence repetitions within each block was reduced from ten to seven. The third change of the procedure, was to get rid of the semi-random Block 5. The participants were tested only once—at the end of the second session. In so doing the hope was to eliminate the possible influence of the fifth semi-random block on subsequent consolidation.

Experiment 2

Method

The target display, the target sequence, the semi-random blocks, the interfering task, and the methods of measuring learning were all identical to those used in the first experiment.

Participants

Two hundred and eighty seven Brooklyn College undergraduates participated in this study. Each of the participants signed-up for the experiment as part of an introduction to psychology course requirement. All participants were given experimental credit upon completing all sessions of the experiment.

The Learning Sessions

Each block consisted of 84 trials made up from 7 repetitions of the twelve-step sequence. While in Experiment 1 there were twelve learning blocks all together—six in Session 1 and six in Session 2, in this experiment the number of blocks over both sessions was reduced to six. During Session 1 subjects were run through two training blocks where all targets followed a sequence. Sequence knowledge was not tested at the end of Session 1 in order to not introduce interfering material. The other four blocks were run during Session 2. The targets in the first two of these four blocks followed a repeating sequence, the fourth block was semi-random and during the final block the sequence was once-again restored as in the previous experiment.

Design and Procedure

As in Experiment 1, Interference groups were used to study retroactive interference and the No-Interference groups were used to study distributed learning. A number of additional groups were added to both of these procedures and these changes are outlined below.

In the first experiment two No-Interference groups were studied—a group with a five-minute interval between sessions and a group with a 24-hour break between sessions. To these two NI groups two additional groups were added in Experiment 2. The first group is a control group that only participated in one learning session. This group was run through two training blocks and was immediately tested for sequence knowledge with a semi-random block. The fourth block for this group was the last, during which the sequence was again restored. The purpose of the control group is to measure sequence knowledge and motor skill at the end of the first session. Since in this experiment, unlike the first, performance is not measured at the end of the first session for all groups, the control group is needed to measure the learning that takes place in just one session. With this group, the amount of knowledge that was gained in the second session alone can be calculated in a between-groups manner by comparing the performance of the various groups to the control group.

The second group that was added for the NI condition is a 5-Hour NI group. This group will have a 5-hour break between the first and the second session. The purpose of adding this group is to examine the time course of consolidation more closely.

One group was also added to the Interference conditions. In Experiment 1 four Interference groups were used. In the 5-minute, 5-hour, and 24-Hour I conditions the time interval between the first and the second session was always 24 hours, what was varied was the time interval between the first session and the interference task. The problem of proactive interference was controlled for by the 29-Hour group. In the 29-Hour group a 24 hour period was interposed between the first learning session and the interfering task and, unlike in the 24-Hour I condition, an additional five hours was interposed between the interfering task and the second learning session. The purpose of this 5-hour interval is to minimize the proactive interference effect.

In Experiment 2 an additional 3-Day I group was added. The rationale behind this group was to control for the possibility that five hours is not enough to prevent proactive interference. In this group a 24-Hour break was interposed between the first learning session and the interfering task. Another 24 hours was then interposed between the interference task and the second learning session. This condition was also used by Goedert and Willingham (2002).

The combined design of this study has nine groups. Among the No-Interference conditions were included four groups: a control group, the 5-Minute NI group, the 5-Hour-NI group and the 24 –Hour NI group (see Figure 3). The interference groups included five conditions: the 5-Minute I group, the 5-Hour I group, the 24-Hour I group, the 29-Hour I group and the 3-Day I group (see Figure 4).

The No-Interference Groups

The NI groups, not including the control group, were run through the full six blocks of the SRT task. The six blocks were divided into two separate sessions. The first session consisted of two learning blocks. The second session consisted of two learning blocks followed by a semi-random block, which was again followed by a block of sequence targets (see Figure 3). The independent variable for the I groups is the time interval between the two sessions. The critical question being asked here is whether a longer time period between the two acquisition sessions will result in better learning.

The Interference Groups

Like the NI groups, the I groups will all be run through six blocks of the SRT procedure. Five minutes, 5 hours or 24 hours following the first session an interfering task will be introduced, with the aim of disrupting what was learned in Session 1. Also, the time interval between the interfering task and Session 2 will be varied to either 5 minutes, 5 hours or 24 hours. The timing parameters of the I groups are displayed in Figure 4.

Measuring Learning and Consolidation

Motor skill, sequence knowledge and overall learning are measured here in the same way as in the first experiment. Motor learning is measured by the RT changes between the first block and the fifth block. Sequence knowledge is measured by the extent to which RTs in Block 5 are slower than in the 4th and 6th blocks, and overall learning is evaluated by subtracting reaction times of Block 6 from those of Block 1.

As in the first experiment consolidation theory makes specific predictions about the performance of the Interference groups and the No-Interference groups on all measures.

- First, the control group is expected to perform worse than all other groups.
- The control group is expected to have relatively minor motor learning effects. In the first experiment most motor learning took place between, not within sessions. Since the control group is the only group that only has one session, motor learning effects are expected to be low.
- Among the No-Interference groups the 24-Hour group is expected to perform better than all other groups.

- Among the I groups the 5-Minute I groups should perform worse than all other I groups.
- The 29-Hour and the 3-Day groups should perform maximally since both the proactive and the retroactive interference effects in these groups are minimal. As in the NI groups, we do not have an a-priory hypothesis about the performance of the 5-hour group.
- It is predicted that the 5-Minute I group and the control group should not be very different from each other. Biggest differences are expected to be found between the 5-Minute I group and the 24-Hour NI group, the 29-Hour I group and the 3-Day I group.

Results/Discussion

The Effect of Interference on Sequence Learning and Motor Skill

In the first analysis the overall effect of interference on both motor skill and sequence knowledge was examined in the same manner as in Experiment 1. This is the critical analysis to determine whether the manipulation change in the second experiment made a difference. The motor skill and sequence knowledge of all three NI groups excluding the control group (i.e. the 5-minute NI group, the 5-hour NI group and the 24-hour NI group) were compared with the combined performance of the five groups that did have an interference session (i.e. the 5-minute I, 5-hour I, 24-hour I, the 29-hour, and the 3-day I groups). A MANOVA was run with interference being the independent variable and sequence knowledge and motor skill being the dependent variables. The MANOVA showed overall differences between the Interference and the No-Interference conditions F (2,214) = 416.5, p. < .001. In addition, for sequence knowledge the No-Interference groups performed better than the Interference groups F(1, 215) = 8.5, p < .01 while the opposite was found for motor learning where the I group's motor performance was better than the No-Interference groups F(1,215) = 8.1, p < .01 (see Figure 15) .

Both of these results were anticipated. Interference had a detrimental effect on sequence knowledge, the theoretically predicted effect that was expected according to consolidation theory was not found in Experiment 1. Performing the interference task under the conditions of Experiment 2 clearly reduced sequence knowledge performance suggesting that the earlier failures were indeed due to ceiling effects. The design changes that were made in this experiment had the desired effect.

As in Experiment 1 motor performance was affected positively by the interfering task, an unsurprising result since the interference task actually provides three additional blocks of motor practice. During the interference task the subjects' motor performance improves, but this happens at the expense of unlearning the sequence.

Block- to-Block Effects

As in experiment one, the rates at which performance improved from one block to the next were compared. For this analysis all the I and the NI groups were collapsed together. Each individual subject's RTs on each learning block (i.e. the first four blocks) were subtracted from the previous block. The RTs of the second block were subtracted from the first, the RT of Block 3 were subtracted from Block 2 and the RT of Bock 4 were subtracted from Bock 3 (see Figure 16). A within-groups ANOVA showed that there were differences in the rate of improvement between the blocks F (2, 486) = 78, (p, < .001). Contrast analysis further showed that, as in Experiment 1, the greatest improvement took place between rather than within sessions (all ps < .001). This result further supports consolidation theory for it shows that greatest memory improvements occur during a break between learning rather during the learning process itself.

To further look at the within session effects the nine groups of this experiment were compared to each other. A one way between subjects ANOVA showed that the between-session improvements were not the same for all groups F (7, 236) = 3.5 (p = .001). Contrast analyses showed that the greatest differences on this measure are found in the NI groups (see Figure 17). Specifically, the between-session improvements of the 24-hour NI group were significantly better than the 5-hour NI group (p. < .05), and the 5-minute NI group (p. < .05, one tailed). The 5-Minute group was not different from the 5-

Hour I group (p. > .05). This finding shows that distributing the learning sessions improves over a 24 hour period improves performance. However, in the above analysis cognitive knowledge and motor skill are looked at together. As we will see below, this is the reason that no block-to-block differences were found between the I groups. Below, we tease apart the cognitive and the motor component of this procedural task and examine the possible differences in the rates of consolidation between them. We begin by examining the consolidation of cognitive knowledge (i.e. sequence knowledge).

Sequence learning: Reaction time.

The questions of the following analysis are whether the time interval that was interposed between the two learning sessions, and whether the time interval that was interposed between Session 1 and the interference task, would differentially affect sequence knowledge. In the first series of analyses all nine groups were submitted to a one-way ANOVA with the aim of looking at whether sequence knowledge improves as a function of time interval and interference.

A one-way between-subjects ANOVA showed that there were differences among the nine groups, F (8, 243) = 3.8, p < .001 (See Figure 19). To further examine the results of the ANOVA a series of planned contrasts was carried out. For ease of presentation in the following analysis, the results of the NI groups analysis will be presented first, then the I conditions will be examined, followed by an overall look at all of the groups together. While the analysis of variance was run with all nine groups together, conceptually it is easier to present the planned comparison tests and the post-hoc analysis separately for the two sets of groups.

The No-Interference groups.

As expected, planned contrasts showed that sequence knowledge of the control group, in which subjects were only run through one learning session, was significantly lower than sequence knowledge of all three No-Interference groups, where subjects practiced two sessions separated by either a 5-minute, 5-hour, or 24-hour interval, p. < .05 (one-tailed). A second session, therefore, significantly improved sequence knowledge even when that second session was practiced a mere 5 minutes after the first. Importantly, performance of the 5-minute No-Interference group did not differ from that of the 5-hour No-Interference group (p. > .6). However, sequence knowledge of the 24-Hour NI group was significantly better than the 5-minute and the 5-Hour NI groups (p < .05). This finding suggests that improvements in cognitive knowledge do not begin to occur immediately after learning. Rather at least five hours need to pass before consolidation-based improvements will occur for sequence knowledge.

The Interference groups.

Among the five Interference groups, the 5-minute Interference group performed worse than the 29-hour Interference group (p. < .05), the 5-Hour I group and the 24-Hour I group and the 3-Day group (p. < .05, one tailed). There were no differences between the 5-Minute I group and the 24-Hour I group due most probably to proactive interference. The interfering task disrupts performance most when it is performed five minutes after learning.

All groups combined.

The one-session control group performed exactly the same as the 5-minute interference group (p. > .9). This is a particularly important finding. The skill acquired in the first SRT session by the 5-minute interference group was entirely wiped out by the interference session that followed 5 minutes later. Also, the 24-hour NI group outperformed all I groups, including the 29-hour I group and the 3-day group. This was unexpected. In our hypothesis we reasoned that if the interfering task is interposed after a sufficient time interval, for example 24 hours, it will no longer effect the knowledge that was attained in the first learning session. This was reported by Walker et al. (2003). However this was not the case in this study. The interfering task disrupted performance no matter when it was performed, but the greatest effect was seen for the 5-minute I group. In that group maximal disruptive effects were seen. A longer time interval seems to have shielded the memory from the large interference effects that are seen in the 5-minute condition, but memory did not become entirely resistant to interference. This finding is discussed in detail below.

Summary of Sequence Knowledge Consolidation

Looking at all groups one by one paints the following picture: One session of the SRT task is sufficient to produce reliable learning of approximately 30ms. (As measured by RT difference between Block 5 and the average of Blocks 4 and 6). An additional practice session of the same length increases this learning effect by roughly an additional 20ms. When the second practice session is performed five hours after the first the size of this sequence learning effect does not change. However, after a 24-hour delay between the sessions there is an additional gain of approximately 20ms, effectively doubling the learning size achieved in the first session and bringing overall sequence learning up to 70 ms.

A 24-hour break was therefore the most effective time delay to have between sessions for the development of sequence knowledge in our study. However, when an interfering task is interposed immediately after the first session, sequence learning performance drops to the level of the group that only learned one session! In this condition, performance is not only worse than in the 24-hour NI group, it is also worse that the 5-minute and the 5-hour NI conditions.

The fact that sequence knowledge of the 5-minute I group is essentially the same as the control group suggests that whatever was learned in the first session was wiped out by the interfering task. However, when the interfering task is not presented immediately after the first session but is presented five hours later performance now returns to the level of the 5-minute NI condition. A five hour break between the first session and the interference condition therefore serves to protect the knowledge that was gained in the first session from being erased. However, interference presented at this time or later still prevents memory from improving further, since the 5-Hour I, the 29-Hour I and the 3-Day group perform worse than the 24-NI group. The implication seems to be that interference in this setting acts to prevent consolidation-based improvements no matter when it is presented.

Sequence Learning: Errors Rates

All of the analyses that were performed using reaction times as a measure of learning were also performed using error rates. In the previous set of analyses sequence knowledge was measured by increases in reaction time during Block 5. Here learning is assessed by looking at changes in errors over the same blocks by taking the average number of errors on Blocks 4 and 6 and subtracting them from the errors made on Block 5.

All nine groups were combined together to examine whether sequence learning effects can be measured by using error rates. A within subjects t-test was used to compare the RTs on Block 5 with the average RTs of Blocks 4 and 6. The results were significant, t (253) = 10.2, p < .001 (see Figure 20). A one-way ANOVA was then used to examine whether there were groups differences in sequence knowledge. No group differences were found among the nine experimental conditions. SRT error rates in this experiment were much less sensitive than reaction times as a learning measure.

Motor skill: Reaction Time Measures

Motor skill was examined by taking the difference between the RTs on Block 5 and Block 1. As expected, a one sample t-test showed that the average motor skill performance of the control group was not significantly different from the test value of zero t (25) = .3 (p. > .05) (see Figure 21). All other groups did acquire motor skill in the course of the study. All one-sample t-tests were significant. This finding is intriguing given the results of the previous experiment where no significant motor learning occurred after four SRT blocks. Given that in Experiment 2, four SRT blocks were sufficient to acquire motor skill for the 5-Minute NI group, it seems that a break between sessions is an essential element without which motor learning does not take place. Some break, even a very short one, seems to be necessary for the formation of motor skill. The 5-Minute NI group had a 5 minute break in Experiment 2 during which some consolidation might have taken place, whereas in the first experiment subjects were not given this break, hence there was no motor learning in that condition.

This does not seem to be the case for sequence knowledge because the control group does acquire significant levels of sequence knowledge in this experiment. The implication of the results presented here is that the ability to acquire coordinated motor skill is more reliant on a period of inactivity than the acquisition of cognitive knowledge. The data also imply that there is an initial rapid stage of consolidation of motor skill that is essential for motor learning. These possibilities will be discussed in more detail below.

A one-way between-subjects ANOVA showed that there were motor skill differences among the nine groups F (8, 244) = 6.9 $p < .001$. Planned contrasts showed that the control group performed significantly worse than all other groups (p. < .05) and that the 5-minute NI group also performed worse than all other groups with the exception of the control group. No other significant motor skill differences were found between the nine groups.

A Summary of Motor Skill Consolidation

There seem to be two important time periods for the consolidation of motor skill. The first period is rapid and occurs immediately after learning. The second period takes place some time within the first five hours after learning. Following this period motor skill consolidation is complete and no further improvement occurs. Motor consolidation seems to be complete in the first five hours following practice, whereas sequence knowledge seems to need 24 hours. This interpretation will be further explained below.

Motor-Skill Error Rates

In addition to reaction time, motor skill was also examined comparing error rates on Block 1 and on Block 5. A within-subject t-test showed that on Block 5 subjects made more errors than on Block 1 $t(251) = -6.3$. $p < .001$.

The only groups whose error rates were not higher on the fifth block than on the first block were the 5-Hour and the 24-Hour NI groups. One tailed t-tests showed that the

5-hours group's performance t(27) = .6 (p > .5) and the 24 hour group's performance t(30) = 1.2 (p. > .2) were not significantly different from zero. These two groups seem to have benefited most in terms of motor performance as measured by error rates. The interference task seems to affect error rate performance no matter when it is performed. It is not clear why all Interference group made more errors on Block 5 than on Block 1. It is possible that the Interfering task, while increasing the overall speed of the responses might have affected the accuracy negatively.

Overall Learning-Reaction Times and Error Rates

Overall learning is assessed by subtracting the mean reaction times in Block 6 from those of Block 1. This measures how much faster subjects become over the course of the experiment. A within-subjects t-test showed that the overall performance of all groups was significantly faster on Block 6 than it was on Block 1 t (252) = 18.3, p. < .01. Further, a one-way between subjects ANOVA showed that the overall performance of the groups differed from each other F (8, 244) = 8, p. < .01 . (See Figure 22). Below, the groups are compared to each other, starting with the NI conditions.

No Interference groups: Overall learning.

As expected, the one-session control group learned significantly less than all of the other groups. The 5-minute NI group learned less than the 5-hour group (p. < .05) and the 24-hour NI group. The 5-hour and the 24-hour NI conditions did not differ from each other.

The interference groups.

As predicted, the 5-minute Interference group performed significantly worse than the 5- hour, the 29-hour, and the 3-day Interference groups (p. < .05), but not worse than the 24-hour interference group (p. > .2). It is likely that the performance of the 24-Hour I group was affected by proactive interference, as was expected. The 29-hour, the 5-hour and the 3-Day interference groups did not differ from each other, or from the 24-hour NI group (p. > .6). It is important to keep in mind here that overall learning is the combination of both motor skill and cognitive knowledge. While the results of this analysis are important in order to have a sense of the overall change in subjects' behavior over the course of the experiment, to understand the way in which consolidation unfolds over time the overall effects should be teased apart into their cognitive and motor components.

Overall learning: all groups combined.

After practicing one session of the SRT task overall RTs decrease by approximately 20ms. An additional session of practice five minutes later provides an additional 40ms boost in performance. However, when a 24-hour break is interposed between the first and the second session, performance improves by an additional 50ms—performance almost doubles. The same is true when a five-hour break is interposed between the sessions.

The Interference and the No-Interference groups are not, in the strictest terms, directly comparable to each other on the overall learning measure (and on the motor learning measure) because the I groups had three extra blocks of training to improve their motor performance, and hence they are expected to be faster. Since the overall learning measure is a combination of sequence knowledge and motor skill it might be expected that the I groups get a boost in performance from having had the extra three blocks of practice.

Despite the extra practice during the interference tasks the 24-hour NI group performed the same as all I groups. All t-tests comparing the 24-Hour NI group to the I groups did not show significant differences (all p’s > .05). Also, the 5-minute NI group performed significantly worse than all other groups with the important exception of the 5-minute I group. All t-tests comparing the 5-Minute NI group to the other groups were statistically significant (all p’s < .05).

From these results an important principle emerges. Overall improvements across the study were the same for most of the groups. However improvements occurred for different reasons in the different groups. For the I conditions the improvements were due to increased motor ability. For the NI groups the improvements were due mostly to improvements in sequence knowledge. This finding underscores the importance of teasing apart the motor and the cognitive component of motor tasks while examining performance changes over time.

Overall learning: error rates.

The number of errors on Block 6 was subtracted from the number of errors made on Block 1. None of the between-group comparisons reached significance. However, one-sample t-tests showed that two of the group’s performances did improve significantly over time. These were the 24-hour NI group and the 30-hour I group [p. < .05 (one-tailed)], whose improvements in error rates were significantly greater than zero (See Figure 23).

General Discussion

Two general themes regarding the consolidation of implicit procedural knowledge emerged in this experiment. First, implicit procedural knowledge improves as it consolidates, and it becomes resistant to interference as it consolidates, in keeping with both the classic paradigms of retroactive interference and distributed learning. While Goedert and Willingham (2002) did not find evidence of consolidation in implicit procedural tasks, our study shows that this was likely due to their procedure, not to the implicit nature of the task. In our first experiment, where the experimental conditions resembled those of Goedert and Willingham's study, only the motor skill of the implicit procedural task showed evidence of consolidation. This is almost certainly due to a ceiling effect. When the length and the number of blocks are decreased in the second experiment, and when the semi-random block is eliminated from the first learning session, reliable consolidation effects are seen in both motor and cognitive aspects of procedural knowledge.

The second theme was that different types of implicit procedural knowledge consolidate in different ways. Specifically, motor skill does not consolidate within the same time frame, and is not prone to the same type of interference, as is the cognitive knowledge that is acquired in implicit procedural tasks. An examination of the data in this experiment further shows the following six findings:

- Implicit procedural knowledge, both cognitive and motor, improves as it consolidates i.e. distributed learning is better than massed practice.

- Cognitive and motor aspects of procedural knowledge do not improve at the same rate: Motor skill improves during the first five hours after learning while sequence knowledge only begins to improve sometime between 5 hours and 24 hours after learning
- Cognitive procedural knowledge becomes resistant to interference as it consolidates i.e. a time gradient was found in the retroactive interference effect for sequence knowledge.
- Cognitive and motor aspects of procedural knowledge are not prone to interference in the same way: While sequence knowledge is disrupted by the interfering task in this study motor skill improves following this task
- The time frame of the development of resistance to interference and the time frame of the development of performance improvements are not the same i.e. during the first five hours memory becomes resistant to interference and only after that does it begin to improve.
- Motor skill has two stages of consolidation: the first is rapid and takes place within the first couple of minutes. The second is longer and takes place sometime within five hours. Below each of these findings is discussed.

The Sequential Reaction Time task was used in a novel way in this experiment to investigate both the cognitive and the motoric aspects of implicit procedural learning. The novel element in the analysis of the SRT task was to separate the overall gain in RTs across the entire study into two components: the gain that is due to having learned the sequence, and the gain that is due to the improvements in pure motor skill.

Cognitive procedural knowledge was assessed after four blocks of training by comparing RTs of semi-random targets to the RTs of sequentially presented targets.

General motor skill was measured by comparing RTs of the semi-random targets to the initial RTs at the beginning of the experiment (see Figure 5). We begin the examination of consolidation of procedural knowledge by looking at overall performance improvement which includes both motor skill and sequence knowledge

The Effect of Distributed Learning on Procedural Knowledge: Overall Learning Effects

Distributing the SRT learning sessions had a powerful effect on performance in both Experiment 1 and Experiment 2. In the first experiment, performance improved dramatically after a break between the two sessions. Importantly, the greatest improvements occurred following a longer break between sessions. The same was true in the second experiment; greatest between-block improvements took place between the two sessions, and a longer time interval lead to even higher levels of improvement. Also, in the second experiment the overall learning effect was twice as great in the 24-hour NI condition as it was in the 5-minute NI condition.

Comparing the overall improvement across the NI groups in the second experiment shows the extent to which distributed learning improves performance. The control group's performance increased by 20ms from the first to the last block (Block 1 to 4). The 5-minute NI group's performance increased by 50 ms from the first to the last block (Block 1 to block 6). Therefore two additional blocks improved overall performance by approximately 30ms.

While two additional blocks improve performance by roughly 30ms. inserting a longer time interval between the two sessions results in a 90ms. improvement—a 200% increase in performance. As Underwood has described, and as has been noticed by researchers such as Jost working in the 1800s, the time interval between practice sessions can more than double the effect of practicing a procedural task. As predicted by the last one hundred years of research, distributing the learning of procedural tasks greatly affects performance.

The Distributed Learning Effect: Consolidation or Fatigue?

The effect of distributing practice sessions in procedural tasks has been reported by many investigators in the past. For example, in one of the most striking studies of this kind (Baddeley & Longman 1978) subjects took typing lessons in either a distributed or in massed practice fashion. The distributed learning group practiced for one hour, once a day. The second group practiced for one hour in two separate daily sessions. The third group had one 2-hour daily sessions and the forth, massed practice group, had two 2-hour daily sessions i.e. the fourth group practiced for four hours each day.

After 55 hours of practice the distributed learning group, which had 55 one–hour daily sessions, was able to type over 80 words per minute. The second group, that had two 1-hour daily sessions, and the third group, that had one 2-hour daily session, could only type 70 words per minute. The massed practice group that practiced four hours a day was only able to type 60 words per minute. In fact, even after 80 hours of practice the massed practice group was only up to 70 words per minute. In a nutshell these results show that practicing 1 hour per day for 50 days is better than practicing for 4 hours per day for 13 days.

Importantly, however, Baddeley et al. did not interpret this result as having anything to do with consolidation. Rather they proposed that there is a limit to how much a person is capable of learning in a given amount of time. Since there are various chemicals that are needed in order for the formation of new neural connections to take place, they claimed, after a while these chemicals will be depleted and no further learning will be possible. This position is similar to the fatigue hypothesis that Jost wrote about and that has plagued the distributed learning literature ever since. For example, it can be claimed that the 24-hour NI group performed better than the 5-minute NI group because the 24-hour group had a chance to rest between practice sessions.

There are two sets of findings in our data that strongly suggest that fatigue, if important at all, is certainly only a small part of the story. First, compare the sequence knowledge of the 5-minute I group with the sequence knowledge obtained by the 24-hour NI condition (see Figure 19). While both groups had a 24-hour rest period before the second session, the 24-hour NI condition performed much better than the 5-minute I condition. Fatigue can hardly explain this effect. The fact that both groups are tested 24 hours after training, and only the NI group gets better while the I group gets worse, shows that the interference task is disrupting the memory trace for what was learned in the first session, and suggests strongly that consolidation plays a large role in this effect.

According to the fatigue hypothesis the distributed learning effect that is evidenced in our study by superior performance of the 24-H NI group relative to the 5-Minute and to the 5-Hour NI groups is due to fatigue, not consolidation. But if that is the case, the prediction would be that the 5-Minute Interference group's performance should be as good as the 24-Hour NI group and better that the 5-Minute and the 5-Hour NI group. However the opposite result was obtained. The 5-Minute I group performs worse than all NI groups. This results shows that the time interval that follows learning is critical for the retention of what was learned- a prediction made by consolidation theory and not made by the fatigue hypothesis.

The second result that argues against the fatigue hypothesis comes from comparing the sequence knowledge of the 5-minute I group to the 24-hour I, and the 29-hour I groups. All four groups performed an interfering task after the first session. However, the 5-minute I group performed it on Day 1 while the other groups performed it on Day 2. Further, the 24-hour I group performed the interfering task and the second session back-to-back. It is in these two groups then, (i.e. the 24-hour and the 29-hour I groups) that worse performance would be predicted by the fatigue hypothesis. Since in these groups two tasks are being performed one after the other, by the second session the fatigue should decrease performance. However the 5-minute I group should perform maximally because subjects in this groups only perform one session on day 2 .

Importantly, we should also note that the design of the second experiment was purposely made to be short. This was done to minimize the possibility of ceiling and fatigue effects. The entire study was so short that we feel strongly that fatigue effects should be minimal.

DL, RI, Cognitive Knowledge and Motor Skill

Having established that there are reliable consolidation effects in the SRT task and that these effects are not likely to be due to fatigue, the next step is to look more closely at the complex ways in which consolidation unfolded over time in this study. Over the last one hundred years the distributed learning paradigm and the retroactive interference paradigm have been used to investigate memory consolidation. A point that has received virtually no attention in the consolidation literature, however, is that the DL and the RI paradigms do not necessarily tap into the same aspects of the consolidation process. While the distributed learning paradigm shows that memory improves with the passage of time, the presence of a retroactive interference gradient demonstrates that memory becomes less fragile and builds up resistance to interference over time. Importantly, the results of this study show that time course over which resistance to interference and performance improvements unfold is not the same. Rather, for sequence knowledge memory becomes resistant to interference in the first few hours following learning and only then does the memory begin to improve. However, in order to understand the way in which memory improvements and resistance to interference unfold over time an important point must be kept in mind: Two different kinds of procedural knowledge were examined in this study. Importantly, the time course of the DL and RI effects are not the same for cognitive knowledge as they are for motor skill. In what follows we examine the complex picture that emerges from looking at the DL effect, the RI effects, cognitive knowledge and motor skill. The complex interplay of different types of consolidation processes and the way in which they unfold for different types of knowledge systems is presented below.

We begin by examining the results of the distributed learning effects. First the DL effects for cognitive knowledge are examined followed by the DL effects of motor skill. Then the retroactive interference effects are examined first for cognitive knowledge and then motor skill. At the end, a model of the different aspects of the consolidation process and the way in which they unfold over time for cognitive knowledge and motor skill is presented.

The Effect of DL on Procedural Knowledge: Cognitive Knowledge and Motor Skill

The novel findings in this study come from probing into how the distributed learning effect unfolds over time, and how it plays itself out for different aspects of procedural skill. By splitting the procedural task into its cognitive and motor components cognitive and motor skill were shown to be dissociable in a number of ways.

In the course of completing the SRT task subjects acquire both a general motor skill and a cognitive representation of the sequence. The fact that RTs to semi-random stimuli are faster on the 5th block than they were at the beginning of the study shows that although subjects are only performing sequenced finger movements throughout the learning phase of the study, they pick up a general motor skill that is independent of sequence knowledge.

Motor skill is only half of the story. Reaction times in the SRT task also become faster because of learning the sequence itself. This element is seen during the semi-random 5th block when the sequence is removed and RTs to semi-random locations are seen to be markedly slower than RTs for the sequenced targets. The RT differences between semi-random and non-random blocks illustrate the extent to which the knowledge of the sequence itself contributes to performance. An analysis of sequence knowledge as a function of break length shows that as time goes by sequence knowledge consolidates, and performance improves as a result. Best performance on the SRT task in this study was achieved by allowing for a 24-hour interference-free interval between sessions.

While the comparison of the three NI groups showed that the 24-hour interval was optimal for consolidation to take place for sequence knowledge, improvement did not manifest itself during the first five hours following learning. The performance of both the 5-minute and the 5-hour NI groups are statistically indistinguishable. The improved performance of the 24-hour NI group shows that consolidation based improvement begins at least five hours after learning.

However, for motor skill a different picture emerges. While a break between sessions greatly adds to the motor learning effect, the time frame over which the improvement takes place is shorter than it is sequence knowledge. While motor performance of the 5-hour NI group in Experiment 2 is greater than the 5-minute NI group, extending the break to twenty-four hours does not result in further improvements. The motor performance of the 24-hour NI group is exactly the same as in the 5-hour NI group, a results that suggest that within the first few hours motor memory stops improving.

In addition, there seems to be an initial, rapid period of motor memory consolidation that is critical for performance. This initial stage of motor consolidation is clearly seen when three groups are examined: The 5-Minute NI group in Experiment 1, the control group in Experiment 2 and the 5-Minute NI group in Experiment 2. No motor learning takes place in both the control group of Experiment 2 and the 5-Minute NI group in Experiment 1. The control group only has two learning sessions and a lack of motor learning in this group simply demonstrates that two blocks of practice is insufficient for the acquisition of motor skill. On the other hand the 5-Miniute interference group in Experiment 2 had four blocks of practice and still there is no motor learning effect. However, in the 5-Minute NI group of the second experiment significant subjects do learn the motor skill, and importantly, this happens within four blocks. Why should the 5-Minute NI group learn in the second experiment but not in the first? The only difference between the groups that can account for the differences in motor learning is that in Experiment 2 there is a five-minute break between the first two blocks and the last two blocks. This five-minute time interval seems to be critical for either the learning or the expression of motor skill.

Thus, the time course of improvement is different for the cognitive and motoric aspects of procedural knowledge in the SRT task. Motor skill seems to have at least two stages of consolidation: An initial stage that occurs within the first few minutes after learning and a longer stage that continues for a few hours. After this time motor improvements appear to be complete. Sequence knowledge on the other hand only begins to improve five hours after learning and continues to do so for at least twenty-four hours. There is therefore a dissociation in the way in which motor learning and cognitive knowledge consolidates. Motor learning consolidation takes place within the first 5-hours following learning. Cognitive representations however require a longer time interval of at least twenty-four hours to consolidate.

The Effect of Interference on Procedural Knowledge: Cognitive Knowledge and Motor Skill

While 24 hours was found to be an optimal interval for sequence learning in this study, all the I groups performed more poorly than the 24-hour NI group, despite having had the same 24-hour break between the two learning sessions. This difference is produced by the interfering task which disrupted the consolidation-based effects that normally take place within the 24-hour interval following learning. However, an unexpected picture emerges when the cognitive and motor components are looked at separately.

The extent to which the interfering task disrupts performance on the SRT task depends on whether one looks at the cognitive or the motor representations. While the interfering task clearly disrupts sequence knowledge, the opposite is true of motor skill, which actually improves following the interference task.

The data show that interfering tasks disrupt the consolidation of sequence knowledge i.e. the cognitive representation of the structure of the task. Interference does not however disrupt the formation of motor skill. Importantly, this dissociation only happens provided that the training session is not overly long. In the first experiment where both sessions were twice as long as in Experiment 2, sequence knowledge was not disrupted by the interfering tasks, a result that is traceable to one of two reasons. Either a) a sufficiently long first session makes the memory robust enough to not be effected by interference or, b) sequence knowledge is disrupted by the interfering task after the first session but acquired back through practice during the long second session. Either of these possibilities can explain why the interfering task did not disrupt performance in the first experiment. Motor skill, on the other hand, improved following the interfering task in both in Experiment 1 and Experiment 2.

If this finding has any generalizability it will be of most importance for future studies of consolidation of procedural tasks. The reason is that virtually every task that has a procedural component can be divided into its cognitive and motoric, or structured and non-structured, aspects. It is only by teasing apart the two components of the task that investigators can hone in on what is really consolidating. Without untangling procedural tasks into their motor and cognitive parts any consolidation finding is sure to be smaller and less reliable, since decreases on the cognitive aspects of the task following interference will be coupled with improvements of motor ability.

As and example, if someone learns to play a guitar song, and then practices a different song immediately afterwards, the prediction made by consolidation theory is that the second song will interfere with the retention of the first. However, while the second guitar song might have interfered with the memory for how to play the first, the motor skill that is involved in finger placement and the general ability to move fingers quickly from one bar to the next might have actually improved. So learning a second song, while interfering with the memory for how to play the first, might have contributed to the general ability to play a guitar.

When people get better on a structured procedural task such as typing, playing the piano, or riding a bicycle, they are in fact acquiring both a task-specific and a task-independent motor skill. The ability to separate a motor task into separate, structured and non-structured components can provide clues as to what aspects of the task are being consolidated and what aspects are being disrupted following interference. While this interpretation might be intuitive it is nevertheless important enough to be pointed out from a methodological point of view. Important nuances of the consolidation process will be missed if the two components of procedural learning are not separated.

Interference and the Retroactive Interference Gradient

While the effects of interference on memory have been intensely studied in the neurosciences providing insight into the neurochemical processes that take place following a learning episode, behavioral investigations of interference have painted a confusing picture in the last one hundred years. Retroactive interference was first described over a century ago by Müller and Pilzecker (1900). According to their hypothesis memory is fragile immediately after its initial formation and the passage of time makes it more robust and therefore immune to interference. However, in the 50 to 60 years following Müller's work dozens of studies examined the effect of RI on memory and almost none of them found the temporal gradient that Müller and Pilzecker predicted. In addition, recognition, relearning and word stem completion studies showed that strong effects were only found when recall was used as a memory measure, suggesting that RI doesn't so much interfere with consolidation as it interferes with memory retrieval. One possible entailment of this pattern of results is that it is only explicit declarative memory that is disrupted by the effects of interference; implicit memory may be mostly immune to these effects.

A different story emerges when procedural tasks are examined. Recent literature shows that procedural tasks are prone to interference whether they are implicit or explicit, and that there is a time gradient involved (Walker et al., 2003; Brashers-Krug et al., 1996). The data reported in this experiment are consistent with the view that there is a time gradient to the effects of retroactive interference for implicit procedural tasks. In Experiment 2 interference tasks inserted immediately after the first session produce powerful interference effects, but memory becomes harder to disrupt with the passage of time. Five hours after the first session the memory trace strengthens so that it is no longer susceptible to interference. Extending the time interval between the first session and the interfering task to 24-hours does not confer an additional benefit in terms of increased resistance to interference.

The first five hours following learning seem to be the critical time during which memory is most prone to interference. A comparison of the I and the NI groups shows that performing an interfering task during this period not only stops the memory from improving, but can actually erase what was learned during the first session.

Sequence knowledge of the 5-minute I group is not only lower than in the other I groups, it is also lower than in the 5-hour and the 5 minute NI groups. In fact, the performance of the 5-minute group is indistinguishable from the control condition where participants only learn one session of the SRT task. The 5-minute I group performs as if it only had one session of practice with the SRT task, although in reality it had two sessions.

Interference tasks that are interposed shortly after learning not only hinder the consolidation-based improvement of memory, they actually seem, at least under these conditions, to be able to erase the very memory trace that was established during learning! Taken as a whole, these results also suggest that the interference is with the actual memory rather than with its retrieval. The question of whether the interference task disrupts the storage or the retrieval of memory warrants a deeper look. Everyone has had the experience of not being able to remember something only to have it pop back into their mind at some later point in time. Not being able to retrieve a memory is no indication that the memory is no longer stored in the brain, as studies with amnesiacs have certainly shown. What if while trying to remember we gave the person some help, a hint perhaps? Such a prime should increase the likelihood of remembering the item, provided, of course that it is still stored. In many ways this is exactly what implicit forms of testing are—ways of helping the subject to retrieve a stored memory. Amnesiacs benefit from hints such as word stems and word fragments and are able to retrieve items that would otherwise not be available to them.

Procedural tasks are different in this regard. There is no simple way of making a procedural task easier to retrieve. There is no word-stem completion equivalent for procedural tasks. In a certain sense actually engaging in the task itself is the most optimal way of bringing back the skill. This is part of the reason that procedural tasks are considered implicit--the mere performance of the task brings the ability to perform it back—provided of course that it is still encoded and that the motor and muscular faculties are intact.

When a person engages in a motor task over a sufficient period of time and the motor skill does not come back there is a greater justification to conclude that the memory trace for the task is no longer present than if declarative knowledge is being examined. It is for this reason that the equivalent performance of the 5-minute I group and the control group suggests strongly that the memory trace that was established during the first practice session of the 5-minute I group has been virtually completely erased by the interfering task. It isn’t that the participants in the 5-minute I group have the memory and are failing to retrieve it properly. Rather, the memory is no longer present at all. If this effect is replicated in future studies it will have important implications for the neurochemical investigations of memory, and the study of brain plasticity in general. Is it possible that the structural changes within neurons that take place during learning are actually undone following an interfering task? Perhaps they are not allowed to form in the first place? Studying this process at a molecular and/or fMRI levels would be an intriguing possibility that can further bridge together psychological and neurobiological investigations of memory formation

A Synopsis of the Stages of Consolidation for the Cognitive aspects of Procedural Tasks

The picture that is emerging here points clearly to the fact that there are two different consolidation processes. One way in which memory consolidates is that it becomes resistant to interference as time passes. The second aspect of consolidation is that of memory improvement. An important finding in this study, and one that has only recently begun to be discussed in the literature (Walker, in press), is that the improvements of memory and the build up of resistance to interference do not happen at the same time. Rather one follows the other.

When the distributed learning and the retroactive interference results are put together an interesting picture emerges. From the performance of the 5-minute I group in which the interfering task wiped out all traces of the first session it can be inferred that the initial few hours are very important for the stabilization of memory. During this time cognitive aspects of procedural memory are quite vulnerable to the effects of interference.

While the initial few hours make the memory resistant to interference, performance improvements occur later. The first few hours following learning in a sequential task is an important interval of time during which memory starts out being fragile and susceptible to erasure, but during which memory is simultaneously developing resistance to interference. During the hours that follow, if undisturbed, a memory will continue to undergo a second stage of consolidation which is characterized by improvements in performance.

The same dual pattern of consolidation was recently reported by Walker et al, (2003; in press) using an explicit version of the SRT task. In Walker et al's. (2003) study consolidation of procedural knowledge of subjects who were explicitly told about the sequence was found to follow a similar time course in terms of the development of resistance to interference during the first few hours, with the consolidation based improvements in performance taking place over a 24-hour period. It therefore seems that consolidation unfolds in the same general way whether the sequence knowledge is "known" implicitly or explicitly.

For motor aspects of procedural skill a different picture emerges. While sequence knowledge improves during the latter parts of a 24-hour period, motor skill improves during the initial few hours that follow learning. Sequence knowledge and motor skill do not consolidate over the same time interval (see Table 2).

Putting It All Together: Some Speculations

Recent neuroscientific studies show convincingly that consolidation is a fundamental process of memory formation. In all likelihood every new learning episode initiates a cellular cascade of events that involves gene expression and protein synthesis, which in turn lead to structural changes within cells. This process is an important element in the biological basis of memory. The important question that has not been adequately addressed so far in either psychological or biological literatures is whether the consolidation process is different for different forms of memory. The data collected in this series of studies and the literature that has been reviewed here presents, in our view, compelling evidence that the process of consolidation is not the same for the various memory systems.

Moreover, any coherent theory of consolidation must take into account a distinction between declarative and procedural memory. First, there are biological boundaries within which these memory systems are instantiated (see Squire, 2004). The mere fact that the biological lines of demarcation for these systems are distinct, and that the declarative and the procedural systems also have separate evolutionary histories, strongly suggests that the very modes of operation of these systems—the ways in which they encode, store and retrieve information—might be found to be different from one another.

Behavioral examinations of declarative and procedural systems also reveal differences. Declarative memory is disrupted by interfering tasks, but the passage of time does not change the extent to which declarative memory is disrupted. There appears to be no time gradient over which declarative memory becomes immune to the effects of interference. Further, in declarative memory experiments interference seems to merely suppress the ability to retrieve information rather than erase the memory traces themselves.

Procedural memory is also disrupted by interference, but unlike declarative memory the greatest effect occurs immediately after the learning episode; the extent to which interfering material disrupts performance decreases as time passes. Further, as the results here show, interfering material does not merely suppress the expression of the learned material during learning—it erases it.

Theoretically an interfering task can disrupt memory in one of two ways: the interfering material can act on the stored memory itself by erasing the traces for that memory, or the interfering task can disrupt the ability to retrieve the memory while leaving the actual trace intact. The results of most experiments that deal with the consolidation of declarative knowledge strongly suggest that interference tasks disrupt the ability to retrieve items, without affecting the memory traces themselves. This becomes clear when sensitive measures of memory are used such as savings, word-stem completion, and even recognition; all measures on which subjects' performance is unaffected by interfering tasks.

Also, although subjects score lower on recall tests for, say, a word list when they learn a second word list, this is typically not because the second word list erased the memory of the first. Rather, the lower scores following the presentation of secondary material are mostly due to an inability to recall certain words and also from intrusion errors. Subjects make intrusion errors when they forget which words came from which list, and when they are asked to recall the words from a specific list they often mistakenly report words from the other list as well. Intrusion errors are strongly related to source memory-the ability reconstruct the context within which the items were presented. Subjects in declarative retroactive interference experiments not only have to remember a word from a list but also often have to place its source: they have to know if the word came from the first or the second list. It is these abilities i.e. source memory and recall that are disrupted by interfering tasks.

In procedural memory studies, on the other hand, interfering tasks probably act on the memory itself, not just the ability to retrieve it. Following an interfering task procedural knowledge is unlearned. When procedural knowledge is examined carefully, i.e. when the motor component is factored out and only the cognitive representation of the task structure is examined, interfering tasks are seen to disrupt the actual encoded memory trace—not just the way in which the memory is retrieved.

But why should that be? Why should declarative memory and procedural memory not consolidate in the same way? Specifically, why is it that interfering tasks affect declarative memory and procedural memory in such different ways? A possible explanation might lie in the differences in which declarative and procedural memories are encoded and in the differences between the retrieval processes that operate on declarative and procedural memory.

A Strategic/Associative Retrieval Theory of RI Effects

In order to see how the retrieval mechanisms are different in declarative and procedural systems, and in turn to understand how these retrieval mechanisms should be effected differently by interference, it is necessary to make a distinction between two types of retrieval: associative/cue dependent retrieval and strategic retrieval(Seman, 1922; Moscovitch, 1995).

Sometimes memories pop into consciousness spontaneously. When we encounter a familiar smell an episode might come to mind of where we were the last time that we came across that aroma. Hearing a song might automatically remind us of a time in our life when we listened to that song often. Memories are context dependent and they are also associative. Thinking about or perceiving a stimulus usually brings with it a set of associated thoughts and memories, and often this happens involuntarily and without effort. When memories come to mind in this way, they are remembered via the process of associative retrieval. Associative retrieval is automatic and items are remembered in response to a stimulus, whether internal or external, by way of involuntary, mechanical associations.

At other times memories are retrieved in a more goal-directed way, through an effortful attempt to remember or to reconstruct some specific event from the past. Say you remember being at the airport last week but cannot recall what you were wearing. You might try to think back to that morning and attempt to recall and to reconstruct the events of that day, in order to aid the recall process. This is an example of strategic retrieval, which is voluntary and goal directed. Strategic retrieval is engaged in when someone is trying to consciously recollect a fact or episode and uses a particular strategy to achieve that goal. Most importantly for our purposes recall, to a large degree, is dependent on strategic retrieval. Implicit memory, on the other hand, is much less dependent on strategic retrieval. Implicit memory is almost always retrieved associatively.

There are other differences between associative and strategic retrieval. Associatively retrieved memories do not have a chronological theme to them. After a memory is associatively retrieved temporal context can then be further established by strategic retrieval. Source memory is also something that is dependent on strategic retrieval. When a stimulus is retrieved associatively, in addition to lacking a sense of time, it also lacks a sense of place.

As mentioned above, interfering tasks primarily disrupt the ability to recall an item and the ability to determine where and when an item was encountered—not the memory for the item itself. Because the memory itself is intact following interfering tasks, the framework being developed here is that interference tasks in declarative memory experiments interrupt strategic but not associative retrieval. In declarative tasks interference disrupts the ability to retrieve information via strategic processes. Taking this perspective explains two important facts. First, a strategic retrieval theory of retroactive interference effects in declarative memory explains why RI tasks do not disrupt implicit memory. Implicit memory mostly uses associative retrieval processes. Secondly, it explains why no time gradient has been observed in declarative RI experiments. The theory of consolidation is a theory of encoding and storage—not retrieval. While there are theoretical reasons for suspecting the memory traces continue to strengthen after they are initially formed, the extent to which that trace will be retrieved appropriately does not necessarily fall within the domain of consolidation theory. The extent to which retrieval processes can be interfered with might very well not have a time gradient.

While items can be retrieved from declarative memory through either associative or strategic retrieval, implicit procedural memory is usually retrieved via associative processes only. The very nature of the learned domain in implicitly learned tasks is associative. In the SRT task, for example, subjects are detecting patterns of covariation between the targets as they appear on the screen. Associations are being established between the targets while subjects are engaged in the task and these links continue to form after learning. Within the current framework it is these very links that are disrupted by interference tasks. If the statistical structure of the interfering material is different from that of the original task the associations learned during that task will be unlearned. In implicit procedural tasks interference disrupts the very associations that have been established during learning. This is the reason that the interfering tasks affect declarative and procedural memory so differently.

A *Computational/Evolutionary Theory of Procedural Consolidation*

Similar reasoning might help explain the differences in consolidation between cognitive procedural and motor skill memory. Our data show that these two memory systems differ in two important ways. First they are not equally prone to the effects of interference. The same interference tasks that disrupt sequence knowledge actually improve motor performance. The second difference between the cognitive and motor procedural memory lies in the way that they consolidate. Sequence knowledge consolidates in two stages. During the first stage that lasts for about 5 hours the memory becomes immune to interference but does not improve. During the second stage of consolidation the memory has become immune to interference and consolidation-based improvements begin. Motor memory, on the other hand, appears to have two stages of consolidation that are complete within the first few hours, during which motor memory improves.

Why should these two types of procedural knowledge consolidate in such different ways? Why should cognitive aspects be more prone to interference and go through two stages of consolidation, while the motor memory only one? Here, as above, the key might lie in the associative nature of the cognitive knowledge that is acquired in implicit procedural tasks, such as the SRT task.

Cognitive, in the context of these experiments, describes the mental processes that are involved in detecting patterns of covariation among events in the environment. They can be procedural as in the SRT task. They can be also be non-procedural as in a variety of other situations used to study implicit learning such as the Artificial Grammar paradigm, the dot classification task, classical conditioning, operant conditioning, and other non-procedural SRT tasks. What all of these tasks have in common is that in order for learning to take place the organism must extract statistical regularities from the world, encode that regularity, consolidate and store it in long term memory. Detecting patterns of covariation is the basis of all learning and forms the very building blocks out of which more complex forms of learning evolved (Reber, 1993) The simplest organisms have evolved this ability to learn very simple stimulus-response relationships among events, such as habituation, sensitization, classical and operant conditioning—all of which are examples of an implicit cognitive ability to learn about the complexities of our world's structure (Rescorla and Wagner, 1983).

But not all learning involves extracting associative relationships from the world. Some learning, such as learning to climb, run, and other types of coordinated body movements involve the learning of a general motor program, one that is less associative in nature. One possibility as to why motor procedural skill and cognitive procedural knowledge should consolidate at different rates might come from considering this issue from an evolutionary/computational perspective.

Motor skill starts improving right away while sequence knowledge only starts to improve some time after learning. A theoretical argument can be made that the time course of consolidation for the development of motor programs and that of associative learning *should* be different. The key feature of associative learning is that an organism be able to extract the *correct* pattern of covariation from a complex environment. In an ever-changing world a pattern that is noticed by an organism at any one point might or might not be a real or an important feature of that environment, i.e. the "pattern" might be noise rather than a signal. Therefore it would be deleterious for an organism to permanently encode every association that it comes across.

One well-known example of this principle comes from Pavlov's classic studies where dogs only salivated to the bell but not to Pavlov. The reason is that his presence did not consistently predict food while the bell did. Sometimes when Pavlov was around there was food and sometimes there wasn't. When an organism encounters a new association, such as the presence of Pavlov at the time of a meal, before consolidation has a chance to permanently incorporate the learned association into an animal's memory system, a consistency check has to take place. Was this association an important one, is it reliable, are there contradictory factors involved? For this reason in associative learning the consolidation process does not start right away. A time interval after learning is needed to allow the organism to become sure that no further contradictory associations are encountered. If they are, the association is unlearned and is not allowed to consolidate. The initial time interval following learning is a crucial time where an organism must decide whether what it learned is consistent with its past experiences and also with those that immediately follow and thereby, whether the new association should be encoded into long-term memory.

The same is not true for motor skill. When a motor skill is learned there is no fear that it is the "wrong" thing to have learned. Motor skill therefore should start to consolidate immediately. A difference in consolidation between motor skill and sequence knowledge should theoretically be expected in both the time frame of consolidation-based improvement and in the susceptibility to interference tasks.

The above model is consistent with some recent findings in the cognitive neurosciences. It has long been known that there are two important learning systems in the brain: the striatum (an input structure to the basal ganglia) and the prefrontal cortex. Recent studies are showing that the time course of activity following learning within these systems is not the same. The onset of activity within the striatum is rapid and takes place immediately after learning. The activity within the prefrontal cortex, on the other hand, starts a substantial amount of time after learning is over (Pasupathy and Miller, 2005). Since the striatum and the basal ganglia are known to be involved in motor tasks, while the prefrontal context is more involved in the processing of cognitive information the results of Pasupathy and Miller are consistent with the framework outlined here. Although the time-frames that were dealt with in their study are much shorter than those examined in this study, the existence of multiple systems of learning that operate on different time scales should inspire future studies that will examine the activation that takes place after learning within these structures further. Functional MRI studies can potentially provide insights in this area of research.

Some fMRI research has already shown that brain activity after associative procedural tasks is different when the procedural tasks are missing a structural component (Pignaux et al. 2003). In their study increases in brain activation were seen during REM sleep after subjects learned an SRT task. However, when the targets were semi-random no activation occurred during REM sleep. In Shadmehr and Holcomb's, (1996) studies where the tasks involved the manipulation of a joystick, PET scan data showed that brain activity occurs during the initial six hours following learning. This finding is also consistent with the theoretical model being proposed here. When the procedural knowledge is associative, off-line processing continues to take place many hours after learning; however, pure motor skill consolidation processes are complete in the initial few hours that follow learning (see Table 2).

This general framework helps explain a number of other experimental findings. For example, it explains the discrepancy between Brasher-Krug et al.'s (1996) results and that of Walker et al.'s (2001) results. In Brasher-Krug's study consolidation seems to have completed after 4 hours while in Walker's studies it usually takes at least 12 hours and also requires sleep. However, Walker et al.'s procedural task is associative while Brasher-Krug et al.'s is non-associative. The idea that motoric knowledge starts to consolidate immediately while cognitive procedural knowledge needs a longer time period is consistent with these findings.

While our data provides a general framework within which to view a number of recent findings in the cognitive neurosciences, other experiments and further refinements of our approach via computational models will, of course, be needed to further substantiate these ideas.

Conclusion

In this thesis a novel framework was provided within which to view memory consolidation. We proposed that four distinctions must be made between memory systems: explicit declarative memory, implicit declarative memory, cognitive procedural memory and motor memory. The full model of the memory systems and the way in which the consolidation process unfolds for each of them is presented in Table 1. These systems have been shown to be different in a number of ways: a) in the extent to which they are prone to interference, b) in the time course over which they improve, c) the different brain systems within which they are instantiated, and d) the processes that are disrupted by interference.

Explicit Declarative Memory

Explicit declarative memories are affected by interference no matter when the interfering task is presented. This is because the interfering task does not erase the actual memory trace for the memorized item, but rather disrupts the ability to retrieve that item and to reconstruct the context within which it was encoded. Time does enhance performance on declarative memories i.e. distributed learning is better than massed practice, and declarative memories become immune to the effects of brain trauma with the passage if time. These consolidation effects probably happen as a result of system-level consolidation, a process known to involve the hippocampus. Declarative memory is known to be strongly reliant on this brain structure. Additionally, sleep probably plays a major role in the consolidation of explicit declarative memory.

Implicit Declarative Memory

Implicit declarative memory (implicit memory for words and events) has been shown to not be disrupted by interfering tasks. This is because interfering tasks disrupt strategic retrieval and this retrieval-- a process that is not necessary for the retrieval of implicit memory.

Cognitive Procedural Memory

Procedural memory can be divided into two major components: cognitive and motor. Our studies demonstrate that cognitive procedural memories are most susceptible to interference immediately after learning and then some time later become immune to retroactive interference effects. The interference task can erase the memory that was established during learning if it is presented immediately following learning. Unlike declarative knowledge, in implicit procedural tasks the interfering material actually disrupts the links that are established during learning.

After a few hours have passed procedural memory is no longer susceptible to the effects of interference but the consolidation process continues. The second stage of consolidation begins and continues for at least 24 hours. During this stage the memorial representations strengthen, resulting in improved performance on the task after a 24-hour period.

The consolidation of cognitive procedural memory is likely independent of the hippocampus, however this has not been empirically established. Rather, it probably takes place within the regions that encode and store the memory. The striatum and the basal ganglia might be involved in the initial stages of the consolidation process. The prefrontal areas might be involved during the later stages. As of now not enough is known about the brain regions that are involved in the various consolidation processes and the involvement if the basal ganglia and the prefrontal cortex is largely speculative. Evidence is also beginning to accumulate that sleep is an important factor for the consolidation of the cognitive knowledge that is acquired during the performance of procedural tasks.

Motor Procedural Memory

The fourth type of memory--procedural motor memory-- is not affected by the same type of interference tasks as is cognitive procedural memory. The reason is that cognitive procedural memory is disrupted because the associations in the interfering task are contrary to those of the primary task. The motor aspects of the task however are not reliant on associative learning. Motor skill becomes better as a result of enhanced motor coordination that comes with practicing the task. Interfering tasks provide more opportunity to engage in the task and therefore actually enhance subjects' performance rather then disrupt it. There are two stages of consolidation of motor skill. The first occurs with in the first few minutes after learning and the second continues for a few hours. Consolidation of motor skill is not dependent on the hippocampus, and in all likelihood involves the striatum and the basal ganglia.

Final Remarks

An attempt was made here to review the last one hundred years of consolidation research, and to present a unified framework within which to view DL and RI findings. We have incorporated diverse literatures in a variety of fields, including distributed learning, retroactive interference, consolidation, declarative and procedural memory, implicit and explicit memory, and neurobiological investigations of memory. In so doing we have undoubtedly overlooked many pertinent studies, and theoretical point of view. No literature review of this scope can be fully comprehensive. However we hope that the model provided here, which divides memory into four specific types and makes specific statements (predictions) about DL and RI effects in each of them, should present a concrete framework within which researchers studying consolidation can formulate further hypothesis and continue to modify and refine our conception of consolidation further. To this effect a number of follow up studies that spin themselves out of the research here are presented below.

Future Research

The Consolidation of Motor and Cognitive Procedural Knowledge: a More Direct Approach

Our study showed that procedural tasks could be dissociated into motor and cognitive components. Future studies should examine the difference between motor and cognitive knowledge more directly by utilizing tasks that are purely motor and purely cognitive. For example, an SRT task where targets are presented semi-randomly is a purely motoric task with virtually no cognitive component. This task can be used to examine the way in which motor skill improves over time. This would allow for a direct examination of consolidation of motor skill. Also, are there tasks that can disrupt motor skill? While in our study interfering tasks did not disrupt motor performance because their statistical structure did not conflict with that of the primary task, perhaps there are other motor tasks that can produce such interference.

Cognitive procedural task can also be examined more directly. A single-button SRT task developed by Litman et al (in preparation) requires virtually no motor ability, but does involve the ability to learn complex patterns, as in the regular SRT task. The results of our experiment predict that consolidation will take place over a period of 24-hours in this task and the extent to which this knowledge is disrupted by interference will be time dependent. Our prediction is that performance on this task should become immune to interference after the first five hours and then improve further during the time that follows. By examining the semi-random SRT task and the one-button task the consolidation of motor memory and cognitive procedural memory can be ascertained more directly. Also the single-button SRT task can be used to examine the consolidation of procedural memory in Parkinson’s patients.

Varieties of Procedural Knowledge:, SRT Tasks, and Amnesiacs.

What is the nature of consolidation in cognitive procedural tasks in amnesiac patients? The cognitive knowledge that is acquired on the standard procedural SRT task is implicit. However the cognitive knowledge that is acquired on explicit versions of the SRT task is explicit. One intriguing question here concerns amnesiac patients. Will consolidation occur for amnesiac patients only on the regular SRT task but not on the explicit version of the task? If both the implicit and the explicit SRT tasks are teased apart with regard to their motor and cognitive components, we should expect that consolidation should take place on both versions of the SRT task on the motor part of the task. But what about the cognitive part? One possibility is that the implicit cognitive knowledge will be intact in amnesiacs for it is not dependent on the hippocampus. But the picture is less clear for the explicit part of the task. This brings us back to a question raised in the beginning if the paper, is the cognitive knowledge that is gained in the explicit version of the SRT task better thought of as being explicit procedural knowledge, or is it better to think of it as declarative knowledge of associative information?

If the explicit knowledge that is attained in the explicit version of the SRT task is dependent on the hippocampus then consolidation should not take place in amnesiac patients. It is also possible that even when knowledge is attained explicitly implicit knowledge also plays a role. We might then expect that consolidation would take place for amnesiacs but not to the same extent as for normals since for normal participants both implicit and explicit processes are functioning while amnesiacs have to rely purely on their implicit systems (see Litman & Reber, 2005).

In order to perform the above experiments the SRT task should be made as much as possible like Walker et al.'s (2001) task. In Walker et al.'s task the dependent measure is how many repetitions of the sequence a subject can make in a given time frame—usually 30 seconds. This can also be done for the standard SRT task. At the end of each block a subject will be told how many buttons they managed to press and would be encouraged to beat their record on the following block. This should equalize the Nissen and Bullemer and Walker et al.'s procedures and make them more comparable one to another. In addition it would provide an extra incentive for subjects to be as fast possible on the Nissen and Bullemer version of the SRT task. The lack of a motivating factor in the standard SRT procedure might also explain why the learning effects from a standard SRT task are not as high as in Walker's task. In fact, simply comparing the learning effect between the two procedures should prove useful in and of it self.

Sleep

Finally, the effects of sleep on the consolidation of motor and cognitive procedural knowledge should be examined more thoroughly. Many studies have shown that the consolidation of procedural knowledge requires sleep. In our study, while a twenty-four hour interval is necessary for consolidation to complete it is not clear whether the effects are due to the mere passage of time or to the fact that subjects slept during that time interval. By monitoring the sleep patterns of subjects in a sleep lab the effect of sleep and sleep stages on the consolidation of procedural knowledge can be examined.

The consolidation of memory has been described as the way in which memory passes from long term-to short memory. However, this is just the beginning of a very complicated and interesting story. The details of this story are sure to unfold in future studies where amnesia, Parkinson’s disease, sleep and the neural systems that underlie the various memory structures are examined in more detail.

Experiment 1: Distributed learning

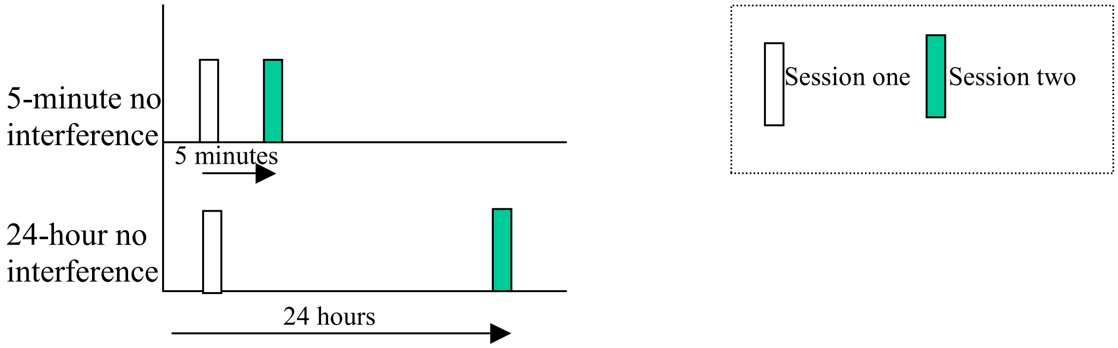


Figure 1: Two groups are employed in this experiment. The 5-minute group performs two sessions of the SRT task with a 5 minute interval between the two sessions. The 24-hour group performs two sessions of the SRT task with a 24-hour interval between the sessions. Both groups are tested at the end of both the first and the second session. The distributed learning procedure does not have an interference condition. No secondary task separates the two SRT sessions. Both sessions consist of six blocks. The first four blocks consist of a repeated sequence, the fifth block is semi-random and the sixth block also consists of a repeated sequence.

Experiment 1: Retroactive interference

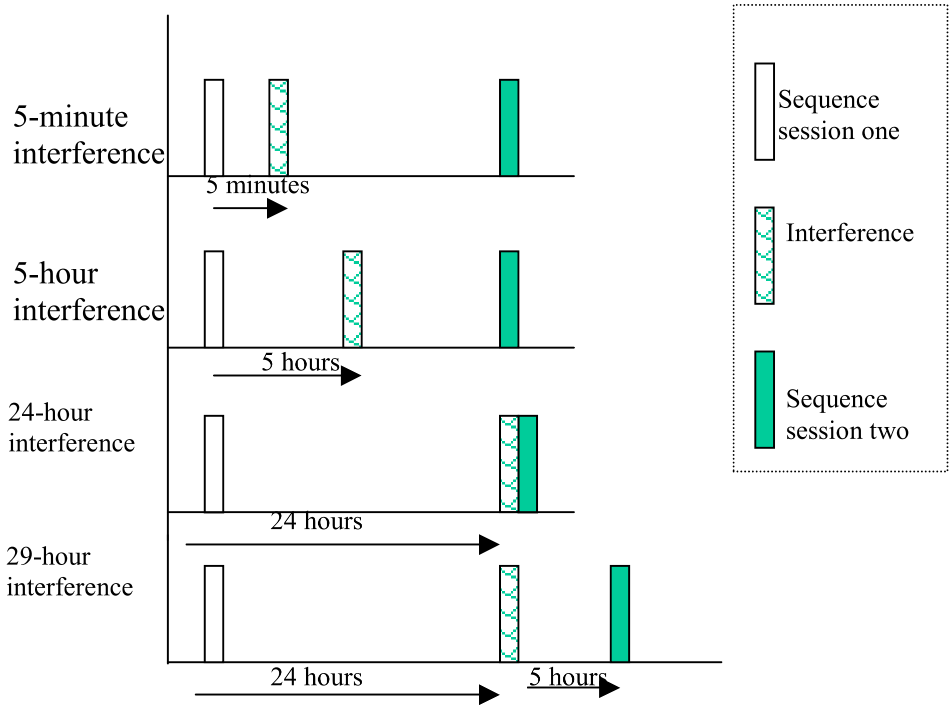


Figure 2: Four groups are employed in this experiment. Each group performs three SRT sessions. The first and the third session consist of a repeated sequence. They are separated by either a twenty-four hour period in the 5-minute, 5-hour or the 24-hour conditions, or a twenty-hour period in the 29-hour condition. The interference session is interposed between them either 5 minutes, 5 hours or 24 hours after the first session. The interference sessions consist of three blocks of targets that are presented according to a semi-random pattern.

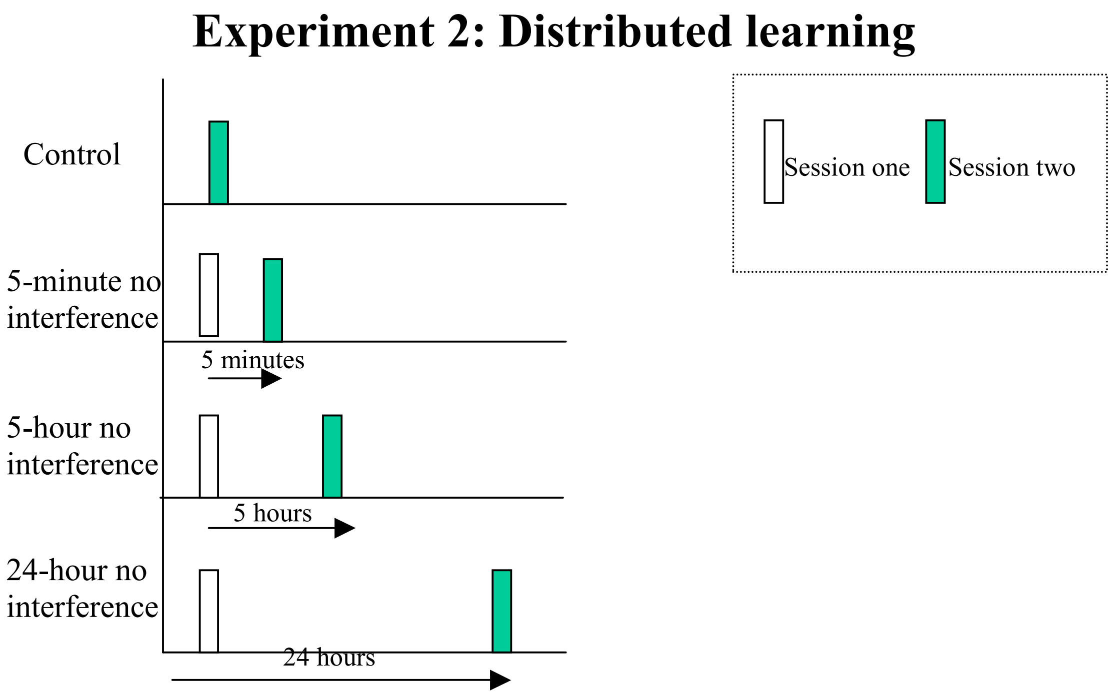


Figure 3: Four groups are employed in this experiment. The control group performs only one session of the SRT task. The other groups perform two sessions of the SRT task. The first session consists of two blocks in which the targets follow a repeated pattern. The session consists of two blocks with a repeated pattern followed by a semi-random block and then by another block where the targets follow a repeated sequence. The 5-minute group performs two sessions of the SRT task with a five-minute interval between the two sessions. The 5-hour group has a five-hour break between the two sessions and he 24-hour group performs the two sessions of the SRT task with a 24-hour interval between the sessions. All groups are tested at the end of the second session. The distributed learning procedure does not have an interference condition. No secondary task separates the two SRT sessions.

Experiment 2: Retroactive interference

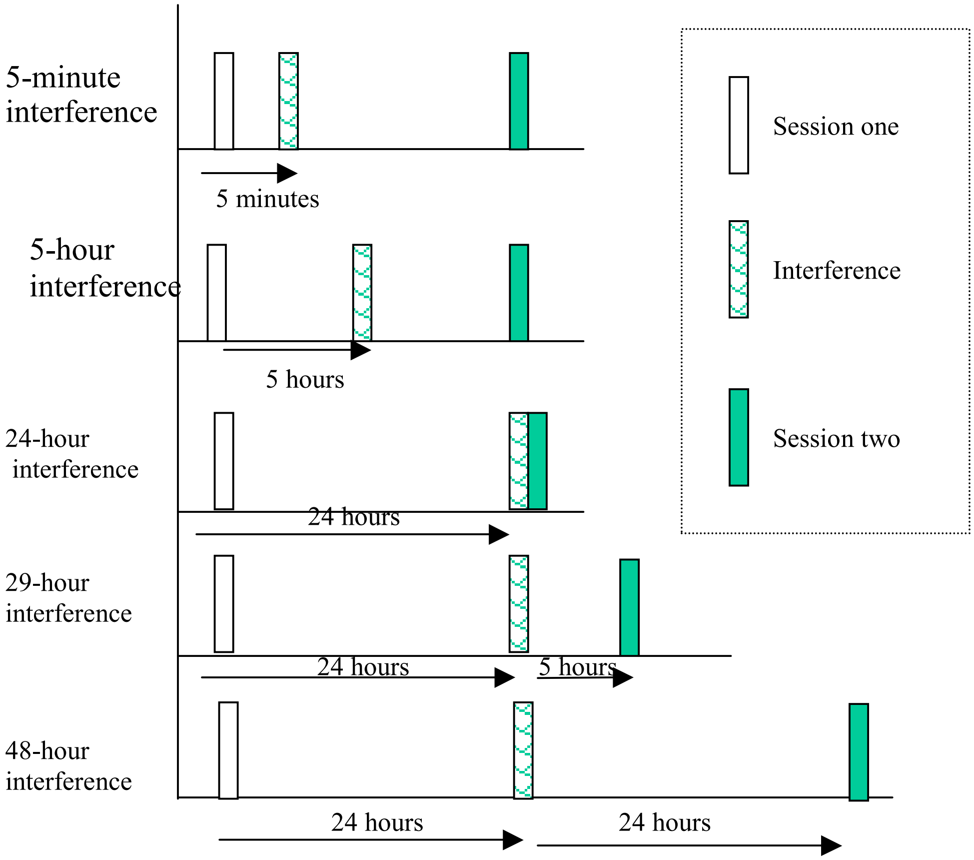


Figure 4: Four groups are employed in this experiment. Each group performs three SRT sessions. The first and the third session consist of a repeated sequence. They are separated by either a twenty-four hour period in the 5-minute, 5-hour or the 24-hour conditions, or a twenty-hour period in the 29-hour condition. The interference session is interposed between them either 5 minutes, 5 hours or 24 hours after the first session. The interference sessions consist of three blocks of targets that are presented according to a semi-random pattern

The components of the SRT task

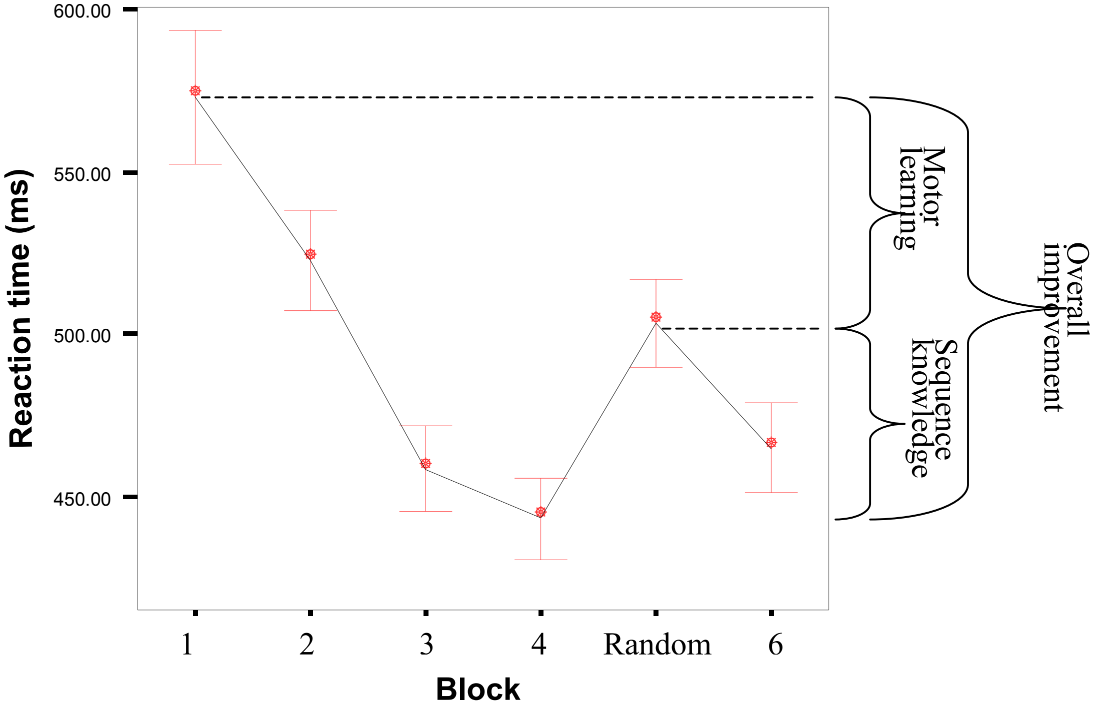


Figure 5: Represented in this figure are the various skills that are learned during the course of the SRT task. Motor learning is measured by taking the difference in reaction times between the first and the fifth blocks. Sequence knowledge is measured by taking the difference between the fifth and the average of the sixth and the fourth blocks. Overall learning is measured by examining the difference in reaction times between the first block and the last block.

Experiment 1: Reaction Time Performance on Session 1 and Session 2

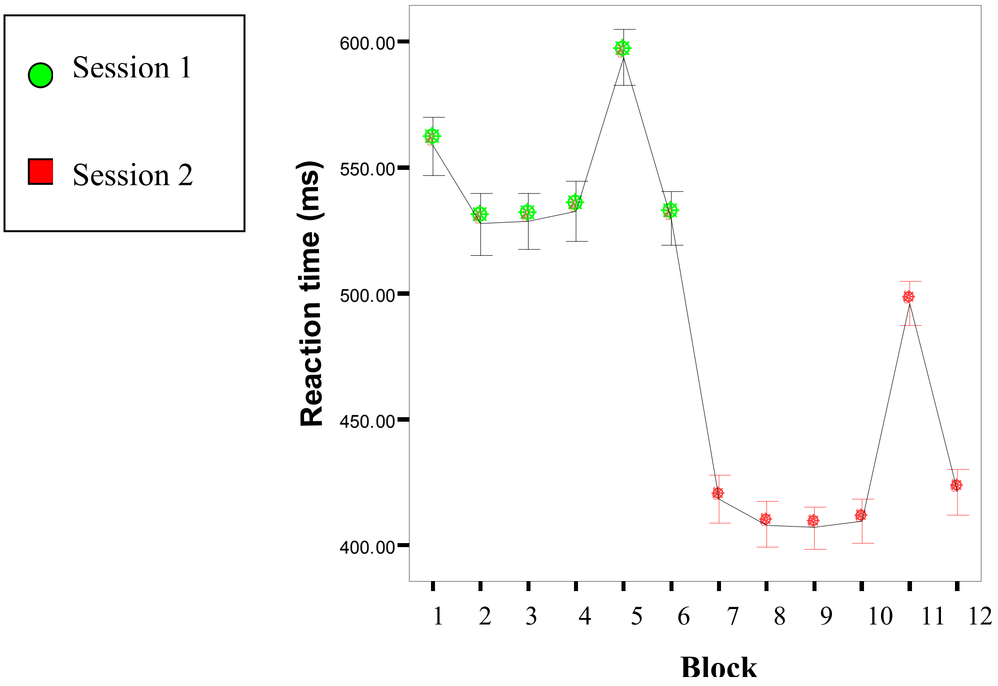


Figure 6: Combined reaction time performance of six groups of subjects (N = 104) across two sessions of the SRT task. Medians were calculated for each of the ten repetitions of a sequence within each block. The means of the medians on each block were obtained for each subject. The average of all subjects for each block is plotted on the graph. Performance on the first session is presented in green and the second session is presented in squares. A time interval of either 5 minutes, 5 hours or 24 hours separated the first and the second session. These three conditions are collapsed together in this graph. Blocks 5 and 11 are transfer blocks where targets do not follow a repeated pattern. On these blocks, targets are presented semi-randomly.

Experiment 1: Error rates on Session 1 and Session 2

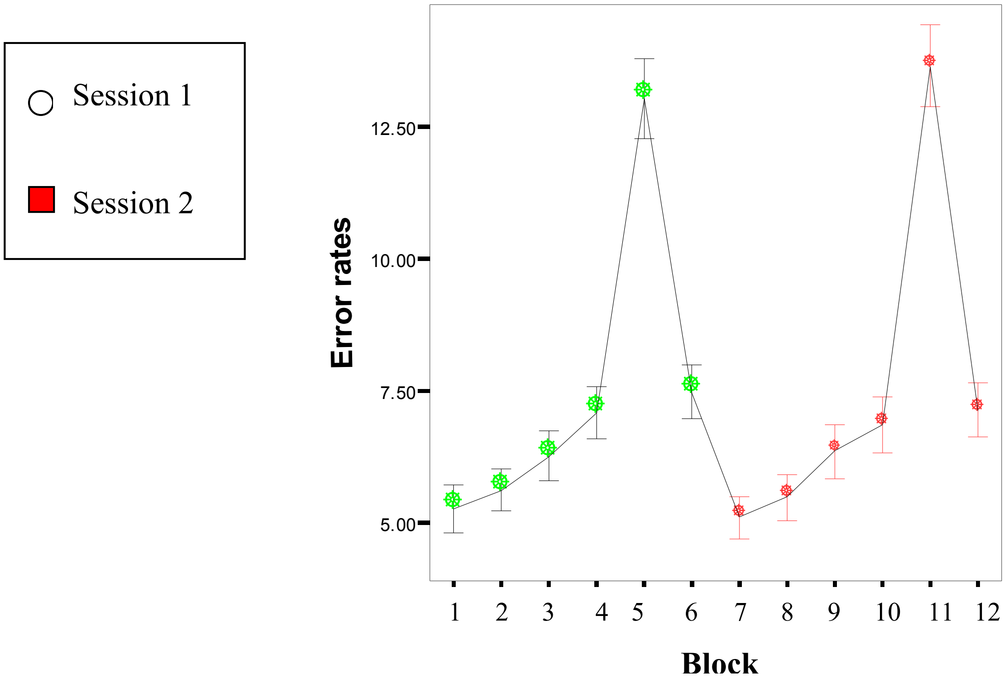


Figure 7: Combined error rates of six groups of subjects (N = 104) on twelve blocks of the SRT task. The total number of errors in each block are plotted on the above graph. Performance on the first session are presented in green and the second session is presented in red. A time interval of either 5 minutes, 5 hours or 24 hours separated the first and the second session. The performance of these groups are collapsed in this graph. Blocks 5 and 11 are transfer blocks where targets do not follow a repeated pattern. On these blocks, targets are presented semi-randomly.

Experiment 1: Block-to-Block Improvements

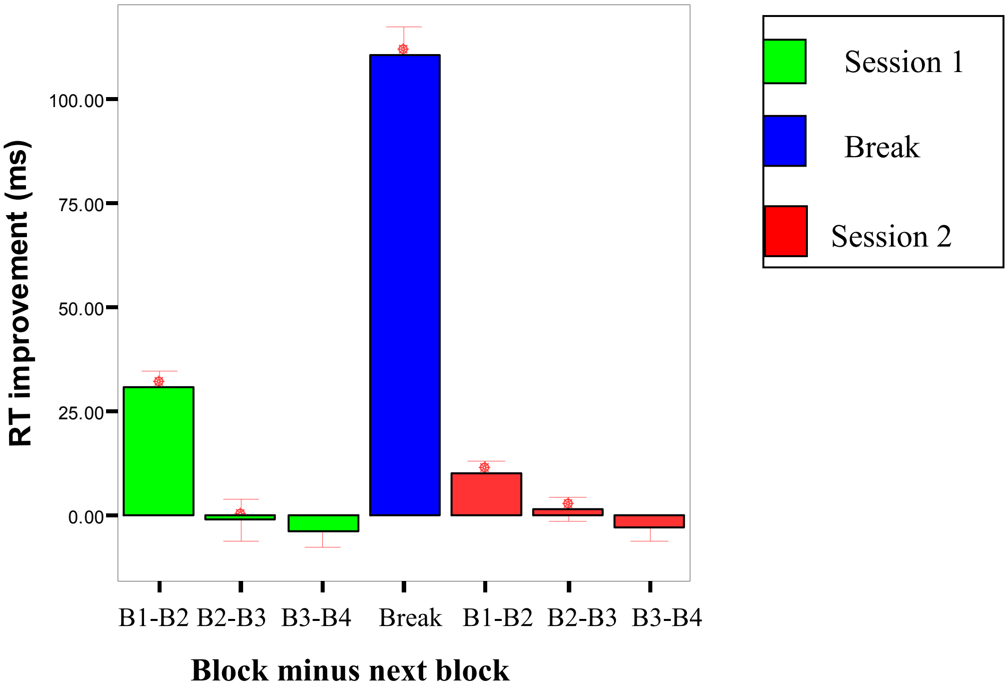
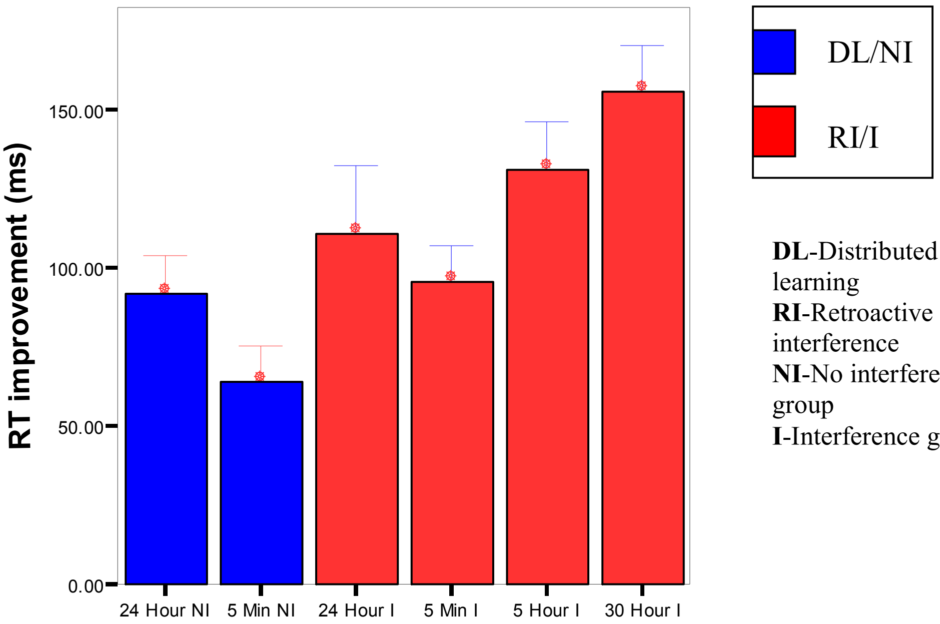


Figure 8: Reaction time differences between the first consecutive four blocks of Session 1 and Session 2. The data from Figure 6 was used as the starting point for this graph. For example, B2-B1 presents the RT difference between Block 1 and Block 2 on the first session, where RTs of Block 2 were subtracted from that of Block 1. The blue bar marked “break” shows the RT differences between Block 6 of Session 1 and Block 1 of Session 2.

Experiment 1: Improvement From Last Block of Session 1 to First Block of Session 2

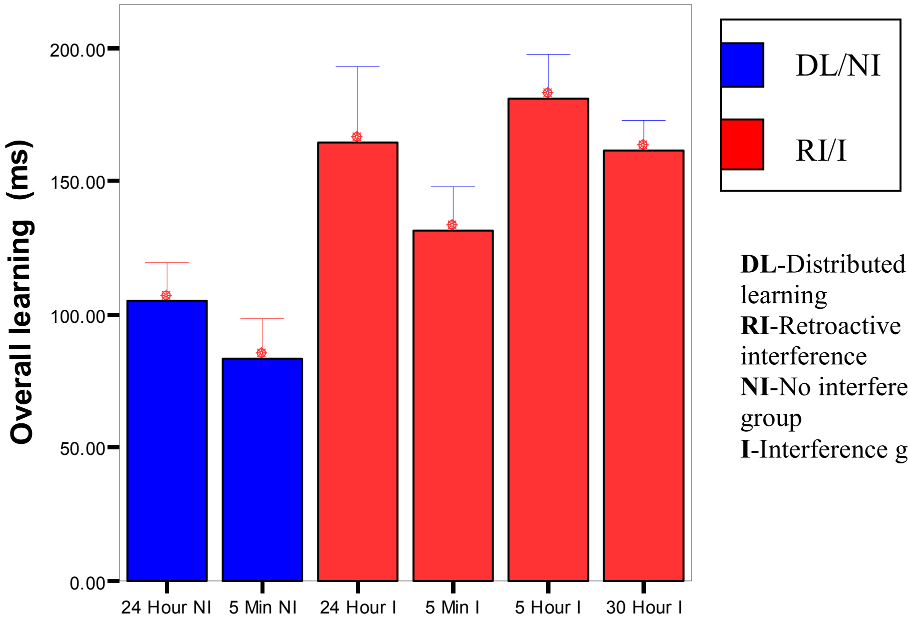


DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 9

Figure 9: Reaction time differences between the last block of Session 1 and the first block of session 2 (refer to “Break” bar from Figure 8 in Figure 6). This difference is presented as a separate bar for each of the six conditions in the study. The bars representing the No-Interference groups are blue and the bars representing the Interference groups are red.

Experiment 1: Overall learning

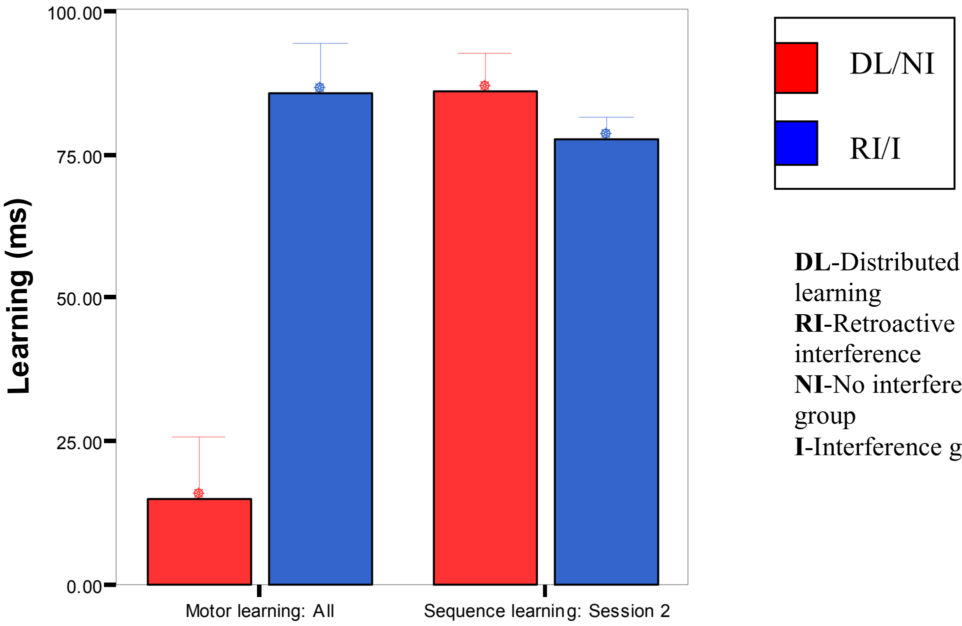


DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 10

Figure 10: Overall learning across both sessions for each of the six groups in Experiment 1. Overall learning is calculated over both sessions by subtracting reaction times on the last block of the second session from the first block of the first session (Block 1 minus Block 12 in Figure 6). The bars representing the No-Interference groups are blue and bars representing the Interference groups are red.

Experiment 1: The effect of Interference on Sequence knowledge and Motor Skill

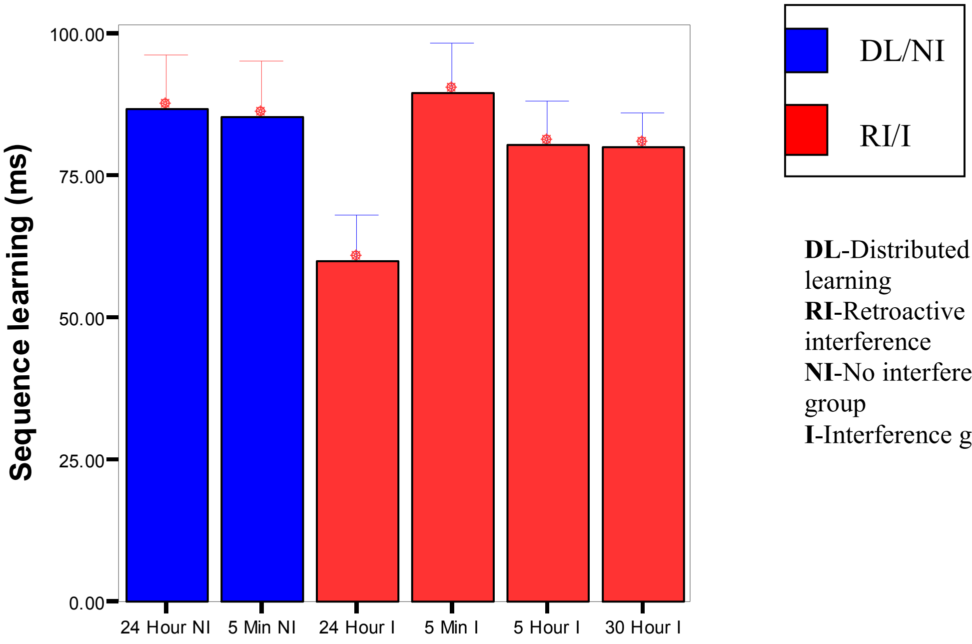


DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 11

Figure 11: The data presented in Figure 6 was used as a starting point for this analysis. Two measures--motor skill and sequence knowledge-- are plotted separately for the Interference and the No-Interference groups. Motor skill was measured by subtracting the reaction times on the 5th block of Session 2 (Block 11 in Figure 6) from the first block of Session 1 (Block 1 in Figure 6). Sequence knowledge is measured by taking the RT differences between the average of Block 4 and 6 of Session 2 and (Block 10 and 12 in Figure 6) Block 5 of Session 2 (Block 11 in Figure 6). The red bars show the combined performance of the four interference groups. The blue bars show the combined performance of the two No-Interference groups.

Experiment 1: Sequence knowledge on the Second Session

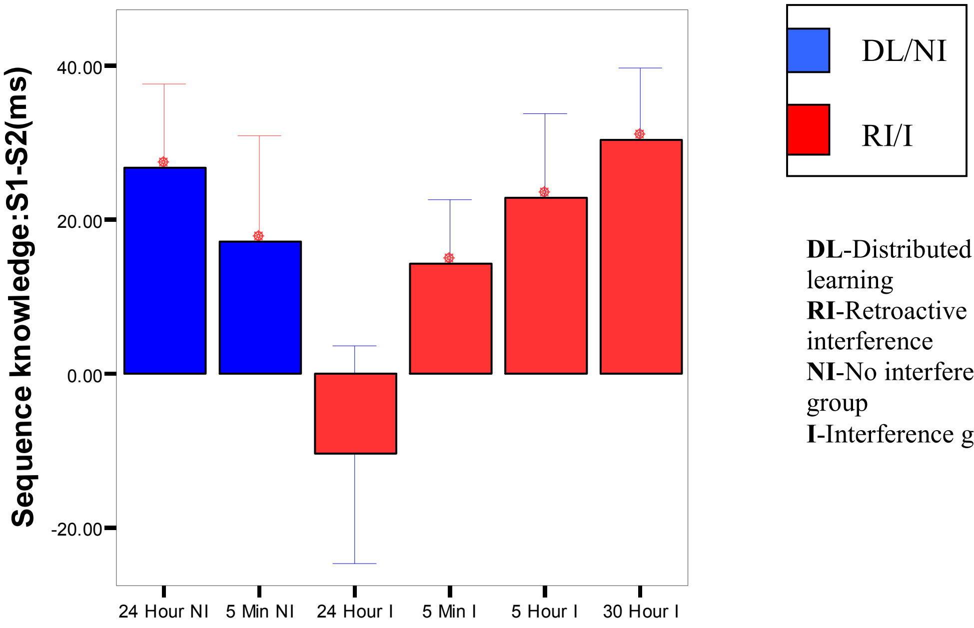


DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 12

Figure 12: Sequence knowledge on the second session (see Figure 11) is presented separately for each of the six groups. Sequence knowledge is measured by taking the RT differences between the average of Block 4 and 6 of Session 2 and (Block 10 and 12 in Figure 6) and Block 5 of Session 2 (Block 11 in Figure 6). The red bars show performance of the four interference groups. The blue bars show the performance of the two No-Interference groups

Experiment 1: Sequence Knowledge Consolidation

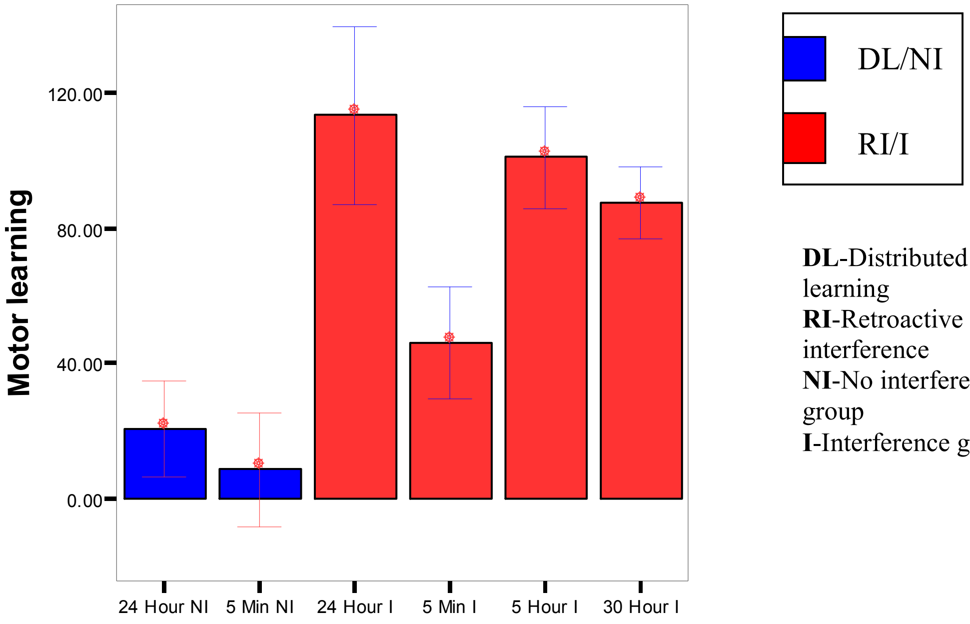


DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 13

Figure 13: Sequence knowledge consolidation is measured by subtracting the sequence knowledge on Session 1 from Sequence knowledge on Session 2 for each of the six groups in Experiments 1. Sequence knowledge on Session 1 (SK1) is measured by taking the RT differences between the average of Block 4 and 6 of Session 1 (Block 4 and 6) and Block 5 of Session 1 (Block 5) (Refer to Figure 6). Sequence knowledge on Session 2 (SK2) is measured by taking the RT differences between the average of Block 4 and 6 of Session 2 (Block 10 and 12) and Block 5 of Session 2 (Block 11). Consolidation of sequence knowledge is measured by subtracting SK1 from SK2. The blue bars show performance of the four interference groups. The red bars show the performance of the two No-Interference groups

Experiment 1: The Motor Learning Effect Across Both Sessions

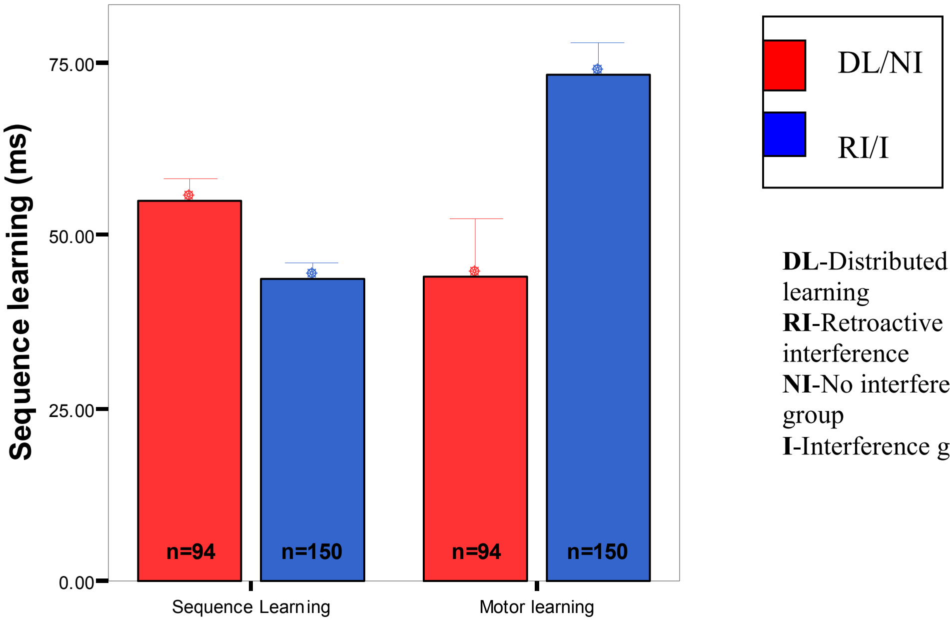


DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 14

Figure 14: Motor skill across both sessions (See Figure 10) is presented separately for each of the six groups in Experiment 1. Motor skill is measured by taking the RT differences between the average of Block 1 of the first session (Block 1) and Block 5 of the second session (Block 11 in Figure 6). The red bars show the performance of the four interference groups. The blue bars show the performance of the two No-Interference groups.

Experiment 2: The Effect of Interference on Sequence Knowledge and Motor Skill



DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 15

Figure 15: Two measures--motor skill and sequence knowledge-- are plotted separately for the Interference and the No-Interference groups. Motor skill was measured by subtracting the reaction times on the 3rd Block of Session 2 (Block 5 in Figure 18) from the first block of Session 1 (Block 1 in Figure 18). Sequence knowledge was measured by taking the RT differences between the average of Block 2 and 4 of Session 2 (Blocks 4 and 6 in Figure 18) and Block 3 of Session 2 (Block 5 in Figure 18). The red bars show the combined performance of the four interference groups. The blue bars show the combined performance of the two No-Interference groups.

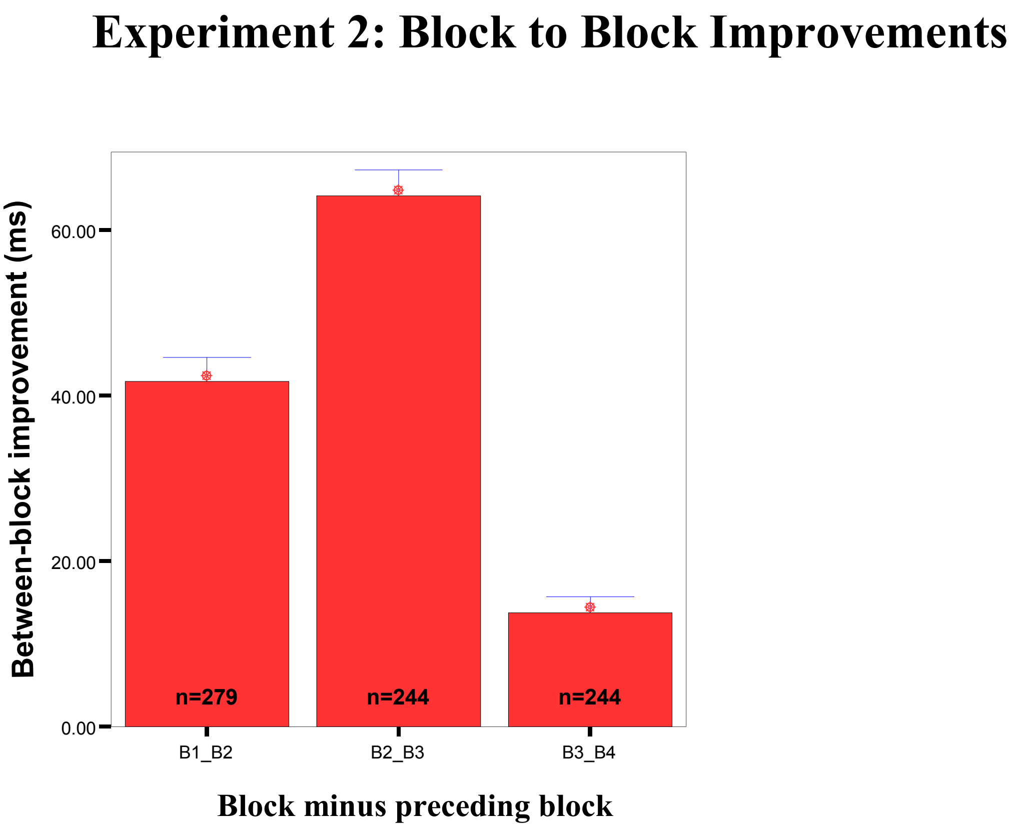
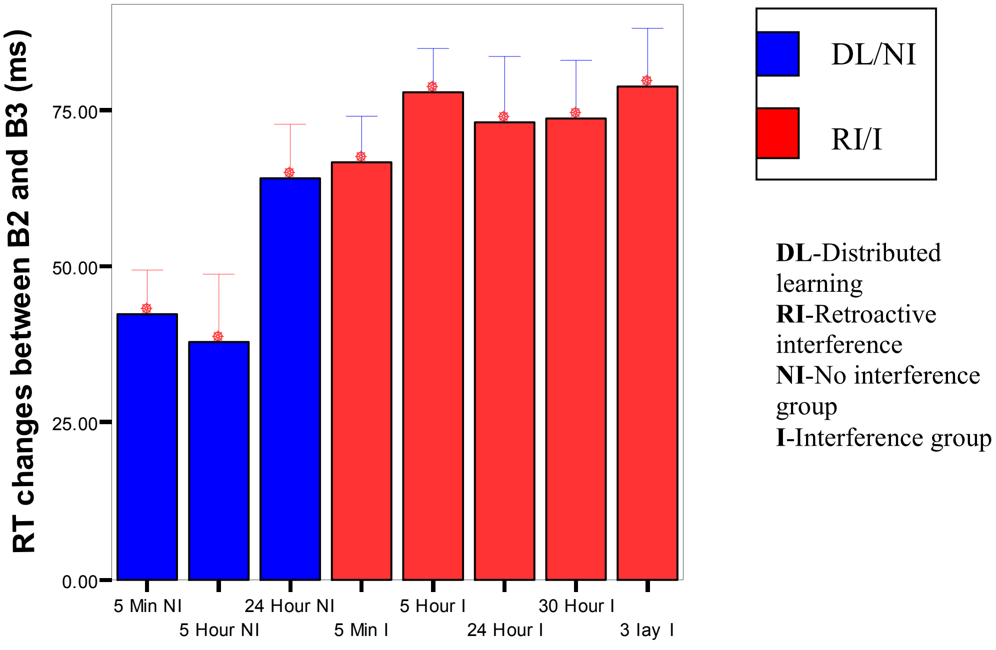


Figure 16: Reaction time differences between the first four consecutive blocks of Experiment 2 (refer to Figure 18). The first two blocks are from the first session and the second two blocks are from the second session. B2_B3 shows RT differences between the last block of session one and the first block of Session 2. The combined performance of all nine groups from the second experiment, including all the Interference and the No-Interference groups, are presented here. For the data that plots the RT differences between Block 1 and Block 2 (B1_B2) the control group is also included, hence N= 279 in the condition. Data from Figure 18 was used as the starting point for this graph.

Experiments 2: Improvement From Last Block of Session 1 to First Block of Session 2



DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 17

Figure 17: Reaction time differences between the last block of Session 1 and the first block of Session 2 (refer to Figure 18). This difference is presented as a separate bar for each of the nine conditions in the study. The No-Interference groups are blue and the Interference groups are red.

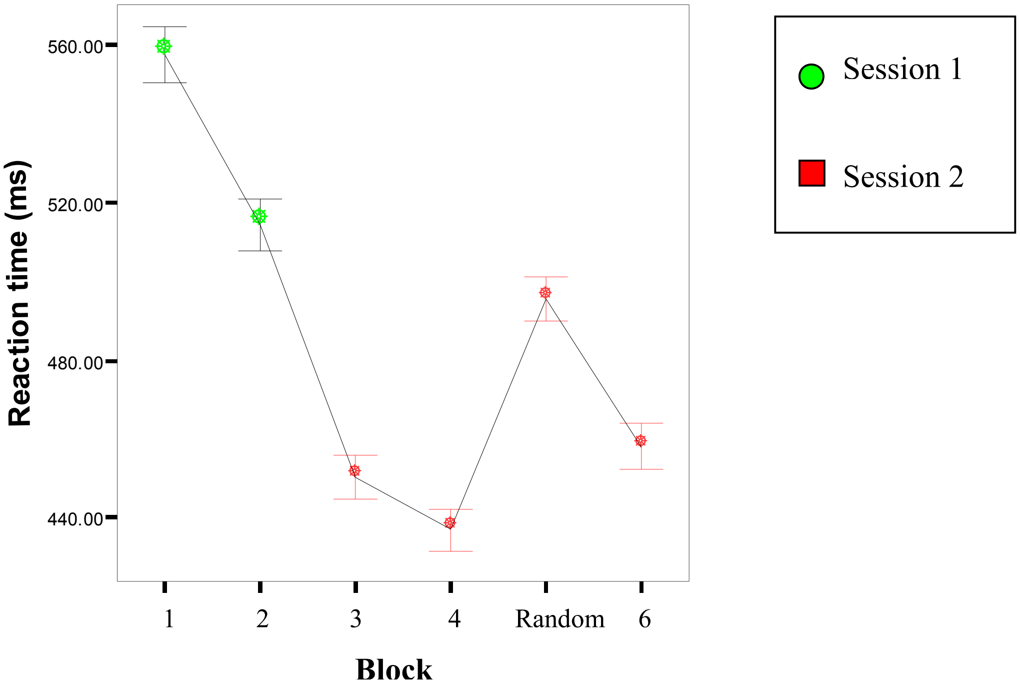
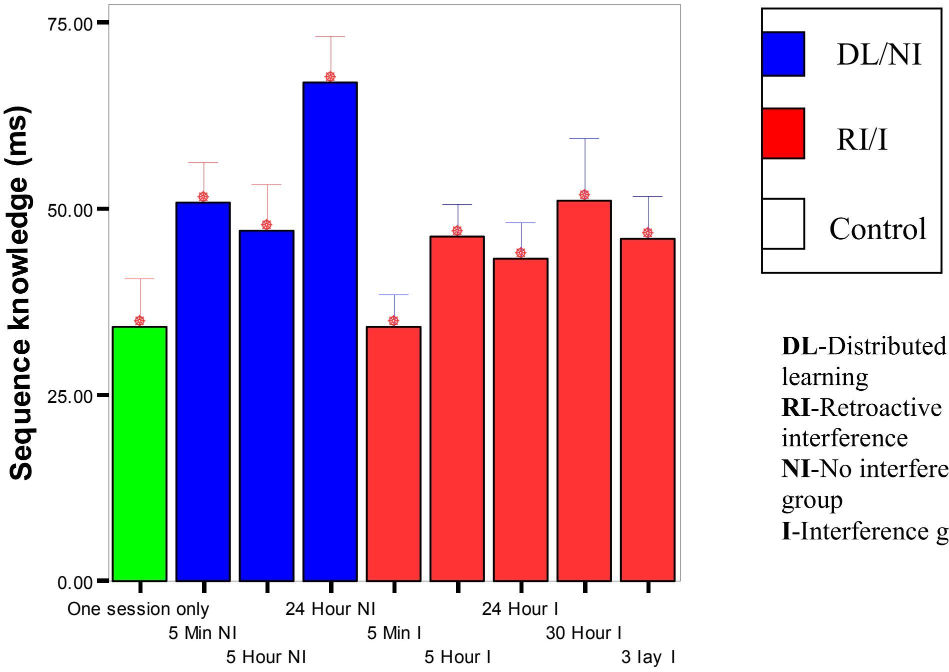

Experiment 2: Session 1 and Session 2

Figure 18: Combined reaction time performance of 9 groups of subjects (N = 244) on six blocks of the SRT task. Medians were calculated for each of the seven repetitions of a sequence within each block. The means of the medians on each block were obtained for each subject. The average of all subjects for each block is plotted on the graph. The first two error bars (green) represent RTs from the first SRT session. The last four error bars (red) represent the RTs from the second session. Blocks 5 is the transfer block where targets do not follow a repeated pattern. On this block targets are presented in a semi-random fashion.

Experiment 2: Sequence knowledge on the Second Session



DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 19

Figure 19: Sequence knowledge is presented separately for each of the nine groups of Experiment 2. Sequence knowledge is measured by taking the RT differences between the average of Block 2 and 4 of Session 2 (Blocks 4 and 6 in Figure 18) and Block 3 of Session 2 (Block 5 in Figure 18) see Figure 18. The solid bars show performance of the four interference groups. The blue bars show the performance of the two No-Interference groups. The green bars show the performance of the control group that only participates in one SRT session.

Experiment 2: Session 1 and Session 2 Errors

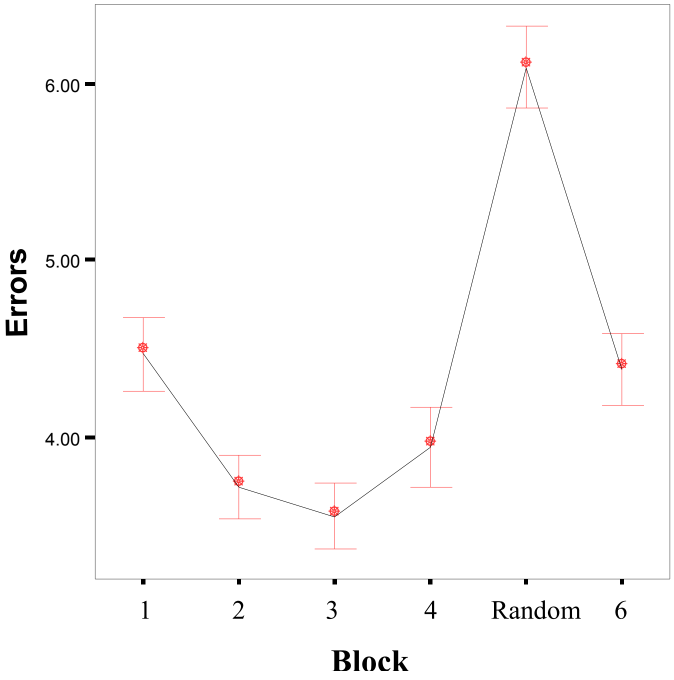
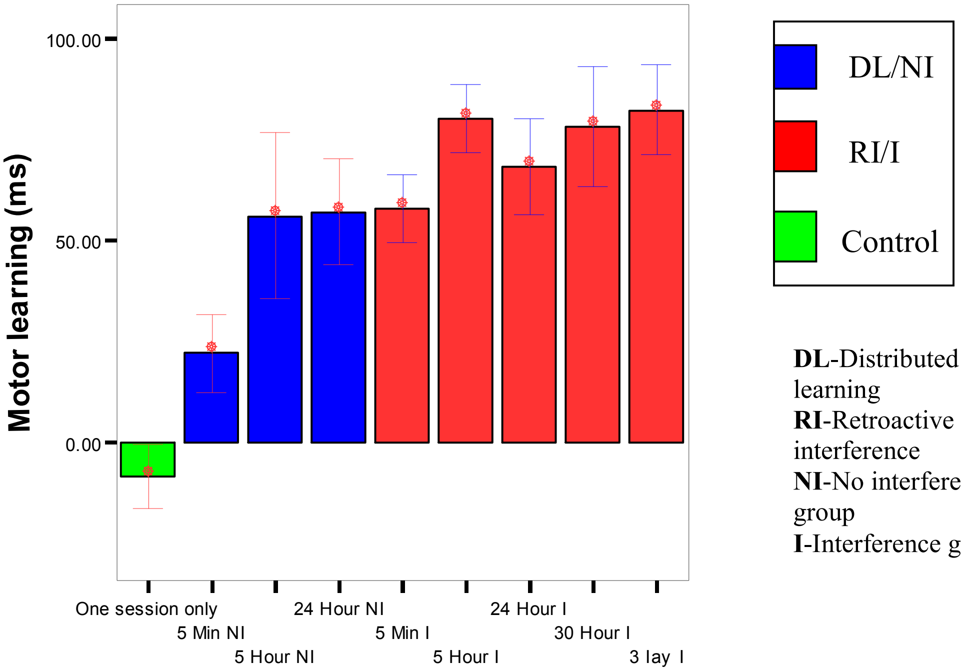


Figure 20: Combined error rates of nine groups of subjects (N = 244) in Experiment 2 on six blocks of the SRT task. Block 5 is a transfer block where targets do not follow a repeated pattern. On this block targets are presented semi-randomly.

Experiment 2: The Motor Learning Effect Across Both Sessions

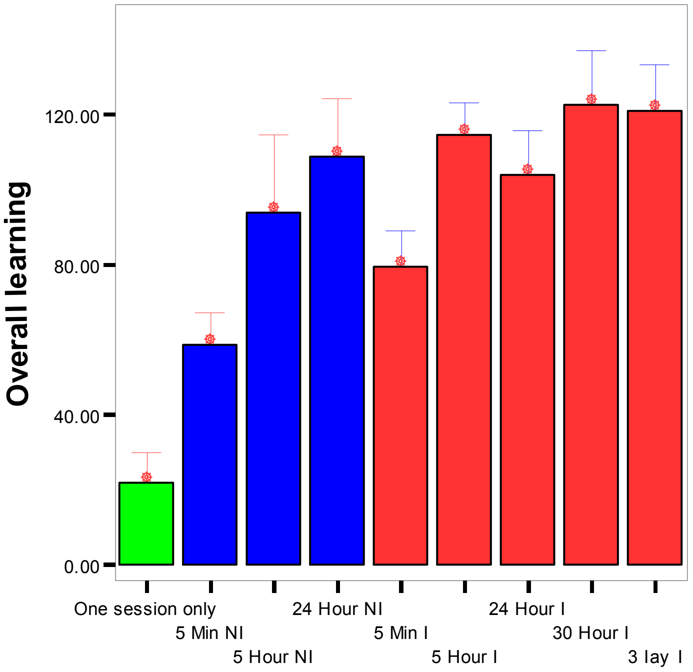


DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 21

Figure 21: Motor skill across both sessions is presented separately for each of the nine groups in Experiment 2. Motor skill is measured by taking the RT differences between the average of Block 1 of the first session (Block 1) and Block 3 of the second session (Block 5 in Figure 18). The red bars show performance of the four interference groups. The blue bars show the performance of the two No-Interference groups. The green bar shows the performance of the control group, whose motor performance is measured immediately after the end of the first session.

Experiment 2: The Overall Learning Effect Across Both Sessions



🟦 DL/NI

🟥 RI/I

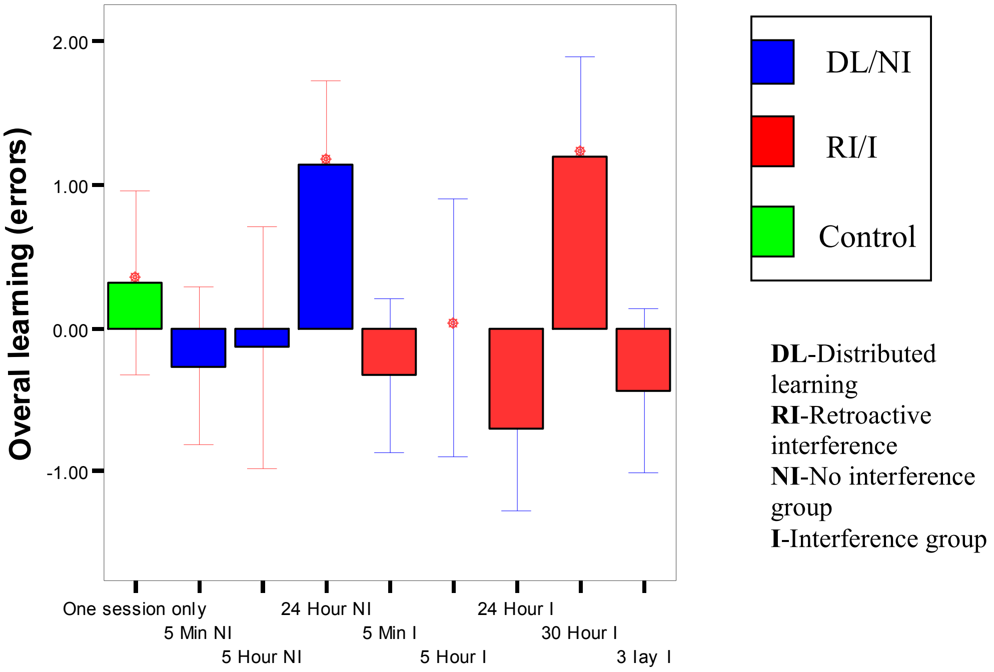
🟩 Control

DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 22

Figure 22: Overall learning across both sessions, for each of the nine groups in Experiment 2. Overall learning is calculated by subtracting reaction times on the last block of the second session from the first block of the first session (Block 1 minus Block 6 in Figure 18). Blue bars represent the No-Interference groups, red bars represent the interference groups and green bars represent the control group.

Experiment 2: The Overall Learning Effect Across Both Sessions as Measured by Errors



DL-Distributed learning
RI-Retroactive interference
NI-No interference group
I-Interference group

Figure 23

Figure 23: Overall learning as measured by error rates for each of the nine groups in Experiment 2. Overall learning is calculated by subtracting the number of error rates on the last block of the second session from the first block of the first session (Block 1 minus Block 6 in Figure 18). Blue bars represent the No-Interference groups, red bars represent the interference groups and green bars represent the control group.

Table 1: A breakdown of the DL and RI effects for four memory systems

	Disrupted by interference	Retroactive Interference gradient	Distributed learning effects
Explicit Declarative memory	Yes	No	Yes-moderate
Implicit Declarative memory (Priming)	No	No	Yes-moderate
Cognitive procedural	Yes	Yes	Yes-strong
Motor procedural	No*	No	Yes-strong

* In the SRT study presented in this experiment motor skill was not disrupted by secondary material. However it is possible that other tasks will interfere with motor skill in the SRT and other tasks.

Table 2: The time course and hypothesized brain regions involved in memory consolidation of four memory systems.

Consolidation:	**Minutes**	**Hours**	**Days**	**Sleep**	**Brain region**
Explicit Declarative memory	DL*: No	DL: Possibly	DL: Yes	Yes	Hippocampus
	RIG: NA	RIG: NA	RIG: NA		
Implicit Declarative memory (Priming)	DL: No	DL: Possibly	DL: Yes	Yes	Distributed/None hippocampal
	RIG: NA	RIG: NA	RIG: NA		
Cognitive procedural	**DL: No**	**DL: NO**	**DL: Yes**	Yes	Prefrontal cortex/ None hippocampal
	RIG: No	**RIG Yes**	**RIG: No**		
Motor procedural	**DL: Yes**	**DL: Yes**	**DL: No**	No	Basal Ganglia/ None hippocampal
	RIG: NA	**RIG: NA**	**RIG: NA**		

DL—Distributed learning effects
RIG—Retroactive interference gradient
Bold entries are based directly on the experimental findings presented in this paper. All other entries are based on the literature review provided in this paper.

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