Targeted memory reactivation, errors, and sleep-dependent memory consolidation: Implications for off-line motor learning

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Abstract

Memory consolidation benefits from sleep and is fundamental for motor learning. However, sleep-dependent consolidation occurs for a range of motor memories, some of which may be associated with successful practice trials and some of which may be associated with unsuccessful practice trials, or errors. Consequently, the aim of this thesis was to investigate whether it is possible to enhance sleep-dependent consolidation rates by constraining the learning environment in order to regulate errors during practice.

Chapter 1 reviews literature relevant to this question. Chapter Two presents an experiment in which we investigated whether sleep-dependent consolidation is likely to result in a higher rate of learning when many successful trials occur at the end of practice compared to when many unsuccessful practice trials occur at the end of practice. Results showed that the Successful-trials group displayed significant improvements in performance following a night of sleep, whereas the Unsuccessful-trials group did not. We concluded that sleep resulted in better learning in the successful trials group than the unsuccessful trials group because memories of more successful trials and fewer unsuccessful trials consolidated. A serial-position effect may explain these findings; however, more work is needed.

Chapter Three presents a follow-up experiment in which we used the same apparatus and protocol as in Chapter Two. However, we incorporated targeted memory reactivation to promote greater off-line consolidation of successful trials in the successful trials group, and of unsuccessful trials in the unsuccessful trials group. Results showed that both groups displayed significant improvements in performance following a night of sleep. We concluded

that targeted memory reactivation may have augmented consolidation of successful trials at the expense of unsuccessful trials, but more work is necessary. The role of dopamine in memory consolidation was discussed.

The results of this thesis provide some support for the premise that it is possible to enhance sleep-dependent consolidation rates by constraining the learning environment in order to regulate errors during practice. Theoretical and practical implications of the findings are discussed in Chapter Four.

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They say “it takes a village to raise a child” – it has taken more than a village to get me here. To an extent, I’m not meant to be here, let alone finishing a Master’s degree. To my support village, thank you all for giving me the skills and opportunity to leave Porirua so that I didn’t become another statistic, as most thought I would. This is to breaking the cycle!

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Thesis Organisation

This thesis consists of four chapters. Chapter One provides a review of relevant literature, which provides the reader with background knowledge of sleep and memory consolidation processes, motor learning, and targeted memory reactivation. Current limitations and gaps in sleep consolidation and targeted memory reactivation research are highlighted. Chapters Two and Three present original research that investigates whether it is possible to enhance off-line learning rates by constraining the learning environment in order to regulate errors during practice. Finally, Chapter Four provides a conclusion based on the findings of Chapters Two and Three, outlines identified limitations, and provides direction for future research.

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Chapter One

Literature Review

1.1 Memory

Memory is a complex component of human function in which various neural structures and systems intricately interact to facilitate the learning process. Memory is defined by the Oxford English Dictionary (2022) as "the action of remembering; recollection, [or] remembrance." Zlotnik and Vansintjan (2019) suggest that popular culture sees memory as "some kind of physical thing that is stored in the brain; a subjective, personal experience that we can recall at will" (p. 1). The American Psychological Association (2022) defines memory as "the ability to retain information or a representation of past experience, based on the mental processes of learning or encoding, retention across some interval of time, and retrieval or reactivation of the memory" (para. 1). These definitions suggest that human memory is more than just 'remembering'… rather, memory is a range of mental processes that culminate in the storage of knowledge that later influences, or has potential to influence, behaviour. Consequently, there are many and varying theories and opinions about how memory operates (i.e., systems and mechanisms), with debates raging across the decades.

1.1.1 Brief History

Early debates about memory systems revolved around whether there was one or multiple memory systems (Baddeley, 2007). Prior to the early 1950s, popular belief was that there was a single memory system, in which learning was the formation of associations that eventually become independent of the hippocampus (Baddeley, 2007; Zlotnik & Vansintjan, 2019). A

two-store memory system was popularised by Donald Hebb who suggested that short-term memory was dependent on electrical activity in the brain, but long-term memory was a function of more durable neurochemical changes (Amtul & Rahman, 2015; Baddeley, 2007; Furley & Memmert, 2010; Fuster, 2006; Horwitz, 2003). Additional support for the two-store memory system came when Scoville and Milner (1957) found that patients suffered from varying degrees of retrograde amnesia following bilateral medial temporal-lobe resection of hippocampal structures. These patients were unable to retain new perceptual memories over a minute-long period; however, they were able to recall memories from previous months (Baddeley, 2007; Bennet & Hacker, 2008; Scoville & Milner, 1957; Squire, 2009), illustrating that there is more than one kind of memory responsible for learning.

1.1.2 Modal Model of Memory

Following on the findings of Scoville and Milner (1957), and consistent with the popularity of the two-store system amongst psychologists, Atkinson and Shiffrin (1968) developed the influential *Modal Model.* The *Modal Model* comprises of three parallel components of memory: sensory memory, short-term memory, and long-term memory.

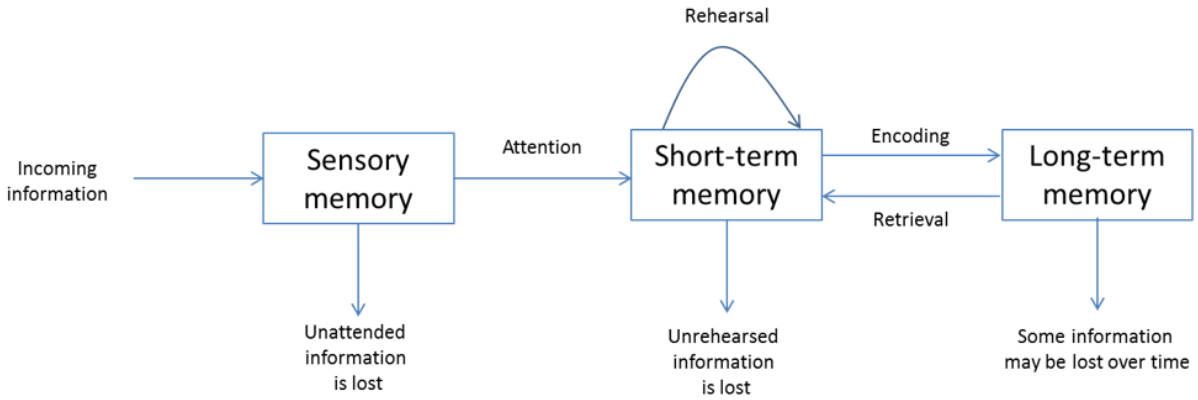

Figure 1.1 *Atkinson and Shiffrin's (1968) Modal Model of Memory.*

Sensory memory is a temporary store where sensory information received by the body (i.e., auditory, visual, or haptic) awaits processing and transferral into the short-term memory, henceforth referred to as working memory (WM) –Baddeley and Hitch (1974) proposed that short-term memory is a form of working memory that actively holds and manipulates sensory information, which can be maintained indefinitely through rehearsal, or consolidated into long-term memory for future retrieval (Baddeley, 2007; Shiffrin & Atkinson, 1969). However, if sensory information is not tended to and transferred into WM, it is ultimately forgotten (Atkinson & Shiffrin, 1968; Shiffrin & Atkinson, 1969). Importantly, the amount of information that can be concurrently held in WM is limited (Abernethy et al., 2007), which can lead to information decay (forgetting) if it is not tended to (Shiffrin & Atkinson, 1969). Finally, long-term memory is described as a permanent depository of information (Shiffrin & Atkinson, 1969), organised, and altered through neural processes (Amtul & Rahman, 2015; Bailey et al., 2015; Paller, 2009). As such, memory consolidation refers to a process during which fragile, temporary memories are transformed, encoded, and strengthened/enhanced into more stable and long-lasting structures (Squire et al., 2015; Song, 2009). However, it is important to note that long-term stores have been further disseminated into specific sub-categories.

1.1.3 Types of Long-Term Memory

Long-term memories can be categorised as either *declarative/explicit* or *procedural/implicit* memories, each of which have their respective subsets. Declarative/explicit memories are those that can be consciously called to mind (using WM) and articulated, specifically pertaining to episodic memories (specific events) and semantic memories (general information). Procedural/implicit memories, however, are those of which we are often not consciously aware and cannot articulate. These can include very well learned motor or cognitive tasks, such as riding a bike or doing the times tables, respectively. They can also

include conditioned responses, such as habits (Abernethy et al., 2007; Bennet & Hacker, 2008; Furley & Memmert, 2010; Masters, 1992; Maxwell et al., 2017; Paller, 2009; Paller et al., 2020; Song, 2009; Stickgold, 2005). A key difference between declarative and procedural memories is that the former relies on conscious awareness and WM. Consequently, Song (2009) and others (e.g., Masters, 1992) suggested that the conscious learning of a skill, as stated by traditional motor learning paradigms, poses a paradoxical issue. Traditional motor learning paradigms often are premised on learning skills in a conscious manner (that ultimately becomes unconscious), despite the procedural nature of motor memories (Maxwell et al., 2001; Song, 2009).

1.1.4 Memory Proceduralisation

The paradoxical paradigm that Song (2009) and others referred to is known as *proceduralisation*, whereby declarative/explicit knowledge becomes procedural/implicit knowledge, through rehearsal and consolidation (Masters, 1992; Maxwell et al., 2001). Fitts and Posner (1967) proposed that during learning knowledge accrues and is modified through three stages, a cognitive, an associative and finally an autonomous stage. During the *cognitive* stage, learning is explicit, rules based, makes many demands on WM, and performance is slow and highly variable. During the *associative* stage, learning becomes less explicit and is associated with the development of links between specific stimuli and necessary action responses. WM involvement also decreases during the associative phase compared to the cognitive phase, and performance is more refined. Finally, during the *autonomous* stage performance is implicit and non-verbalizable with little or no WM or cognitive involvement, and performance is smooth, effortless, and fast (Abernethy et al., 2007; Furley & Memmert, 2010; Masters, 1992).

1.2 The Role of Errors in Learning

Typically, numerous errors are committed by individuals as they practice, especially when they are new to a skill or when the skill is complex. The commission of errors can promote explicit learning, as individuals heavily rely on WM to formulate, test, and modify performance hypotheses, based on environmental feedback and task errors or success (e.g., Capio et al., 2013; Capio et al., 2012; Maxwell et al., 2017; Maxwell et al., 2001; Poolton et al., 2005). This results in the accumulation of large amounts of declarative knowledge, of which the performer is explicitly aware. It has been found, however, that committing fewer errors during practice promotes implicit learning, with far less reliance on WM to formulate, test and modify performance hypotheses. When few errors occur during learning individuals are less likely to test and modify hypotheses about their movements (there is little need if performance is without errors). This diminishes the need to consciously correct motor performance (Abernethy et al., 2007; Capio et al., 2017; Capio et al., 2013; Capio et al., 2012; Maxwell et al., 2017; Maxwell et al., 2001; Poolton et al., 2005) and tends to result in the accumulation of knowledge that is more implicit, and of which the performer is less explicitly aware (e.g., Masters, 1992). Additionally, when fewer errors are made, the need to unlearn undesired responses (usually associated with the cognitive and associative stages of learning), is alleviated (Poolton et al., 2005).

One learning paradigm that utilises the manipulation of errors to promote implicit motor learning is 'error-reduced learning', during which the learning environment is constrained to reduce errors and increase the likelihood of successful outcomes by gradually increasing task difficulty (e.g., Maxwell et al., 2001). In some cases, error-reduced learning has been shown to promote more effective learning compared to traditional approaches (e.g.,

Capio et al., 2013), but to date the role of errors in motor memory consolidation has not been investigated.

1.3 Neural Processes of Memory Consolidation

Consolidation systems are complex, involving many cognitive components. Explicit/declarative/short-term memories are stored by structures such as the hippocampus and medial temporal lobe, while implicit/procedural/long-term memories are stored by the cerebellum, striatum, and/or amygdala (Amtul & Rahman, 2015; Schönauer & Gais, 2017). Although stored separately, both memory systems are consolidated through interconnected neuronal networks utilising cortico-cortical communication (Fuster, 2006; Horwitz, 2003; Roland et al., 2014). Cortico-cortical communication refers to excitatory/stimulatory neurons in one cortical area sending a sequence of action potentials to target neurons in another cortical area (Roland et al., 2014).

Neurons are cellular structures that form the nervous system, comprised of dendrites (receptors) and axons (transmitter, responsible for action potential generation), both connected to the cell body (Woodruff, 2019). Neurons send and receive signals that enable bodily functions, such as movement, senses, and memory (Queensland Brain Institute, 2018). Action potentials are the electrophysiological signals emitted from a neuron's axon when an 'activation threshold' is exceeded in the neuron's body by stimuli received from the pre-synaptic neuronal axon (Amtul & Rahman, 2015).

Neural synapses are the junction between the axon head of one neuron and the dendrite receptor of another, through which neurons communicate (Queensland Brain Institute, 2017). Synaptic plasticity, changes in synaptic molecular and structural makeup, underlies memory consolidation (Fuster, 2006; Amtul & Rahmnan, 2015; Bailey et al., 2015).

Synapses accumulate, encode, and retrieve cognitive information (i.e., memory) through neuronal interactions (Amtul & Rahman, 2015; Roland et al., 2014).

1.3.1 Neural Plasticity

Long-term synaptic plasticity suggests that when interconnected neurons and neuronal groups are simultaneously stimulated, they will become more strongly interconnected. Namely, each time a specific thought or movement is repeated, the strength of neuronal groups increases, leading to long-term synaptic changes; that is, memory consolidation (Amtul & Rahman, 2015; Fuster, 2006). Moreover, these long-term synaptic changes, and resultingly memory consolidation, are shown to be sleep-dependent processes (Blischke et al., 2008; Feld & Born, 2015; Kempler & Richmond, 2012; Schönauer & Gais, 2017; Stickgold, 2005; Walker et al., 2003; Walker et al., 2005).

1.4 Sleep Stages

Sleep-dependent consolidation has been shown to occur during all sleep stages, excluding N1 (Stickgold, 2005). Over a night of sleep, there are four sleep stages that progress in a cyclical fashion, comprised of three stages of non-rapid eye-movement sleep (NREM), and one stage of rapid eye-movement sleep (REM). Stage one sleep (N1) is the transitionary stage between wakefulness and sleep where body and brain activities begin to decrease (i.e., breathing, heart rate, and muscle activity). Bodily movements are then further decreased during stage two (N2) sleep, with oscillatory activity spikes – sleep spindles – suppressing the perception of external stimuli (i.e., making it harder to be woken up). Sleep spindles are short spikes of electrophysiological activity in the brain, characterized in humans by 11- to 15-Hz oscillations lasting 0.5–3 s. Sleep spindles are responsible for the inability to perceive and respond to external stimulus during N2 and N3 sleep. Additionally, the rhythmic appearance of sleep

spindles during NREM sleep, enables for the aforementioned periods of sensory suppression to be interleaved with periods of low-level sensory reception (Ferini-Strambi et al., 2013; Laventure et al., 2016; Laventure et al., 2018; Schönauer & Pohlchen, 2018). Stages three sleep (N3) is described as slow wave sleep (deep sleep), believed to be restorative sleep, during which bodily recovery and growth are maximised. Bodily functions are also at their lowest level of intensity during N3 sleep. Finally, during REM sleep, brain activity increases to a level that is close to the level of activity during wakefulness, and eye movements increase despite all other muscles remaining in paralysis (Ackermann & Rasch, 2014; Frazer et al., 2021; Siengsukon & Boyd, 2009; Stickgold, 2005; Stickgold & Walker, 2007; Suni, 2020).

1.5 Off-line Enhancement

Off-line enhancement of knowledge acquired during the preceding period of wake occurs during sleep; it is a process during which memories are stabilised or enhanced over time without additional practice (Al-Sharman & Siengsukon, 2013). Short naps have also been shown to promote off-line enhancement (Genzel et al., 2012). Additionally, these enhancements have been shown to occur preferentially for procedural memories during REM sleep, and declarative memories during NREM sleep (Ackermann & Rasch, 2014; Diekelmann et al., 2009; Ferini-Strambi et al., 2013; Ficca & Salzarulo, 2004; Ruch et al., 2012; Siengsukon & Boyd, 2009). This indicates that, various types of memories consolidate during sleep which could affect motor learning efficiency. Consequently, targeted memory reactivation could be used to further enhance the off-line enhancement process, by facilitating the consolidation of specific memories (Furley & Memmert, 2010; Gao et al., 2020; Hu et al., 2015; Johnson et al., 2019; Johnson et al., 2020; Wang et al., 2019).

1.6 Targeted Memory Reactivation

Targeted memory reactivation (TMR) is a tool used to specifically reactivate acquired memories during sleep, and is believed to tap into, and upcycle, normal consolidation mechanisms that require the repeated replay of memories during sleep (Hu et al., 2020; Lewis & Bendor, 2019). Previous studies that have investigated TMR and its effects on motor learning typically replay sensory cues during N2 or N3 sleep (Göldi & Rasch, 2019; Hu et al., 2020; Lewis & Bendor, 2019). The reason for this is that sleep spindles are prominent during these stages, which is thought to facilitate the reception of sensory cues during sleep as there are still low levels of sensory responsiveness, whilst minimising the risk of arousal (Schönauer & Pöhlchen, 2018).

TMR is applied by pairing task performance with a specific sensory cue (usually auditory or olfactory) at the time of initial learning, then replaying the same cue again during sleep (Antony et al., 2012; Göldi & Rasch, 2019; Hu et al., 2020; Johnson et al., 2020; Lewis & Bendor, 2019). This reactivation benefits memory consolidation, via off-line enhancement, by reactivating neural traces formed by newly acquired information from the preceding wakefulness period. Consequently, the neural pathways associated with the reactivated memory will be strengthened, because the interconnected neurons and neuronal groups are simultaneously stimulated via the external cue. Therefore, becoming more strongly interconnected as stipulated by the principle of long-term synaptic plasticity (Amtul & Rahman, 2014; Feld & Born, 2015).

1.6.1 Previous TMR Studies

Rasch et al. (2007) first explored TMR by conducting two identical experiments using a finger-tapping task and a spatial location task. An olfactory stimulus was presented during learning,

and re-presented during either NREM-3 sleep, REM sleep, or waking. The findings from their experiments showed that spatial recall only significantly improved in the group where the olfactory stimulus was applied during both learning and NREM-3 sleep. Since Rasch et al. (2007) first identified that TMR could enhance off-line learning, many studies have explored the beneficial use of TMR for a range of tasks. For example, Gao et al. (2020) used TMR to elicit significant improvements in educational content retention, while Johnson et al. (2021) used TMR to improve motor function of a throwing task in post-stroke rehabilitation.

TMR has been found to benefit various processes, such as linguistic learning (e.g., Göldi & Rasch, 2019), emotional and attitudinal habits (e.g., Ai et al., 2015; Feld & Born, 2015; Simon et al., 2018), and problem solving (Sanders et al., 2019). Regarding motor learning, TMR has been found to improve various skills such as sequential finger tapping (e.g., Blischke et al., 2008; Salfi et al., 2019; Schönauer et al., 2014; Walker et al., 2003), reaction time (e.g., Cousins et al., 2014; Cousins et al., 2016; Koopman et al., 2020; Rakowska et al., 2021; Siengsukon & Al-Sharman, 2011), dance sequences (Genzel et al., 2012), piano playing (Antony et al., 2012), throwing accuracy (e.g., Johnson et al., 2019; Johnson et al., 2020; Johnson et al., 2021), myoelectric arm control (Cheng et al., 2021), and walking gait (e.g., Al-Sharman & Siengsukon, 2013; Benoit et al., 2014; Rochester et al., 2010).

1.6.2 Literature Gaps

A meta-analysis conducted by Hu et al. (2020) found that TMR research has only begun to emerge in the last decade, therefore it is a relatively new research area. As such, the field of research utilising TMR is bound to grow rapidly over the coming years; and while TMR has implications for learning and memory paradigms, many gaps are present due to the recent emergence of the research area. For example, to date, only one TMR study has not been

conducted under lab supervised sleep. Therefore, there is the potential to investigate whether at-home TMR application, without the assistance of polysomnography, could facilitate learning outside of a lab setting.

Additionally, research investigating the effect of TMR on motor learning has only been used to promote the proceduralisation of declarative motor skills. Interestingly, no TMR studies have investigated whether memories of successful of unsuccessful performance can be selectively reactivated to promote rapid learning. As such, the research conducted in this thesis will aim to use TMR in an at-home setting to selectively reactivate successful or unsuccessful performance memories of a motor task.

Chapter Two

Motor errors, sleep consolidation and the recency effect: Evidence for a beneficial off-line learning effect when fewer errors occur during the final stages of practice.

2.1 Abstract

Memory consolidation benefits from sleep and is fundamental for motor learning. However, sleep-dependent consolidation occurs for a range of motor memories, some of which may be associated with successful practice trials and some of which may be associated with unsuccessful practice trials, or errors. This experiment investigated whether sleep-dependent consolidation is likely to result in a higher rate of learning when many successful trials occur at the end of practice compared to when many unsuccessful practice trials occur at the end of practice. Two groups of participants practiced an aiming task in which target size was manipulated so that they committed the same number of successful and unsuccessful trials over the entirety of practice, but one group ended with many successful trials and one group ended with many unsuccessful trials. Results showed that the successful trials group displayed significant improvements in performance following a night of sleep, whereas the unsuccessful trials group did not. We concluded that sleep resulted in better learning in the successful trials group than the unsuccessful trials group because memories of more successful trials and fewer unsuccessful trials consolidated. A serial-position effect may explain these findings; however, more work is needed.

Keywords: Off-line learning, error-reduced learning, error-strewn learning, shuffleboard.

2.2 Introduction

Motor learning is a lifelong process that is deeply interconnected with various aspects of memory. For skills and movements to be learnt, memory traces associated with their performance need to be consolidated. Memory consolidation is a process during which memories become organised and stabilised into permanent, long-term structures (Bailey et al., 2015; Squire et al., 2015; Stickgold, 2005; Witkowski et al., 2021). Models of memory suggest that consolidation occurs when information stored in a short-term store is encoded and transferred into a long-term store. For example, Atkinson and Shiffrin (1968) proposed a modal model of memory, which comprises of three parallel components: the sensory input, a short-term store, and a long-term store. The relationship between sensory input and short-term store is one-way, with sensory information only being transferred from sensory input to the short-term store. However, the short-term store and long-term store interact, with both systems working in tandem to consolidate, store, and retrieve memories (Baddeley, 2007; Shiffrin & Atkinson, 1969). Short-term memory storage is also referred to as "working memory" because sensory information is held in an active state that is available for rapid recall and manipulation (Baddeley, 2015; Buszard et al., 2017).

There is overwhelming consensus that sleep has a beneficial effect on memory consolidation processes (e.g., Diekelmann et al., 2009; Pereira & Lewis, 2020; Walker et al., 2005; Wilson et al., 2012), which results in off-line learning. Off-line learning is a process during which memories are stabilised or enhanced over time without additional practice (Al-Sharman & Siengsukon, 2013; Genzel et al., 2012). Evidence suggests that motor learning benefits from off-line learning, with performance enhanced following sleep compared to similar periods of wakefulness (Al-Sharman & Siengsukon, 2013; Genzel et al., 2012; Kempler & Richmond, 2012; Malangre et al., 2014; Siengsukon & Al-Sharman, 2011). For example, Al-

Sharman & Siengsukon (2013) showed that only participants who slept following initial practice showed off-line enhancement of a novel walking task, when compared to participants who did not sleep.

The *dual-process hypothesis* postulates that rapid eye-movement (REM) sleep preferentially benefits the consolidation of procedural memories, and non-rapid eye-movement (NREM) sleep benefits the consolidation of declarative memories (Ackermann & Rasch, 2014; Diekelmann et al., 2009; Ferini-Strambi et al., 2013; Ficca & Salzarulo, 2004; Ruch et al., 2012; Siengsukon & Boyd, 2009). Declarative memories are those that can be consciously called to mind and articulated – specifically, they are associated with episodic memories (specific events) and semantic memories (general information). Procedural memories, however, are those that cannot be consciously called to mind or articulated, such as well-practiced (motor) tasks, or ingrained habits (Abernethy et al., 2007; Bennet & Hacker, 2008; Furley & Memmert, 2010; Masters, 1992; Maxwell et al., 2017; Paller, 2009; Paller et al., 2020; Song, 2009; Stickgold, 2005).

Interestingly, the dual-process hypothesis implies that various types of memories consolidate during sleep, as particular sleep stages consolidate different memories. However, it is unclear in the literature whether memories of both successful and unsuccessful performance during practice consolidate during sleep, or if there is preferential consolidation of specific memories associated with success (or failure). If memories of successful and unsuccessful performance both consolidate, this could potentially slow the rate of off-line learning that occurs, or even cause worse performance. In particular, novices may be susceptible to such problems because typically they make many unsuccessful practice attempts when first practicing a novel task. Consequently, this study aimed to investigate

whether it is possible to enhance off-line learning rates by constraining the learning environment in order to regulate errors during practice.

To achieve this, we exploited a paradigm that previously has been utilised in the implicit motor learning literature to control the number of errors that occur during practice (e.g., Masters et al., 2019; Masters, 1992). The paradigm constrains the learning environment (often by altering the size or distance of the target) in order to create incremental changes in the difficulty of the motor task. By graduating incrementally from low difficulty to high difficulty, it has been shown that error-reduced learning occurs; whereas by graduating incrementally from high difficulty to low difficulty it has been shown that error-strewn learning occurs (Capio et al., 2013; El-Kishawi et al., 2021; Maxwell et al., 2017; Ownsworth et al., 2017; Wilson & Fish, 2017). Error-strewn learning is consistent with the traditional approach to learning, during which many movement errors occur and efforts are made to correct the movement errors until the desired outcome is achieved (Abernethy et al., 2007; Capio et al., 2017; Capio et al., 2013; Capio et al., 2012; Maxwell et al., 2017; Maxwell et al., 2001; Poolton et al., 2005). This is thought to culminate in an explicit mode of learning that is characterised by access to much conscious knowledge and rules about how to perform the task. Error-reduced learning, on the other hand, is thought to be more consistent with an implicit mode of learning that is characterised by access to minimal explicit knowledge or rules about how to perform the task. That is, the very high number of successful trials (i.e., minimal number of errors) implies that the desired outcome is being achieved. Therefore, efforts to correct movement errors are far less common, resulting in a less explicit form of motor learning (see Masters et al., 2019), for a recent summary of the implicit motor learning approach).

We argued that by manipulating the number of successful and unsuccessful trials (i.e., errors) during practice of a simple shuffleboard task, we could preferentially influence the number of successful and/or unsuccessful memories that undergo off-line enhancement. Two groups of participants practiced the shuffleboard task for an equivalent number of repetitions (five blocks of 25 repetitions). However, we designed the practice schedule so that the groups committed an equivalent number of errors overall, despite one group of participants completing the final block of repetitions with many successful trials (i.e., very few errors); compared to another group that finished the final block of repetitions with many unsuccessful trials (i.e., many errors). Consistent with the recency effect (e.g., Ebbinghaus, 1913; Greene, 1992; Parkin, 2013), we expected that the most recently completed block of repetitions would be most susceptible to consolidation during sleep. As such, it was expected that participants completing many more successful trials at the end of practice would demonstrate more learning following a night of sleep than participants with many more unsuccessful trials.

2.3 Methods

2.3.1 Participants

Participants (n = 30; 12 females, 18 males; age = 20.37 [SD = 1.35] years) were students at the University of Waikato, who provided informed consent prior to participating. With the help of an online software programme, the participants were randomly allocated to an Unsuccessful-trials group (n = 15) or a Successful-trials group (n = 15). The data for 5 participants was excluded from analysis, because box-plot analysis identified the participants as outliers during the pre-test of performance.

2.3.2 Task

Participants completed a shuffleboard task during two sessions (20-30 mins duration) on consecutive days at the same time (i.e., 24 hours apart). The shuffleboard task required participants to slide a wooden disc (diameter 5cm; height 1cm) towards one of three pre-determined targets at the opposite end of a board (length 180cm; width 45cm; side height 2.5cm). On Day 1, participants completed a pre-test consisting of one block of 25 practice trials in which they attempted to slide the wooden disk to strike a target (a vertical pin, 1mm) that was positioned on the back wall of the board (centred). Participants then completed five blocks of 25 practice trials during which the target size was modified in order to constrain the number of errors that occurred. Three target widths were used (Easy, 33cm; Medium, 20.5cm; Hard, 5.5cm). Order of target size for each block differed for each group. For the Unsuccessful-trial group the order was Medium, Easy, Medium, Medium, Hard. For the Successful-trial group the order was Medium, Hard, Medium, Medium, Easy. On Day 2 (post-sleep), participants completed a retention test consisting of a further block of 25 practice trials in which they attempted to slide the wooden disk to strike the vertical pin (1mm) positioned on the back wall of the board.

2.3.3. Measures

Errors during practice. To quantify the number of errors committed by participants in each group (Unsuccessful-trial, Successful-trial) during the practice session on Day 1, we counted the number of occasions in each block of 25 trials when the disc missed the practice target (Easy, Medium, Hard). A trial in which the disc struck either side of the board was also recorded as a miss, regardless of whether it rebounded on to the target.

Test performance. To quantify performance during the pre-test and the retention test, we examined the number of hits (occasions during each block of trials when the wooden disc struck the vertical pin) and accuracy. ScorePutting software (Neumann & Thomas, 2008) was used to obtain the measure of accuracy using photographs of each trial, from a camera that was placed directly above the target. The output measure "distance left or right" was used as the accuracy measure. The distance left or right is measured as the lateral distance between the disc's final position and the intended target line; running through the centre of the shuffleboard from the disc's origin to the centre target (see figure 2.1). For trials in which the disc caromed off the sideboard before reaching the backboard, an arbitrary maximum distance was specified (22.5 cm) because it was not possible to establish the true lateral error. As a consequence of the potential measurement error inherent in this approach, we therefore used absolute values and calculated median accuracy scores rather than mean accuracy scores.

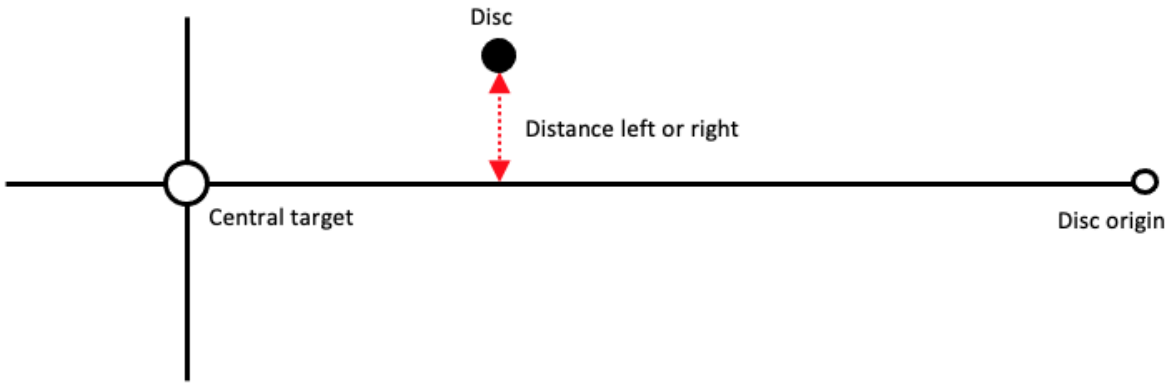

Figure 2.2 *Summary of the distance left or right output measure (Neumann & Thomas, 2008).*

Sleep quality. Quality of sleep was assessed subjectively using the Pittsburgh Sleep Quality Index (PSQI) and a sleep screening questionnaire. Both were administered on Day 2 prior to the beginning of the test session (and following a night of sleep). The PSQI assesses

habitual sleep quality and disturbances over a 1-month period using nineteen self-rated questions. Individual questions generate seven component scores: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction. The sum of scores for these seven components reveals a global score that distinguishes between 'good' and 'bad' sleepers (Buysse et al., 1989). The sleep screening questionnaire provided a self-reported, subjective assessment of the participant's sleep quality during the previous night (i.e., the night between sessions), using a Likert Scale ranging from 1 (very poor sleep) to 5 (very good sleep). The screening questionnaire also assessed pre-sleep activities: caffeine and drug consumption, amount and type of exercise, and sleep disorders.

Actigraph measures. To further quantify sleep, measures of total sleep time (minutes), number of awakenings, and sleep efficiency were retrieved from the Readiband actigraph watch (Fatigue Science, Vancouver, Canada). An awakening was operationalised as any event greater than 5 mins in length during which there was regular movement. Total sleep time was operationalised as the amount of time that participants were asleep between time of initial sleep onset and time of awakening. Finally, sleep efficiency represents how efficient an individual is with their time in bed, operationalised as the total time in bed divided by the total time asleep.

2.3.4 Procedure

Day 1. Participants completed a pre-test of 25 trials during which they attempted to slide the disc as accurately as possible to hit the central target (a vertical pin). They then completed five blocks of 25 practice trials. For the first, third and fourth block of practice trials, participants in both groups shuffled at the medium difficulty target. For the second block of

trials, participants in the Unsuccessful-trial group shuffled at the easy target, whereas participants in the Successful-trial group shuffled at the hard target. The target size switched between groups in the fifth and final block of trials (see Figure 2.2). The result of each trial was verbalised as a "hit" or a "miss" by the research assistant, who also indicated exactly where the disc struck the backboard or the sideboard (if the disc did not strike anywhere, no indication was necessary). The disc's final position or the indication by the research assistant was then photographed for later analysis.

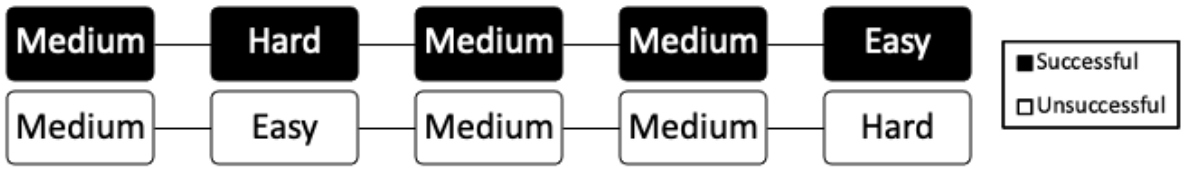

Figure 2.3 *Order of target difficulty level for each group during practice on Day 1. Group 1, Successful Trials; Group 2, Unsuccessful Trials.*

Prior to leaving the laboratory, participants were provided with an actigraph watch (Readiband Model 5; Fatigue Science, Vancouver, Canada), and were instructed that they should not remove the watch unless there was a likelihood that it would get wet (e.g., swimming, showering etc). In order to minimise the influence of external factors on sleep quality, participants were instructed to avoid consuming drugs, coffee, or alcohol for 6 hours prior to going to bed, and to avoid strenuous physical activity for 4 hours prior to going to bed.

Day 2. Participants returned to the laboratory the following day at the same time. Upon arrival, they returned the actigraph (so that sleep data could be downloaded by the experimenter) and completed the PSQI and a sleep screening questionnaire. They then completed a retention test consisting of 25 trials during which they attempted to slide the disc as accurately as possible to hit the central target (a vertical pin).

2.3.5 Statistical Analysis

All analyses were conducted using the Statistical Package for the Social Sciences (SPSS; IBM, New York, USA; version 28). To examine performance during the Pre-test (Day 1) and the Retention Test (Day 2), both the number of hits by participants in each group and median accuracy were subjected to a Group (Unsuccessful-trial/Successful-trial) x Test (Pre-test/Retention-test) repeated measures analysis of variance (RM-ANOVA). Planned comparisons (paired samples, one-tailed t-tests) were used to examine change in performance from the Pre-test to the Retention Test in each group. To examine, the number of errors that occurred during the five blocks of practice trials (Day 1), a Group (Unsuccessful-trial/Successful-trial) x Block (1 to 5) RM-ANOVA was conducted. Planned comparisons (independent samples t tests) were used to examine differences between the groups in each block of trials. A Bonferroni correction (.05/5 tests = .01) was used to adjust for potential Type II errors caused by multiple hypothesis testing.

Independent samples t-tests were used to compare between-group scores for subjective sleep quality, total time asleep, and sleep efficiency. Statistical significance was accepted at $p < 0.05$. One-tailed *p*-values are reported for paired samples t-test analyses, where two-tailed *p*-values are reported for independent sample t-test analyses. Effect sizes are reported as partial eta squared (η_p^2). Partial eta squared effect thresholds are set at 0.01 for small, 0.06 for medium, and 0.14 for large (Lakens, 2013).

2.4 Results

2.4.1. Sleep Measures

Significant differences were not evident between the groups for PSQI score, $t(23) = -1.506$, $p = 0.146$; subjective sleep quality, $t(22) = 0.692$, $p = 0.496$; total time asleep, $t(19) = 0.158$, $p =$

0.876; number of awakenings, t(20) = -0.792, p = 0.438; or sleep efficiency, t(20) = 0.860, p = 0.400. The similarities between these indicators suggests that sleep patterns were not statistically different between the two groups.

Table 2.1 *Descriptive statistics for all sleep measures for both groups.*

	Unsuccessful Trials			Successful Trials		
Measure	*Mean*	*SD*	*Range*	*Mean*	*SD*	*Range*
Subjective Sleep Quality	3.55	0.52	(3 - 4)	3.31	1.03	(1 - 5)
PSQI	5.58	2.57	(2 - 9)	7.00	2.12	(2 - 10)
Sleep Efficiency	83.40	5.60	(75.10 - 93.90)	79.66	13.27	(50.40 - 89.90)
Total Time Asleep	443.50	69.32	(320 - 590)	438.64	71.45	(285 - 515)
Number of Awakenings	4.00	2.28	(0 - 7)	4.91	3.05	(1 - 10)

2.4.2 Practice

The number of errors that occurred during each block of practice trials is shown in Figure 2.3. RM-ANOVA (Group x Practice Block) revealed no main effect of Group, F(1,23) = 0.093, p = 0.763, η_p^2 = 0.004. However, a significant main effect of Block, F(4,92) = 23.909, p < 0.001, η_p^2 = 0.510, and a Group x Block interaction, F(4,92) = 94.942, p < 0.001, η_p^2 = 0.805, were observed. To confirm that our manipulation was effective, we conducted independent samples t-tests between groups for each block of trials. Significant between-group differences were not evident in Block 1, t(23) = 0.125, p = 0.901; Block 3, t(23) = 0.076, p = 0.940; or Block 4, t(23) = -1.219, p = 0.235. Consistent with our expectations, the Successful-trials group committed significantly more errors than the Unsuccessful-trials group in Block 2, t(23) = -12.614, p < 0.001 (15.54 versus 1.75 errors, respectively). Crucially, however, this pattern was reversed in Block 5, with the Successful-trials group committing significantly fewer errors in Block 5 than the Unsuccessful-trials group, t(23) = 13.90, p < 0.001 (0.92 versus 14.33 errors, respectively).

The total number of errors committed by participants in each group during all blocks of practice trials was not statistically different, t(23) = 0.305, *p* = 0.763 (Unsuccessful-trials total errors = 28.08; Successful-trials total errors = 29.38).

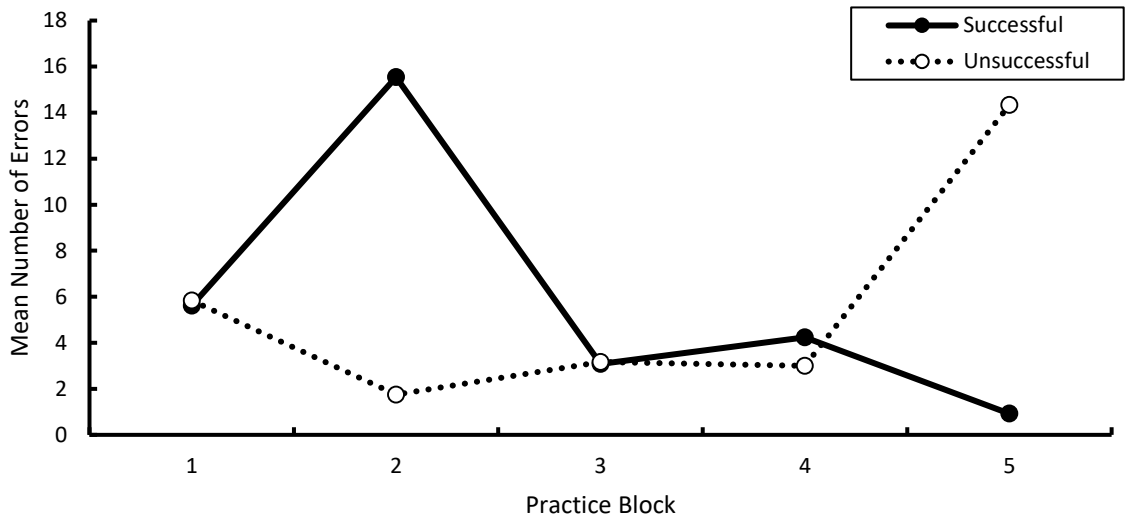

Figure 2.4 *Mean number of errors committed by each group during each practice block.*

2.4.3 Test Performance

Hits. Figure 2.3 illustrates the mean number of hits by each group in the Pre-test and the Retention Test. RM-ANOVA (Group x Test) revealed no significant main effect of Test, F(1,23) = 3.151, *p* = 0.089, $\eta_p^2 = 0.120$, or of Group, F(1,23) = 1.091, *p* = 0.307, $\eta_p^2 = 0.045$. Additionally, a significant Group x Test interaction was not evident, F(1,23) = 1.518 p = 0.230, $\eta_p^2 = 0.062$. Nevertheless, our *a priori* expectation was that the Successful-trials group would demonstrate greater improvement in performance than the Unsuccessful-trials group, so we conducted paired samples t-tests for each group. The Successful-trials group improved significantly from the Pre-test to the Retention Test, t(12) = 2.14, *p* = 0.027; however, the Unsuccessful-trials group did not, t(11) = 0.382, p = 0.355.

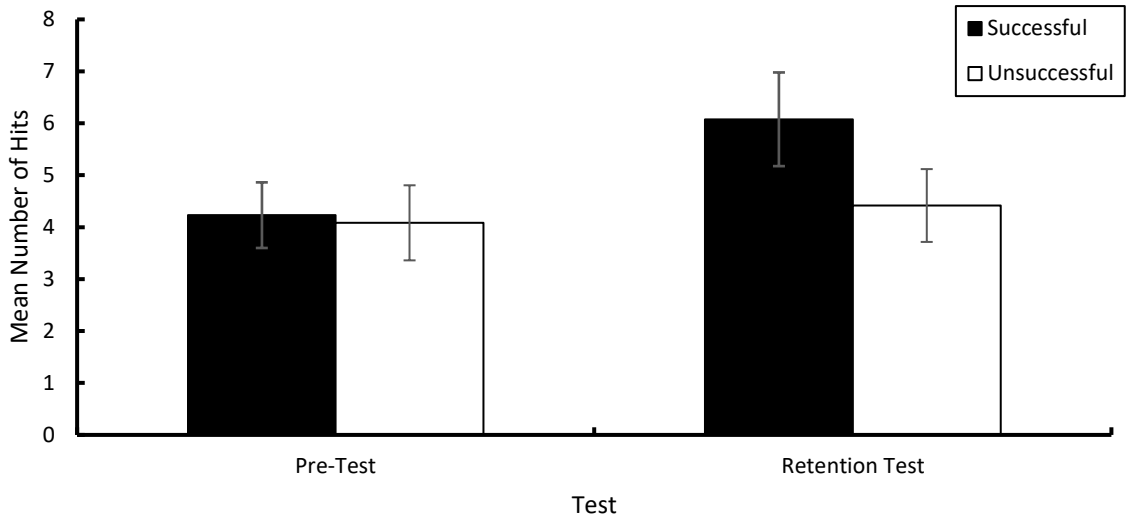

Figure 2.5 *Mean number of hits during the Pre-test and the Retention Test in each group. Error bars represent the standard error of the mean.*

Accuracy. Figure 2.4 illustrates the mean accuracy of each group in the Pre-test and the Retention Test. RM-ANOVA (Group x Test) revealed a significant main effect of Test, $F(1,23) = 10.930$, $p = 0.003$, $\eta_p^2 = 0.322$, but not of Group, $F(1,23) = 0.349$, $p = 0.561$, $\eta_p^2 = 0.015$. A significant Group x Test interaction was not evident, $F(1,23) = 0.892$, $p = 0.355$, $\eta_p^2 = 0.037$. Given our *a priori* expectation that the Successful-trials group would demonstrate greater improvement in performance accuracy than the Unsuccessful-trials group, we conducted paired samples t-tests for each group. The Successful-trials group improved significantly from the Pre-test to the Retention Test, $t(12) = 3.01$, $p = 0.005$; however, the Unsuccessful-trials group did not, $t(11) = 1.67$, $p = 0.061$.

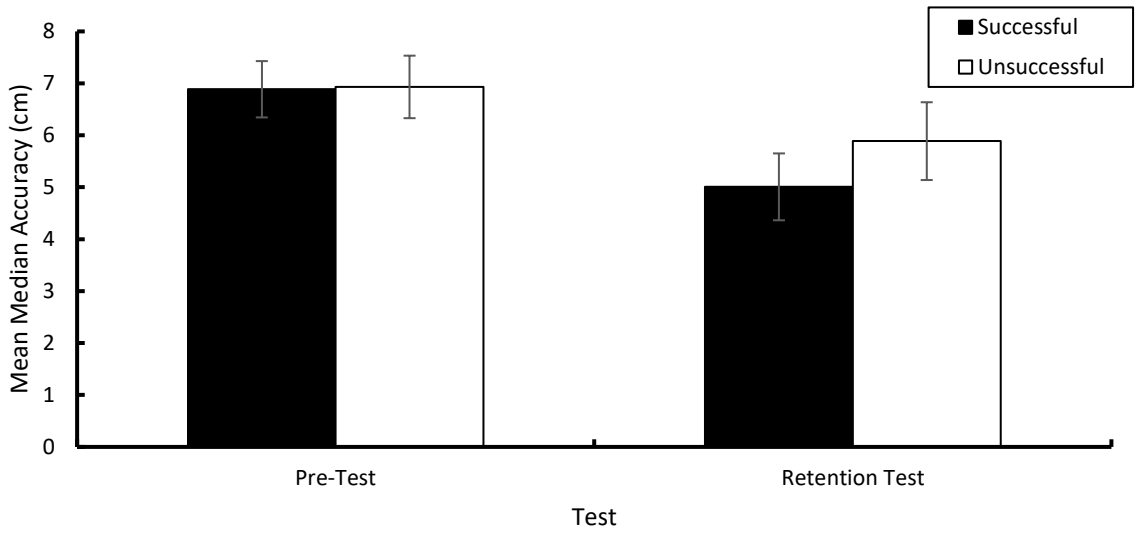

Figure 2.6 *Mean median accuracy during the Pre-test and the Retention Test in each group. Error bars represent the standard error of the mean.*

2.5 Discussion

It is possible that the amount of success and failure that occurs during practice influences the extent to which sleep consolidation results in effective learning. Consolidation of motor memories that primarily represent unsuccessful practice trials may result in less learning than consolidation of motor memories that primarily represent successful trials. Borrowing from previous research that has examined motor learning following error-reduced and error-strewn practice (e.g., Maxwell et al., 2001; Onsworth et al., 2017; Capio et al., 2013; Capio et al., 2017), we counterbalanced the width of targets aimed at during a shuffleboard task in order to manipulate the number of errors that occurred when participants practiced. We succeeded in creating two groups of participants who committed a very similar number of errors throughout the entire practice session, but who ended practice by committing many errors or few errors.

We predicted that consolidation of motor memories primarily associated with successful trials (i.e., few errors) in the final block of practice would result in more learning

following a night of sleep than consolidation of motor memories primarily associated with unsuccessful trials (i.e., many errors). The results indicated some support for our prediction. Participants who completed the final block of trials with few errors displayed significant increases in performance (hits, median accuracy) between the pre-test and the retention test (post-sleep), whereas, participants who completed the final block of trials with many errors displayed non-significant changes in performance.

These findings may be explained by a *serial-position effect, wh*ereby "recall performance is excellent on the last few items (recency effect), good for the first one or two items (primacy effect) and relatively low in between" (Parkin, 2013, p. 81). Consequently, a recency effect in which memories were more salient for the final block of practice trials may have increased the likelihood of consolidation of those trials and thus biased learning in favour of those participants who completed many more successful trials than unsuccessful trials.

However, we also predicted that the Successful-trials group would learn significantly more than the Unsuccessful-trials group, but our results indicate that this was not the case. Consequently, we conducted a follow-up study in which we sought to strengthen the off-line effect associated with consolidation of successful trials in the Successful-trials group and consolidation of unsuccessful trials in the Unuccessful-trials group. We expected that this would magnify the differences between the groups, resulting in greater likelihood that we would observe significant between-group interactions for performance. To do this, we utilised targeted memory reactivation; where we aimed to selectively reactivate successful or unsuccessful performance memories associated with the final block of practice. Targeted memory reactivation (TMR) is a method that uses external cue presentation to generate

paired associations with newly acquired skills. For instance, when a specific sensory cue (e.g., smell, sound etc) is presented during the initial learning of a skill, a paired association is made between the newly acquired information and that specific cue. The external cue is then presented again during sleep to selectively reactivate the neural pathways associated with the paired memory, consequently, strengthening the associated memory (Rasch et al., 2007; Cellini & Capuozzo, 2018). TMR has been used to enhance learning in gross motor skills, such as throwing (Johnson et al., 2019; Johnson et al., 2020) and gait (Benoit et al., 2014), making it plausible that targeted memory reactivation could be used to amplify the between-group interaction we observed in the current study.

2.6 Conclusion

While the results from the experiment presented in Chapter 2 suggest that significant within-group improvements occurred between the pre-test and the retention test when individuals finished practice with few errors compared to many errors, significant between-group interactions were not evident for any of the dependent measures of learning (although moderate to large effect sizes were present). In a second experiment, presented in Chapter 3, we therefore sought to amplify the potential impact of errors on off-line learning by augmenting the sleep consolidation process using targeted memory reactivation.

Chapter Three

Unsupervised targeted memory reactivation promotes increased off-line learning when fewer errors occur late in motor practice.

3.1 Abstract

Memory consolidation benefits from sleep and is fundamental for motor learning. However, sleep-dependent consolidation occurs for a range of motor memories, some of which may be associated with successful practice trials and some of which may be associated with unsuccessful practice trials, or errors. Targeted memory reactivation is a procedure that has been utilised to preferentially reactivate specific memories associated with performance or behaviours when asleep. This experiment investigated whether targeted memory reactivation can be used to increase the likelihood that sleep-dependent consolidation will result in a higher rate of learning when many successful trials occur at the end of practice compared to when many unsuccessful practice trials occur at the end of practice. As in Experiment 1, two groups of participants practiced an aiming task in which target size was manipulated so that they committed the same number of successful and unsuccessful trials over the entirety of practice, but one group ended practice (the final block) with many successful trials and one group ended practice with many unsuccessful trials. During the final block of trials, participants in both groups heard music designed to preferentially reactivate memories associated with successful trials or unsuccessful trials when it was replayed during sleep. Results showed that both groups, Successful-trials and Unuccessful-trials, displayed

improvements in performance following a night of sleep. We concluded that although both the Successful-trials and Unsuccessful-trials group showed improvement, the efficacy of TMR application is in question due to the lack of control groups. The implication of dopamine in memory consolidation, and the sleep disturbance experiences of participants may explain these findings; however, more work is needed.

Keywords: Off-line learning, error-reduced learning, error-strewn learning, shuffleboard.

3.3 Introduction

Motor memory consolidation lays a foundation for human skill development, as it is critical for the learning of all basic movements. During the memory consolidation process, various physical structures (i.e., neurons and other cranial structures) interact to organise and stabilise new memories into permanent, long-term structures (Bailey et al., 2015; Squire et al., 2015; Stickgold, 2005; Witkowski et al., 2021). Neurons are the cellular structures that form the nervous system, comprised of dendrites (receptors) and axons (transmitter, responsible for signal generation), both connected to the neuron cell body (Woodruff, 2019). Neurons send and receive signals that enable functions, such as movement, senses, and memory. Neural synapses are the junction between the axon head of one neuron and the dendrite receptor of another, through which neurons communicate (Queensland Brain Institute, 2017). Synaptic plasticity, changes in synaptic molecular and structural makeup, underlies memory consolidation (Fuster, 2006; Amtul & Rahmnan, 2015; Bailey et al., 2015), because neural synapses accumulate, encode, and retrieve cognitive information (i.e., memory) through neuronal interactions (Amtul & Rahman, 2015; Roland et al., 2014; Amtul & Rahman, 2015; Bailey et al., 2015; Fuster, 2006; Rothschild et al., 2017). Interestingly, the principle of long-term synaptic potentiation stipulates that when interconnected neurons and neuronal groups are simultaneously stimulated, they will become more strongly interconnected (Amtul & Rahman, 2015; Fuster, 2006). In other words, each time a specific thought or movement is repeated, the strength of neuronal groups increases, leading to long-term synaptic changes (i.e., memory consolidation).

The findings from Experiment 1 (Chapter 2) are consistent with the idea that sleep plays an integral part in the memory consolidation processes; however, it remains unclear whether memories of both successful and unsuccessful performance during practice

consolidate during sleep, or if there is preferential consolidation of specific memories associated with success (or failure). While our findings hint that behaviours that occur late in practice may be more strongly associated with consolidation during sleep, there is still no way to know what specific memories consolidate during sleep. However, a recently developed method used to enhance off-line learning could enable us to further investigate whether it is possible to preferentially consolidate memories of successful and/or unsuccessful performance.

Targeted memory reactivation (TMR) is believed to tap into, and upcycle, normal consolidation mechanisms that require the repeated replay of memories during sleep (Lewis & Bendor, 2019; Hu et al., 2020). The application of TMR involves pairing task performance with a specific sensory cue (usually auditory or olfactory) at the time of initial learning, then replaying the same cue again during sleep (Göldi & Rasch, 2019; Hu et al., 2020; Johnson et al., 2019). The replay of a stimulus during sleep is used to reactivate the neural pathways associated with specific memories, strengthening neuronal synaptic pathways for these specific memories as proposed by the principle of long-term potentiation. Various studies have successfully used TMR to improve visuospatial and verbal memories (e.g., Göldi & Rasch, 2019), enhance motor skills (e.g., Genzel et al., 2012; Siengsukon & Al-Sharman, 2011; Johnson et al., 2019; Johnson et al., 2020; Blischke et al., 2008; Walker et al., 2003) and modify implicit social biases (Feld & Born, 2015). For example, Johnson et al. (2019) investigated the effect of TMR on off-line motor learning of a throwing task, by comparing four groups of participants; sleep + TMR, sleep + no TMR, wake + TMR, and wake + no TMR. Participants who slept and received TMR displayed improved throwing accuracy following sleep, indicating that

the TMR has potential to enhance off-line motor learning when compared to traditional off-line learning approaches.

Experiment 1 (Chapter 2) suggested that a final block of practice trials in which few errors occur is preferable to a final block of trials in which many errors occur; however, between-group interactions were not evident for any of the dependent measures of learning, undermining our conviction about our approach. Consequently, we hypothesised that targeted memory reactivation would amplify the potential interaction between the two groups. For participants who committed many errors in the final block of practice, we expected that off-line learning would be non-existent or even negative –because participants learned errors– whereas, for participants who committed many successful trials (few errors) we expected that off-line learning would be dramatic.

We used the identical task (shuffleboard) and design as we used in Experiment 1. That is, two groups of participants practiced the shuffleboard task for an equivalent number of repetitions (five blocks of 25 trials), with the practice schedule designed so that the groups committed an equivalent number of errors overall, despite one group of participants completing the final block of repetitions with many successful trials (i.e., very few errors) and the other group of participants completing the final block of trials with many unsuccessful trials (i.e., very many errors). Unlike Experiment1, however, targeted memory reactivation was applied for both groups during the final block of trials by presenting a musical soundtrack *(River Flows in You*, Yiruma, 2001) . Consistent with the recency effect (e.g., Ebbinghaus, 1913; Parkin, 2013 Greene, 1992), we expected that when the musical soundtrack was replayed continuously throughout sleep, memories of the most recently completed block of trials by each group would be most susceptible to consolidation.

3.4 Methods

3.4.1 Participants

Participants (n = 32; 17 males, 11 females; age = 23.06 [SD = 5.86] years) provided informed consent prior to participation, and were randomly allocated into an Unsuccessful-trials group (n = 16) or a Successful-trials group (n = 16), using an online random number generator. Both groups were exposed to targeted memory reactivation during their final practice block. Two participants had their data excluded from all analyses. One participant withdrew from the study, and the other was excluded because box-plot analysis identified the participant as an outlier based on pre-test performance.

3.4.2 Task

Participants completed a shuffleboard task during two sessions (20-30 minutes duration) on consecutive days at the same time (i.e., 24-hours apart). The shuffleboard task required participants to slide a wooden disc (diameter 5cm; height 1cm) towards one of three pre-determined targets at the opposite end of a board (length 180cm; width 45cm; side height 2.5cm). On Day 1, participants completed a pre-test consisting of one block of 25 practice trials in which they attempted to slide the wooden disk to strike a target (a vertical pin, 1mm) that was positioned on the back wall of the board (centred). Participants then completed five blocks of 25 practice trials during which the target size was modified in order to constrain the number of errors that occurred. Three target widths were used (Easy, 33cm; Medium, 20.5cm; Hard, 5.5cm). Order of target size for each block differed for each group. For the Unsuccessful-trials group the order was Medium, Easy, Medium, Medium, Hard. For the Successful-trials group the order was Medium, Hard, Medium, Medium, Easy. On Day 2 (post-sleep), participants completed a retention test consisting of a further block of 25 practice

trials in which they attempted to slide the wooden disk to strike the vertical pin (1mm) positioned on the back wall of the board.

3.4.3 Memory Reactivation During Sleep

A single classical piano piece, *River Flows in You* (Yiruma, 2001), was used as the external stimulus for TMR application. This piece was chosen due to its distinct melodies, as previous TMR work found that sensory stimuli should be distinct to be paired with learning materials (Donohue & Spencer, 2011). Using Audacity software (version 3.1, Muse Group), the musical piece was put on a continuous 4-hour loop, with volume levels smoothed and with fade-in and fade-out applied to reduce sudden noise fluctuations (Gao et al., 2020). The 4-hour loop is to generally target SWS in the first half of sleep. Furthermore, a 30-minute silent period was also added to the beginning of the piece to allow participants to get to sleep before the music started playing (Göldi & Rasch, 2019).

3.4.4 Measures

Errors during practice. To quantify the number of errors committed by participants in each group (Unsuccessful-trials, Successful-trials) during the practice session on Day 1, we counted the number of occasions in each block of 25 trials when the disc missed the practice target (Easy, Medium, Hard). A trial in which the disc struck either side of the board was also recorded as a miss, regardless of whether it rebounded on to the target.

Test performance. To quantify performance during the Pre-test and the Retention Test, we examined the number of hits (occasions during each block of trials when the wooden disc struck the vertical pin) and accuracy. ScorePutting software (Neumann & Thomas, 2008) was used to obtain the measure of accuracy using photographs of each trial, from a camera that was placed directly above the target. The output measure “distance left or right” was used as

the accuracy measure. The distance left or right was measured as the lateral distance between the disc's final position and the intended target line; running through the centre of the shuffleboard from the disc's origin to the centre target (see figure 3.1). For trials in which the disc did not reach the backboard we measured the lateral distance between the centre of the disc and a line perpendicular to the vertical pin. For trials in which the disc caromed off the sideboard before reaching the backboard, an arbitrary maximum distance was given (22.5 cm) because it was not possible to establish the true lateral error. As a consequence, of the potential measurement error inherent in this approach, we therefore used absolute values and calculated median accuracy scores rather than mean accuracy scores.

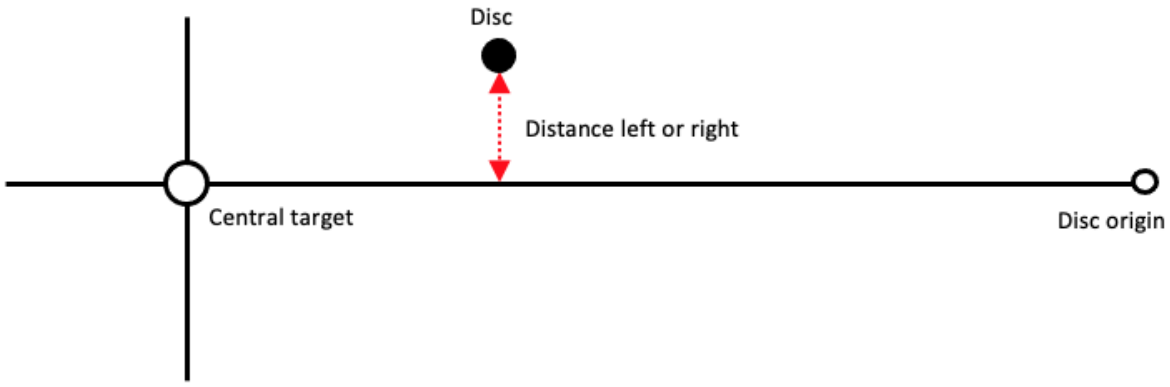

Figure 3.7 *Summary of the distance left or right output measure (Neumann & Thomas, 2008).*

Sleep quality. Quality of sleep was assessed subjectively using the Pittsburgh Sleep Quality Index (PSQI) and a sleep screening questionnaire. Both were administered on Day 2 prior to the beginning of the test session (following a night of sleep). The PSQI assesses habitual sleep quality and disturbances over a 1-month period using nineteen self-rated questions. Individual questions generate seven component scores: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction. The sum of scores for these seven components reveals

a global score that distinguishes between 'good' and 'bad' sleepers (Buysse et al., 1989). The sleep screening questionnaire was used as another subjective measure of sleep, assessing the participant's subjective sleep quality rating from the previous night (i.e., the night between sessions), caffeine and drug consumption, and exercise before sleeping. Additionally, based on the work of Göldi and Rasch (2019) the sleep screening questionnaire also assessed participants' subjective ratings of disturbance during their night of sleep, and the kinds of disturbance(s) they experienced (i.e., music related, headband related, or general disturbances). Music related disturbances were those pertaining to the soundtrack used for TMR (e.g., the selected volume was too loud). Headband related disturbances were associated with the music headband provided to participants (e.g., the headband was uncomfortable and made their head hot). Finally, general disturbances were those that participants would generally experience (i.e., going to the toilet or needing water). Subjective sleep quality was rated using a Likert scale ranging from 1 (very poor sleep) to 10 (very good sleep). The subjective disturbance rating was also scored using a Likert scale ranging from 0 (no disturbance) to 10 (maximal disturbance).

Actigraph measures. To further quantify sleep, measures of total sleep time (minutes), number of awakenings, and sleep efficiency were retrieved from the Readiband actigraph watch (Fatigue Science, Vancouver, Canada). An awakening was operationalised as any event greater than 5 mins in length during which there was regular movement. Total sleep time was operationalised as the amount of time that participants were asleep between time of initial sleep onset and time of awakening. Finally, sleep efficiency represented how efficient an individual was with their time in bed, operationalised as the total time in bed divided by the total time asleep.

3.4.5 Procedure

Day 1. Participants completed a pre-test of 25 trials during which they attempted to slide the disc as accurately as possible to hit the central target (a vertical pin). They then completed five blocks of 25 practice trials. For the first, third and fourth block of practice trials, participants in both groups shuffled at the medium difficulty target. For the second block of trials, participants in the Unsuccessful-trials group shuffled at the easy target, whereas participants in the Successful-trials group shuffled at the hard target. The target size was switched between groups in the fifth and final block of trials (see Figure 3.2). Additionally, *River Flows in You* (Yiruma, 2001) was played at approximately 40 Db through the laptop speaker during the fifth practice block to act as the external cue needed for TMR. The result of each trial was verbalised as a "hit" or a "miss" by the research assistant, who also indicated exactly where the disc struck the backboard or the sideboard (if the disc did not strike anywhere, no indication was necessary). The disc's final position or the indication by the research assistant was then photographed for later analysis.

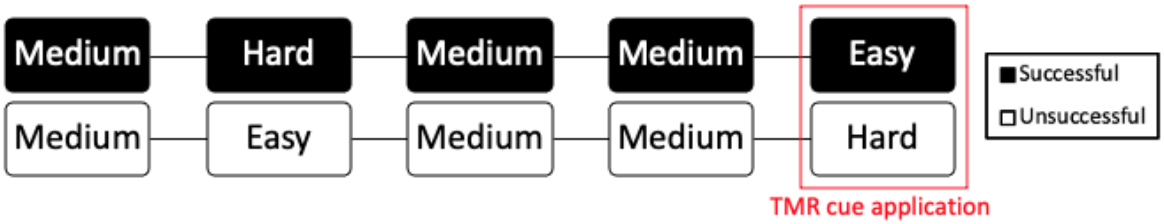

Figure 3.8 *Order of target difficulty during Day One practice blocks for both groups. The red outline indicates which block the TMR cue was applied. Group 1 = Successful Trials; Group 2 = Unsuccessful Trials.*

Prior to leaving the laboratory, participants were provided with an actigraph watch (Readiband Model 5; Fatigue Science, Vancouver, Canada) that was used to monitor their sleep. They were instructed that they should not remove the watch unless there was a

likelihood that it would get wet (e.g., swimming, showering etc). Participants were also given a music headband to connect their phone to via Bluetooth, to play the soundtrack through (Wireless Bluetooth – Sleep-Scarf Headset, Mighty Ape NZ). Volume selection on the music headband was self-selected by the participant, who were instructed to start the track as they felt the onset of sleep approaching. No further manual interaction with the TMR apparatus was needed, as it was expected that the soundtrack had finished its 4-hour loop prior to participants awakening. Furthermore, to minimise the influence of external factors on sleep quality, participants were instructed to avoid consuming any drugs, coffee, or alcohol for 6-hours prior to going to bed, and to avoid strenuous physical activity for 4-hours prior to going to bed.

Day 2. Participants returned to the laboratory the following day at the same time. Upon arrival, they returned the actigraph (so that sleep data could be downloaded by the experimenter), music headband, and completed the PSQI and sleep screening questionnaires. They then completed a retention test consisting of 25 trials during which they attempted to slide the disc as accurately as possible to hit the central target (a vertical pin).

3.4.6 Statistical Analysis

All analyses were conducted using the Statistical Package for the Social Sciences (SPSS; IBM, New York, USA; version 28). To examine performance in the Pre-test (Day 1) and the Retention Test (Day 2), both the number of hits by participants in each group and the median accuracy were subjected to a Group (Unsuccessful-trials/Successful-trials) x Test (Pre-test/Retention Test) repeated measures analysis of variance (RM-ANOVA). Planned comparisons (paired samples t-tests) were used to examine change in performance from the Pre-test to the Retention Test in each group. To examine, the number of errors that occurred

during the five blocks of practice trials (Day 1), a Group (Unsuccessful-trials/Successful-trials) x Block (1 to 5) RM-ANOVA was conducted. Planned comparisons (independent samples t-tests, one tailed) were used to examine differences between the groups in each block of trials. A Bonferroni correction (.05/5 tests = .01) was used to adjust for potential Type II errors caused by multiple hypothesis testing.

Independent samples t-tests were used to compare between-group scores for subjective sleep quality, total time asleep, PSQI scores, and sleep efficiency. Statistical significance was accepted at $p < 0.05$. Effect sizes are reported as partial eta squared (η_p^2). Partial eta squared effect thresholds are set at 0.01 for small, 0.06 for medium, and 0.14 for large (Lakens, 2013).

3.5 Results

3.5.1 Sleep Measures

Independent samples t-test analyses found no significant between-group differences for subjective sleep quality, t(28) = -0.355, $p = 0.725$; disturbance rating, t(27) = 1.275, $p = 0.213$; PSQI, t(28) = -0.518, $p = 0.608$; total time asleep, (t(28) = -0.743, $p = 0.463$; total number of awakenings, t(28) = -0.371, $p = 0.713$; or sleep efficiency (t(28) = -1.713, $p = 0.098$). The similarities between these indicators suggests that sleep patterns were not statistically different between the two groups.

Table 3.2 *Descriptive statistics for all sleep measures for both groups.*

	Unsuccessful Trials			Successful Trials		
Measure	*Mean*	*SD*	*Range*	*Mean*	*SD*	*Range*
Subjective Sleep Quality	5.86	1.70	(3.00 - 8.00)	5.63	1.86	(3.00 - 10.00)
Disturbance Rating	2.57	2.77	(0.00 - 9.00)	3.73	2.12	(0.00 - 8.00)
PSQI	5.93	1.86	(3.00 - 9.00)	5.50	2.56	(1.00 - 12.00)
Sleep Efficiency (%)	84.97	7.33	(73.80 - 97.80)	79.84	8.85	(66.30 - 97.60)
Total Time Asleep (min)	420.71	50.98	(325.00 - 480.00)	399.69	94.33	(250.00 - 565.00)
Number of Awakenings	4.21	3.29	(0.00 - 13.00)	3.81	2.64	(0.00 - 8.00)

3.5.2 Disturbances During Sleep

Frequency analyses found that 26 out of 30 participants (14 = Successful-trials, 12 = Unsuccessful-trials) experienced some form of disturbance while they slept. Fifteen participants (6 = Successful-trials, 9 = Unsuccessful-trials) experienced general disturbances, thirteen (8 = Successful-trials, 5 = Unsuccessful-trials) experienced headband related disturbances, and nine (5 = Successful-trials, 4 = Unsuccessful-trials) experienced music related disturbances.

3.5.3 Practice

The number of errors that occurred during each block of practice trials is shown in Figure 3.2. RM-ANOVA (Group x Practice Block) revealed no main effect of Group, $F(1,28) = 0.943$, $p = 0.340$, $\eta_p^2 = 0.033$. However, a significant main effect of Block, $F(4,112) = 24.232$, $p < 0.001$, $\eta_p^2 = 0.464$, and a Group x Block interaction, $F(4,112) = 137.427$, $p < 0.001$, $\eta_p^2 = 0.831$, were observed. Overall the total number of errors committed during practice by participants in each group was similar (Unsuccessful-trials total errors = 38.21; Successful-trials total errors = 43.94). An independent samples t-test of total errors committed between-groups confirmed that this was the case, $t(28) = 0.971$, $p = 0.340$.

To confirm that our manipulation was effective, we conducted independent samples t-tests between groups for each block of trials. We used a Bonferroni correction (.05/5 t-tests = .01) to adjust for multiple testing. Significant between-group differences were not evident in Block 1, t(28) = 1.624, p = 0.115; Block 3, t(28) = 0.799, p = 0.431; or Block 4, t(28) = 0.594, p = 0.552. However, consistent with our predictions, the Successful-trials group committed significantly more errors than the Unsuccessful-trials group in Block 2, t(28) = 13.451, p < 0.001 (19.19 and 2.86 errors, respectively). Crucially, this pattern was reversed in Block 5, with the Successful-trials group committing significantly fewer errors in Block 5 than the Unsuccessful-trials group, t(28) = -20.901, p < 0.001 (2.50 and 18.43 errors, respectively).

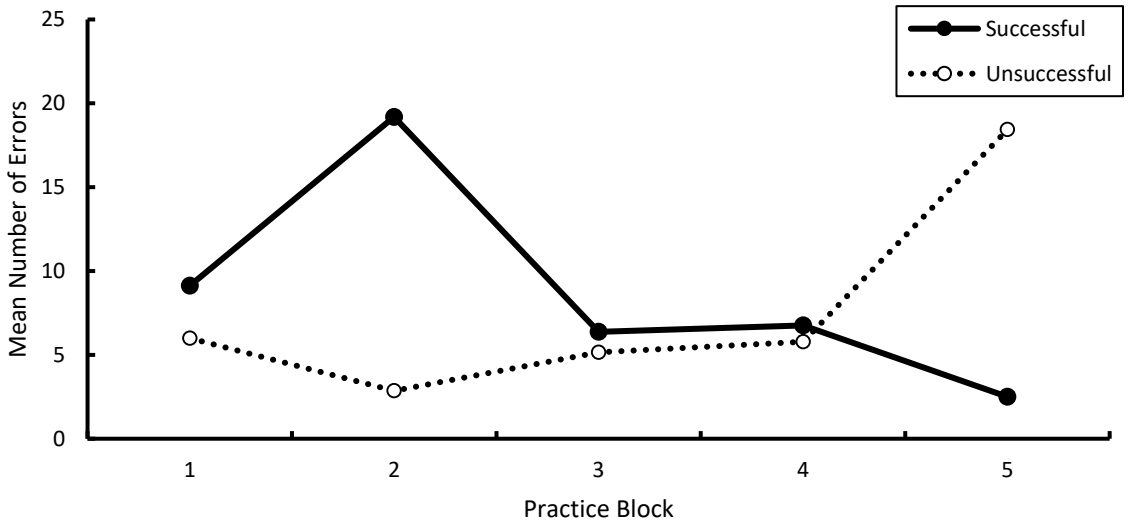

Figure 3.9. *Mean number of errors per practice block for each group.*

3.5.4 Test Performance

Hits. Figure 2.3 illustrates the mean number of hits by each group in the Pre-test and the Retention test. RM-ANOVA (Group x Test) revealed a significant main effect of Test, F(1,28) = 15.903, p < 0.001, η_p^2 = 0.362. However neither a main effect of group, F(1,28) = 0.279, p = 0.602, η_p^2 = 0.010, nor a Group x Test interaction, F(1,28) = 0.700, p = 0.410, η_p^2 = 0.024, were

evident. Nevertheless, our *a priori* expectation was that the Successful-trials group would demonstrate significant pre-test to retention test improvement in performance while the Unsuccessful-trials group would not, so we conducted paired samples t-tests for each group. As expected the Successful-trials group improved significantly from the Pre-test to the Retention test, t(15) = -3.031, $p = 0.004$; however, the Unsuccessful-trials group also improved, t(13) = -2.813, $p = 0.007$.

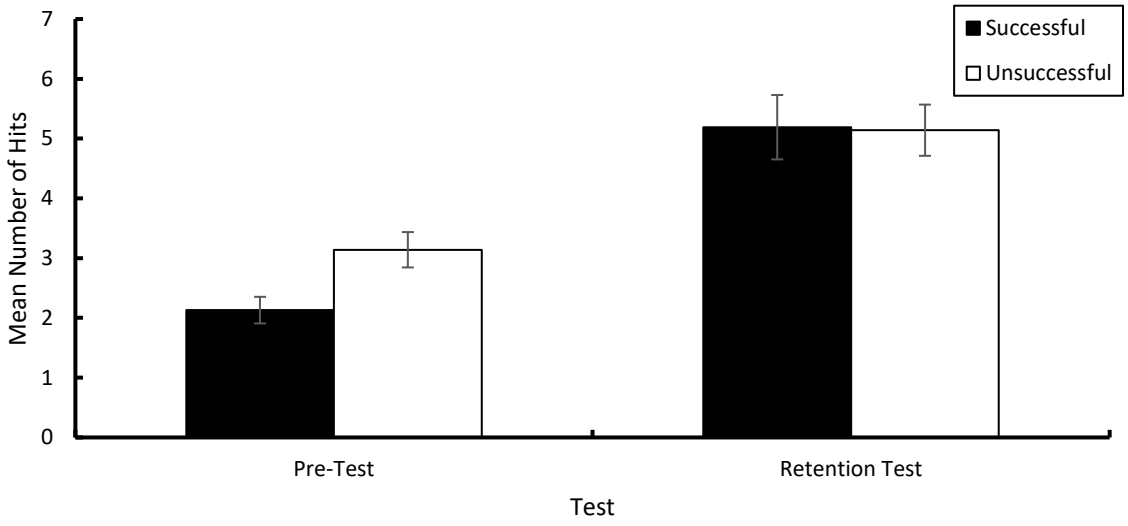

Figure 3.10. *Mean number of hits per group at pre-test and retention test. Error bars represent the standard error of the mean.*

Accuracy. Figure 3.4 illustrates the mean accuracy of each group in the Pre-test and the Retention Test. RM-ANOVA (Group x Test) revealed a significant main effect of Test, F(1,28) = 5.161, $p = 0.031$, $\eta_p^2 = 0.156$, but not of Group, F(1,28) = 0.075, $p = 0.786$, $\eta_p^2 = 0.003$. A significant Group x Test interaction was not evident, F(1,28) = 0.379, $p = 0.543$, $\eta_p^2 = 0.013$. Given our *a priori* expectation that the Successful-trials group would demonstrate a significant pre-test to retention test improvement in performance while the Unsuccessful-trials group would not, we conducted paired samples t-tests for each group. As expected,

the Successful-trials group improved significantly from the Pre-test to the Retention Test, t(15) = 1.780, p = 0.048, while the Unsuccessful-trials group did not, t(13) = 1.561, p = 0.071.

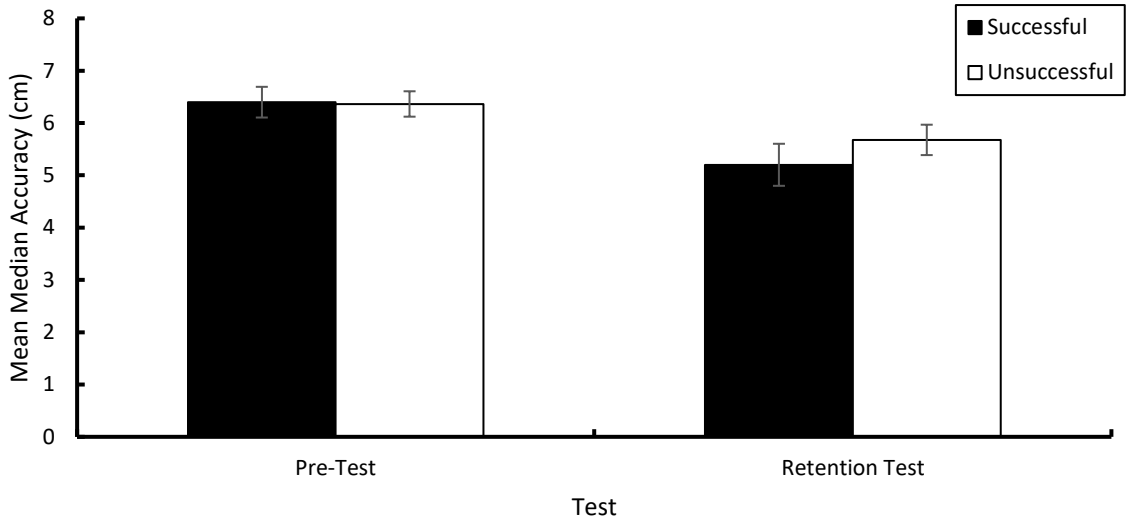

Figure 3.11. *Mean median accuracy at pre-test and retention test for both groups. Error bars represent the standard error of the mean.*

3.6 Discussion

We predicted that significant pre-test to retention test performance (hits and accuracy) improvements would occur for those who finished practice with mostly successful trials, but not for those who finished with mostly unsuccessful trials. In neither case did we find a significant Group x Test interaction; however, *a priori* tests suggested that accuracy improved significantly in the Successful-trials group compared to the Unsuccessful-trials group and the total number of hits increased significantly for both groups. These results are interesting as the application of TMR during the final practice block was included to promote the likelihood of consolidating mostly successful or unsuccessful performance memories, leading to a prediction that due to consolidation of primarily errors, the Unsuccessful-trials group would show no improvement or even worse performance after sleep consolidation.

It is possible that improvements occurred for participants who made many errors during the final block of trials because TMR either reduced consolidation of unsuccessful trials or augmented consolidation of successful trials. During practice, powerful motivational, physiological or hormonal factors may accompany successful trials (or unsuccessful trials), potentially biasing the effect of TMR towards more effective consolidation for memories of either. For instance, the neurotransmitter, dopamine, has been implicated in promoting long-term potentiation, in turn promoting memory consolidation (Ewell & Leutgeb, 2014; McNamara et al., 2014). Dopamine is canonically known as the "feel-good" chemical, and is also known to promote memory, motivation, and the feeling of reward when released (Watson, 2021). During the experiment, the research assistant verbally announced "hit" following successful trials, which could have promoted a sense of reward for participants; potentially causing the release of more dopamine during successful trials.

Another possibility, is that the novelty of hearing the "hit" announcement lead to a more intense dose of dopamine release in the Unsuccessful-trials group during the final block, stemming from the fact that participants heard the "hit" announcement less during the final practice block when compared to the Successful-trials group. It is also possible that a recency effect was not evident, but that the groups displayed similar improvements in performance (i.e., learning) because overall the total number of errors committed during the 5 practice blocks was the same between groups. Consequently, an equivalent number of memories of both successful and unsuccessful trials consolidated during sleep.

Other work investigating the application of TMR in an at-home setting, found that sleep disturbances and habituation to TMR related equipment (i.e., music and headband) were factors that strongly influenced the efficacy of the TMR application (Göldi & Rasch, 2019).

The majority (26 of 30) of our participants experienced some form of sleep disturbance, so it is likely that disturbances and habituation to the TMR equipment may have influenced TMR efficacy. Additionally, we do not know whether the participants actually heard the soundtrack while sleeping or not, whether the headband stayed on, or how high the volume was for the soundtrack. These limitations could have been addressed had we used polysomnography to monitor sleep behaviour in our participants. Polysomnography uses a variety of measures to assess sleep quality, including electroencephalography (EEG). EEG is a method used to record the time and frequency of the electrical signals generated by the cooperative action of brain cells (Blinowska & Durka, 2006). EEG is a useful tool for verifying sleep stage progression because each sleep stage produces a unique frequency and wavelength, identifiable only using EEG (Stickgold, 2005). As such, EEG facilitates the specific presentation timing of the TMR cues. Furthermore, the presence of sleep spindles is only observable using EEG; which is important because an increased presence of sleep spindles has also been associated with an increased benefit of TMR (e.g., Laventure et al., 2018; Rudoy et al., 2009).

Nevertheless, if TMR efficacy was hindered, it would be expected that our findings would replicate those of Experiment 1; where only those who finished practice making successful trials showed significant off-line improvements. As the current findings show that both groups improved post-sleep, it is possible that TMR did in fact influence learning; because consistent with other TMR studies, learning improved following TMR application (e.g., Gao et al., 2020; Hu et al., 2015; Rochester et al., 2010; Antony et al., 2012).

In addition, the lack of control groups (i.e., Successful-trials/Unsuccessful-trials groups without TMR) in this study could explain why the efficacy of TMR application is in question. Without control groups for either learning condition, it is unclear whether the off-line

improvements seen in both groups would have been different between TMR cued groups and control groups; or if TMR application was indeed hindered? Be that as it may, the application of TMR did not magnify the between-group interaction observed in Experiment 1, as per our predictions; regardless of whether application was hindered or not. However, these confounding factors indicate that more work is needed to verify the efficacy of TMR application.

Chapter Four

Summary and Conclusion

4.1 Key Findings

No differences in sleep behaviours were evident between groups in either experiment (*p*'s > 0.05). Planned comparisons suggested that with or without the application of TMR, participants who finished practice with mostly successful trials improved significantly after sleep on both dependent measures of performance. Planned comparisons also suggested that participants who finished practice with mostly unsuccessful trials did not improve significantly after sleep in Experiment 1; however, improvements were evident (for hits $p = 0.007$) following the application of TMR in Experiment 2.

4.2 General Discussion

The findings from Experiment 1 (Chapter 2) indicate some support for the idea that finishing practice with mostly successful trials, and thus few errors, may lead to better off-line learning when compared to finishing practice with mostly unsuccessful trials, and thus many errors. This finding is consistent with the possibility that a recency effect resulted in consolidation of recent memories for a greater number of successful trials compared to unsuccessful trials. However, early work that examined primacy-recency effects in a maze tracing task suggested that a primacy effect may be more likely in human motor learning. Following a small number of 'discovery' trials, participants displayed faster tracking at the beginning of the maze than the end of the maze, causing Cratty (1963) to conclude that early trials were learned before later trials. More recently, Carney and Banaji (2012) found over three experiments that

automatic preference was significantly stronger for first presented items over any subsequent items. Therefore, it is possible that the first experienced memories of performance (i.e., successful and unsuccessful trials during pre-test) became more salient, rather than the last presented (i.e., final block of practice); consequently, increasing their likelihood of being consolidated during sleep. Should this be the case, it would be expected that the Unuccessful-trials group, which made fewer errors during the early stages of practice (because of counterbalancing between easy and hard trials), should have displayed more learning. However, this was not the case in either experiment.

The findings from Experiment 2 (Chapter 3) were not consistent with the first experiment–both groups improved post-sleep, but we expected that TMR would strengthen off-line learning associated with primarily non-errors, by specifically augmenting consolidation of many successful trials but few unsuccessful trials; whereas we expected that TMR would strengthen off-line learning associated with primarily errors, by specifically augmenting consolidation of many unsuccessful trials but few successful trials. It is possible that improvements occurred for participants in both groups because TMR somehow resulted in reduced consolidation of unsuccessful trials but augmented consolidation of successful trials. Consequently, for participants who committed many unsuccessful trials in the final block of practice consolidation did not occur for the many errors (i.e., the errors were less likely to be learned). Interestingly, Oyarzún et al. (2017) found that TMR application adaptively promotes the strengthening and weakening of overlapping memories. Therefore, it is possible that performance memories became overlapped with one another as minute changes in technique could therefore have been the difference between a successful trial and

unsuccessful trial. Consequently, such small changes in technique could result in a very similar movement pattern consolidating for what would be differing outcomes.

One limitation in both experiments is that we did not use polysomnography to monitor sleep behaviour in our participants. Instead, we asked participants to listen to the TMR cue (music) via a music headband, which sounded continuously thorough the first 4-hours of sleep. Consequently, we do not know whether the participants actually heard the soundtrack while sleep or not, whether the headband stayed on, or how high the volume was for the soundtrack. Additionally, we cannot be certain that participants were matched for sleep quality and, thus, opportunity for sleep consolidation. Polysomnography uses a variety of measures to assess sleep quality, including electroencephalography (EEG) to register brainwaves associated with sleep. EEG is a method used to record the time and frequency of the electrical signals generated by the cooperative action of brain cells (Blinowska & Durka, 2006). EEG is a useful tool for monitoring sleep because each sleep stage produces a unique frequency and wavelength, identifiable only using EEG (Stickgold, 2005). As aforementioned, TMR cues for motor skills typically are presented during N3 sleep (Göldi & Rasch, 2019; Hu et al., 2020; Lewis & Bendor, 2019). As such, EEG enables a real-time view of which specific sleep stage an individual is in. In particular, this would have been valuable for Experiment 2 in order to facilitate the specific presentation timing of the TMR cues.

4.2 Limitations and Future Research

Various limitations must be acknowledged within the current experiments, particularly surrounding the efficacy of TMR application in Experiment 2. Therefore, future research should aim to clarify any ambiguity surrounding these limitations. For example, with respect to Experiment 2, control groups could be utilised to establish a clearer picture of the effect of

TMR by comparing Successful-trials with TMR to Successful-trials without TMR, and Unsuccessful-trials with TMR to Unsuccessful-trials without TMR. This would further clarify whether off-line improvements associated with errors during practice are moderated by TMR on not.

It would also be interesting to specifically cue successful (or possibly unsuccessful performance) for consolidation by presenting a cue only on each occasion that a successful trial occurs during practice. In other words, errors would be ignored but successes would be cued for targeted reactivation during sleep. The efficacy of this approach could also be enhanced by implementing electroencephalography monitoring to inform the timing of cues during slow wave sleep, as done in traditional, laboratory-based TMR studies. Should evidence suggest that off-line learning is enhanced by presenting a TMR cue (e.g., a tone) during practice only when a successful trial occurs, there would be good reason to apply the approach to real-world training scenarios. For instance, during practice sessions on the driving range a golf coach could potentially provide a cue (a tone, for instance) each time a pupil performs a swing in the correct way. The pupil might then replay the tone as they sleep, with expectation that memories of the correct swing will be specifically reactivated, and thus consolidated.

Should future research provide evidence supporting the recency effect for motor memory consolidation following sleep, it may then be possible to make simple recommendations for coaching practice. For instance, coaches often call time on a practice session if the athlete or team is beginning to tire and /or make mistakes. Our findings suggest that this may not lead to the best learning outcome because the recency of the high number of errors is likely to result in consolidation of those errors during sleep. Our findings suggest

that coaches should either call time on a practice session during a period in which performance has been very good (with few errors etc) or should provide a rest and then end practice on a low error session.

Another limitation of the experiments is that we used differently sized targets to manipulate errors during practice, yet the tests of performance required participants to hit a small vertical pin. Consequently, successful trials during practice (especially for the easy target, which was 33cm wide) were not necessarily representative of actual performance. That is, a participant could slide the disc in such a way that it was deemed a successful trial during practice (e.g., 32cm wide on the easy target) but which would have been a complete miss during the pre-test or retention test. Future studies should therefore consider using a more representative design in which successful trials during practice are more specifically associated with successful trials during the tests. For example, Krause et al. (2019) compared the use of four commonly delivered tennis practice tasks and their representativeness of competitive match play. They found that the practice tasks promoted 'cooperative' behaviours rather than the 'combative' behaviours associated with match play. These behaviours were representative of the practice tasks completed, which indicates that representative learning is needed to promote typical match play behaviours. Consequently, for the shuffleboard task that we used, a simple alternative might be to use a distance-based method by which to manipulate errors, as commonly used in the error-reduced implicit motor learning literature (e.g., Maxwell et al, 2001; Poolton et al., 2005). Instead of using different target widths we would use different distances from the same target (a small vertical pin) that is used in the pre-test and post-test. This would also help to eliminate another limitation of our experiments, which was associated with discs that struck the side of the shuffleboard

before reaching their intended target. In those instances, it was not possible to quantify accuracy (i.e., the lateral distance of the disc from the target), so we were forced to use medians rather than means of accuracy.

4.3 Conclusion

The findings of this thesis indicate preliminary support for the idea that finishing practice with mostly successful trials could lead to magnified off-line improvements when compared to finishing practice with mostly unsuccessful trials. The approach has implications for domains in which motor learning is important, such as coaching and rehabilitation, as the potential to enhance consolidation of specific memories of success, or reduce consolidation of errors, has promise for promoting a faster rate of off-line learning, and thus more rapid acquisition of skills. However, more work is needed to resolve some of the limitations identified within this thesis before our approach can be more widely adopted.

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Appendices

Appendix 1 – Ethics Approval

The University of Waikato
Private Bag 3105
Hamilton, New Zealand, 3240
0800 WAIKATO (924 528)

HECS Human Ethics Committee
Brett Langley
Telephone +64 77 838 4060
Hecs-ethics@waikato.ac.nz

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

5 September 2022

Tyler Jahnke
Rich Masters
Cat Chang
Merel Hoskens
So Hyun Park

Re: HECS Ethics Approval of Application HREC(HECS)2021#56 "Using targeted memory reactivation to promote off-line learning following error-reduced and error-strewn practice of a motor skill"

Dear Tyler:

Thank you for submitting your amended application HREC(HECS)2021#56 for ethical approval.

We are pleased to provide formal approval for your project, including the following activities:

- Recruitment of approximately 40 participants, male and female, aged 18 to 45 years old.
- Conduct study whereby participants will:
  - Complete a Pittsburgh Sleep Quality Index questionnaire.
  - Practice a motor task (shuffleboard) in either error-reduced or error-strewn conditions
  - Take home an actigraph watch and a music headband for the night, where they will sleep as per their normal sleep schedule. The actigraph watch will monitor sleep, while the music headband will facilitate cue re-presentation for targeted memory reactivation.
  - The following day, repeat shuffleboard task.
- Some data may be recorded using camera, but no identifying features will be recorded and participants will remain anonymous.
- Participants can withdraw from the study at any time and up to 3 weeks following participation.

Please contact the committee by email (hecs-ethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Kind regards,

Brett Langley, PhD
Chairperson
HECS Human Ethics Committee

Appendix 2 – Participant Information Form

School of Health
The University of Waikato
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THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Participant information sheet

Project title: Using targeted memory reactivation to promote off-line learning following error-reduced and error-strewn practice of a motor skill

Researchers: Tyler Jahnke (Master student), Prof. Rich Masters., Dr. Merel Hoskens, Dr. So Hyun Park, Dr. Cat Chang

Purpose: The purpose of this research is to investigate how memory can be influenced during the learning of a new motor task.

Participant requirements:
To participate in this study, it is required that:

- You are aged between 18-45 years old;
- Be a novice to shuffleboard; and
- You do not suffer from any sleeping disorders.

What will you have to do and how long will it take?
You will be asked to give informed consent upon arrival. This will be done after the task has been explained and you have had an opportunity to ask any questions. You will then complete 6 blocks of 25 trials of the shuffleboard task. After which you will be given an actigraph watch and a sleep mask to take with you. You will be provided with an mp3 file to play from a Bluetooth device (i.e., your phone) to the sleep mask while you sleep. The actigraph watch can only be removed while showering, or while participating in any physical activity where it is unsafe to wear. You will then return to the lab at the same time the following day, where you fill a questionnaire that assesses your sleep habits over the past month. Finally, you will then complete 4 more blocks of 25 trials of the shuffleboard task and return the provided equipment.

Potential risks or discomfort:
There are no known risks associated with participation.

Potential benefits:

Although there are unlikely to be any immediate direct benefits to you as a consequence of participating, the data you help us collect may inform adaptations to motor learning strategies.

What will happen to the information collected?

Your personal information, including the data we will obtain from you is strictly confidential. Only the named researchers will have access to all of the data. The information collected in this study may be used for scholarly publications and/or conference presentations and may contribute to or inform Tyler Jahnke's Master's theses. An electronic copy of the theses will become widely available, as the University of Waikato requires that a digital copy of Master's theses be lodged permanently in the University's digital repository: Research Commons. No participants will be named in the publications and every effort will be made to disguise their identity. Some of the data will be collected using a camera. This data will be identified using subject ID, which means that your name cannot be associated with the recorded data. All data will be retained in a secured password protected computer and cabinet for five years. Afterwards, notes, documents will be destroyed, and recordings erased.

Participation and withdrawal:

Your participation is voluntary. This means that you can choose to stop at any time without any consequences. You will have the opportunity to withdraw your results from our study up to 3 weeks following your participation via email or text message to Tyler Jahnke.

Declaration to participants:

If you take part in the study, you have the right to:

- Ask any further questions about the study that occurs to you during your participation;
- Be given access to a summary of findings from the study when it is concluded; and
- Withdraw from the study at any time up until the three weeks following participating in the research.

Any issues, questions or concerns:

If you have any questions or concerns about the research, please feel free to contact Tyler Jahnke (email: tjj5@students.waikato.ac.nz, telephone 022 675 3681), Professor Rich Masters (email: rmasters@waikato.ac.nz, telephone 838 45 00 or ext. 6206) or the chairperson of the HECS Human Ethics Committee, Dr Brett Langley (email: hecs-ethics@waikato.ac.nz).

This research project has been approved by the HECS Human Ethics Committee of the University of Waikato (HREC(HECS)2021#56). Any questions about the ethical conduct of this research may be addressed to the Secretary of the Committee, email hecs-ethics@waikato.ac.nz, postal address, University of Waikato, Te Whare Wananga o Waikato, Private Bag 3105, Hamilton 3240.

Appendix 3 – Participant Consent Form

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THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Consent Form

Project Title: Using targeted memory reactivation to promote off-line learning following error-reduced and error-strewn practice of a motor skill

Researchers: Tyler Jahnke (Masters student), Prof. Rich Masters., Dr. Merel Hoskens, Dr. So Hyun Park

I _____ agree to participate as a volunteer in a scientific investigation as an approved part of a research program at the University of Waikato under the supervision of _____.

The investigation and my part in the investigation have been defined and fully explained to me by _____ and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have and all questions have been answered to my satisfaction.
- I understand that the data collected in this research project may be reported in scientific publications, presentations, teaching, and student theses.
- I understand that I am free to withdraw from the project and ask for my data to be destroyed within three weeks following participation in the research activities, without consequence to myself.
- I understand that my data will be anonymized through a coding system, to protect my identity in the research reporting.
- I am participating in this project of my own volition, and I have not been coerced in any way to participate.

Signature of Participant: _____

Date: ____/____/____

□ I would like to receive a summary of the results of the study to the following e-mail address:

_____

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: _____ Date: ___/____/__

Contact Details for Researchers: If you have any questions or concerns about the research, please feel free to contact Tyler Jahnke (email: tjj5@students.waikato.ac.nz, telephone 022 675 3681), Professor Rich Masters (email: rmasters@waikato.ac.nz, telephone 838 45 00 or ext. 6206) or the chairperson of the HECS Human Ethics Committee, Dr Brett Langley (email: hecs-ethics@waikato.ac.nz).

Appendix 4 – Pittsburgh Sleep Quality Index

Instructions:

The following questions relate to your usual sleep habits during the past month *only*. Your answers should indicate the most accurate reply for the *majority* of days and nights in the past month. Please answer all questions.

1. During the past month, when have you usually gone to bed at night?

   USUAL BED TIME _____

2. During the past month, how long (in minutes) has it usually take you to fall asleep each night?

   NUMBER OF MINUTES _____

3. During the past month, when have you usually gotten up in the morning?

   USUAL GETTING UP TIME _____

4. During the past month, how many hours of *actual sleep* did you get at night? (This may be different than the number of hours you spend in bed.)

   HOURS OF SLEEP PER NIGHT _____

For each of the remaining questions, check the one best response. Please answer *all* questions.

5. During the past month, how often have you had trouble sleeping because you...

   (a) Cannot get to sleep within 30 minutes

Not during the past month ____	Less than once a week ____	Once or twice a week ____	Three or more times a week ____

   (b) Wake up in the middle of the night or early morning

Not during the past month ____	Less than once a week ____	Once or twice a week ____	Three or more times a week ____

   (c) Have to get up to use the bathroom

Not during the past month ____	Less than once a week ____	Once or twice a week ____	Three or more times a week ____

   (d) Cannot breathe comfortably

Not during the past month ____	Less than once a week ____	Once or twice a week ____	Three or more times a week ____

   (e) Cough or snore loudly

Not during the past month ____	Less than once a week ____	Once or twice a week ____	Three or more times a week ____

   (f) Feel too cold

Not during the past month ____	Less than once a week ____	Once or twice a week ____	Three or more times a week ____

   (g) Feel too hot

Not during the past month ____	Less than once a week ____	Once or twice a week ____	Three or more times a week ____

   (h) Had bad dreams

Not during the past month ____	Less than once a week ____	Once or twice a week ____	Three or more times a week ____

   (i) Have pain

Not during the past month ____	Less than once a week ____	Once or twice a week ____	Three or more times a week ____

(j) Other reason(s), please describe _____

_____

How often during the past month have you had trouble sleeping because of this?

Not during the past month _____	Less than once a week _____	Once or twice a week _____	Three or more times a week _____

6. During the past month, how would you rate your sleep quality overall?

   Very good _____
   Fairly good _____
   Fairly bad _____
   Very bad _____

7. During the past month, how often have you taken medicine (prescribed or "over the counter") to help you sleep?

Not during the past month _____	Less than once a week _____	Once or twice a week _____	Three or more times a week _____

8. During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity?

Not during the past month _____	Less than once a week _____	Once or twice a week _____	Three or more times a week _____

9. During the past month, how much of a problem has it been for you to keep up enough enthusiasm to get things done?

   No problem at all _____
   Only a very slight problem _____
   Somewhat of a problem _____
   A very big problem _____

10. Do you have a bed partner or roommate?

    No bed partner or roommate _____
    Partner/roommate in other room _____
    Partner in same room, but not same bed _____
    Partner in same bed _____

If you have a roommate or bed partner, ask him/her how often in the past month you have had...

(a) Loud snoring

Not during the past month _____	Less than once a week _____	Once or twice a week _____	Three or more times a week _____

(b) Long pauses between breaths while asleep

Not during the past month _____	Less than once a week _____	Once or twice a week _____	Three or more times a week _____

(c) Legs twitching or jerking while you sleep

Not during the past month _____	Less than once a week _____	Once or twice a week _____	Three or more times a week _____

(d) Episodes of disorientation or confusion during sleep

Not during the past month _____	Less than once a week _____	Once or twice a week _____	Three or more times a week _____

(e) Other restlessness while you sleep; please describe _____

_____

Not during the past month _____	Less than once a week _____	Once or twice a week _____	Three or more times a week _____

Scoring Instructions for the Pittsburgh Sleep Quality Index

The Pittsburgh Sleep Quality Index (PSQI) contains 19 self-rated questions and 5 questions rated by the bed partner or roommate (if one is available). Only self-rated questions are included in the scoring. The 19 self-rated items are combined to form seven "component" scores, each of which has a range of 0-3 points. In all cases, a score of "0" indicates no difficulty, while a score of "3" indicates severe difficulty. The seven component scores are then added to yield one "global" score, with a range of 0-21 points, "0" indicating no difficulty and "21" indicating severe difficulties in all areas.

Scoring proceeds as follows:

Component 1: Subjective sleep quality

Examine question #6, and assign scores as follows:

Response	Component 1 score
"Very good"	0
"Fairly good"	1
"Fairly bad"	2
"Very bad"	3

Component 1 score: _____

Component 2: Sleep latency

1. Examine question #2, and assign scores as follows:

Response	Score
≤ 15 minutes	0
16-30 minutes	1
31-60 minutes	2
> 60 minutes	3

Question #2 score: _____

2. Examine question #5a, and assign scores as follows:

Response	Score
Not during the past month	0
Less than once a week	1
Once or twice a week	2
Three or more times a week	3

Question #5a score: _____

3. Add #2 score and #5a score

Sum of #2 and #5a: _____

4. Assign component 2 score as follows:

Sum of #2 and #5a	Component 2 score
0	0
1-2	1
3-4	2
5-6	3

Component 2 score: _____

Component 3: Sleep duration

Examine question #4, and assign scores as follows:

Response	Component 3 score
> 7 hours	0
6-7 hours	1
5-6 hours	2
< 5 hours	3

Component 3 score: _____

Component 4: Habitual sleep efficiency

(1) Write the number of hours slept (question # 4) here: _____

(2) Calculate the number of hours spent in bed:

Getting up time (question # 3): _____

− Bedtime (question # 1): _____

Number of hours spent in bed: _____

(3) Calculate habitual sleep efficiency as follows:

(Number of hours slept/Number of hours spent in bed) × 100 = Habitual sleep efficiency (%)

(_____/_____) × 100 = _____%

(4) Assign component 4 score as follows:

Habitual sleep efficiency %	Component 4 score
> 85%	0
75-84%	1
65-74%	2
< 65%	3

Component 4 score: _____

Component 5: Sleep disturbances

(1) Examine questions # 5b-5j, and assign scores for *each* question as follows:

Response	Score
Not during the past month	0
Less than once a week	1
Once or twice a week	2
Three or more times a week	3

#5b score _____

c score _____

d score _____

e score _____

f score _____

g score _____

h score _____

i score _____

j score _____

(2) Add the scores for questions # 5b-5j:

Sum of # 5b-5j: _____

(3) Assign component 5 score as follows:

Sum of # 5b-5j	Component 5 score
0	0
1-9	1
10-18	2
19-27	3

Component 5 score: _____

Component 6: Use of sleeping medication

Examine question # 7 and assign scores as follows:

Response	Component 6 score
Not during the past month	0
Less than once a week	1
Once or twice a week	2
Three or more times a week	3

Component 6 score: _____

Component 7: Daytime dysfunction

(1) Examine question # 8, and assign scores as follows:

Response	Score
Never	0
Once or twice	1
Once or twice each week	2
Three or more times each week	3

Question # 8 score: _____

(2) Examine question # 9, and assign scores as follows:

Response	Score
No problem at all	0
Only a very slight problem	1
Somewhat of a problem	2
A very big problem	3

Question # 9 score: _____

(3) Add the scores for question # 8 and # 9:

Sum of #8 and #9: _____

(4) Assign component 7 score as follows:

Sum of # 8 and #9	Component 7 score
0	0
1-2	1
3-4	2
5-6	3

Component 7 score: _____

Global PSQI Score

Add the seven component scores together:

Global PSQI Score: _____

Appendix 5 – Sleep Screening Questionnaire

Participant number:

1. Full Name:

2. Gender:

- ○ Male
- ○ Female
- ○ Other

3. Age:

4. Dates Partcipated: (E.g., Mon 30th May & Tues 31st May)

5. How would you rate the quality of your sleep last night? (0 = very poor, 5 = average, 10 = very good)

0 1 2 3 4 5 6 7 8 9 10

Sleep quality?

6. Did you experience any disturbances while sleeping last night? This could be related to the sleep mask provided, music playing, or any general disturbances.

- ○ No
- ○ Yes

If YES to question 6 above, how would you rate the disturbance to your sleep? (1 = minimal, 10 = maximal)

0 1 2 3 4 5 6 7 8 9 10

Number of Disturbances?

7. Did you consume coffee / alcohol /drugs in the 6 hours prior to sleeping?

- ○ Yes
- ○ No

8. Did you do any strenuous activity in the 4 hours prior to sleeping?

- ○ Yes
- ○ No

If YES to Q8 above, what kind of activity and for how long?

If YES to question 6 above, what type(s) of disturbances did you experience?

- ☐ Music related
- ☐ Sleep mask related
- ☐ General disturbances (i.e., needed to go toilet, have a drink of water)

Could you please specify the disturbances you experienced? (E.g. music too loud, sleep mask uncomfortable)

9. Have you been previously diagnosed with any type of sleeping disorder?

- ○ Yes
- ○ No

If YES to Q9 above, how long ago? Is it being treated/untreated? And did you take any sleep medication last night?

Appendix 6 – Targeted Memory Reactivation Soundtrack

https://drive.google.com/file/d/1IrhLP9ZMCCt-wGtNirsUV8Pu0P-9Xtm2/view?usp=sharing