Fatiguing verbal working memory to reduce explicit hypothesis testing during skill acquisition: A new implicit motor learning paradigm?

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Abstract

How we learn novel motor skills is crucial for motor performance. Motor skills learned through implicit processes have been shown to have higher neural efficiency, lower likelihood of interference from conscious control during motor output, and more stable performance under pressure, stress, fatigue and multitasking situations (Maxwell, Masters & Eves, 2000; Steenbergen, Van Der Kamp, Verneau, Jongbloed-Pereboom & Masters, 2010; Zhu, Yeung, Poolton, Lee, Leung & Masters, 2015). These performance benefits are sought after in both clinical and sporting domains, and make implicit motor learning a viable alternative to explicit forms of learning. However, current implicit motor learning paradigms have encountered limitations that hinder their practical application (Lam, Maxwell & Masters, 2009; Zhu et al., 2015); therefore, new implicit motor learning paradigms need to be created. This thesis investigated whether cognitive fatigue can be used to encourage novices to perform a novel motor task in an implicit manner. We hypothesized that inducing cognitive fatigue in people would suppress verbal working memory activity, thereby minimising hypothesis testing about the task to be performed and causing implicit motor learning. The research was conducted on thirty-three healthy adults (women=19, men=14; mean age= 23.3±5.5) who reported limited golf experience. All participants were randomly allocated to one of two treatment conditions: control (non-fatigued) or experimental (fatigued). We analysed the differences in verbal working memory performance, motor skill performance and hypothesis testing measures between the two groups. Our results showed that participants in the experimental condition reported a significant increase in subjective feelings of fatigue following the intervention; however, this was not reflected by a decrease in working memory activity. The results also illustrated no significant differences in motor performance or hypothesis testing between the two groups. Overall, the cognitive fatigue task was shown to successfully alter self-reported levels of fatigue (VAS-f), although we speculate that the fatigue

levels produced by the intervention were not sufficient to suppress working memory activity during performance of a novel motor task.

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I would like to dedicate this thesis to my grandparents, William Albert Boaz and Nessie Boaz.

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Abbreviations

CMP - Cognitive motor processing

DLPFC - Dorsolateral prefrontal cortex

EEG - Electroencephalogram

HCL - High cognitive load

LCL - Low cognitive load

tDCS - Transcranial direct current stimulation

TloadDback - Time load Dual-back

VAS-f - Visual analogue scale for fatigue

WM – Working memory

Thesis Overview

The format of this thesis includes four chapters:

Chapter 1 provides a conceptual background to the topic, identifying the issues surrounding the use of conscious control (i.e., movement specific reinvestment) during motor performance. This introductory chapter demonstrates the implications of learning motor skills explicitly and the benefits of shifting to implicit processes during motor performance.

Chapter 2 contains a review of literature, extending the information provided in Chapter 1, delving further into the concepts of working memory, motor skill learning and cognitive fatigue.

Chapter 3 presents an experiment, which examines the impact of cognitive fatigue on verbal working memory activity, motor performance and hypothesis testing. This chapter is presented in the style of an individual journal article.

Chapter 4 summarises the overall findings with respect to the literature and provides recommendations for future research.

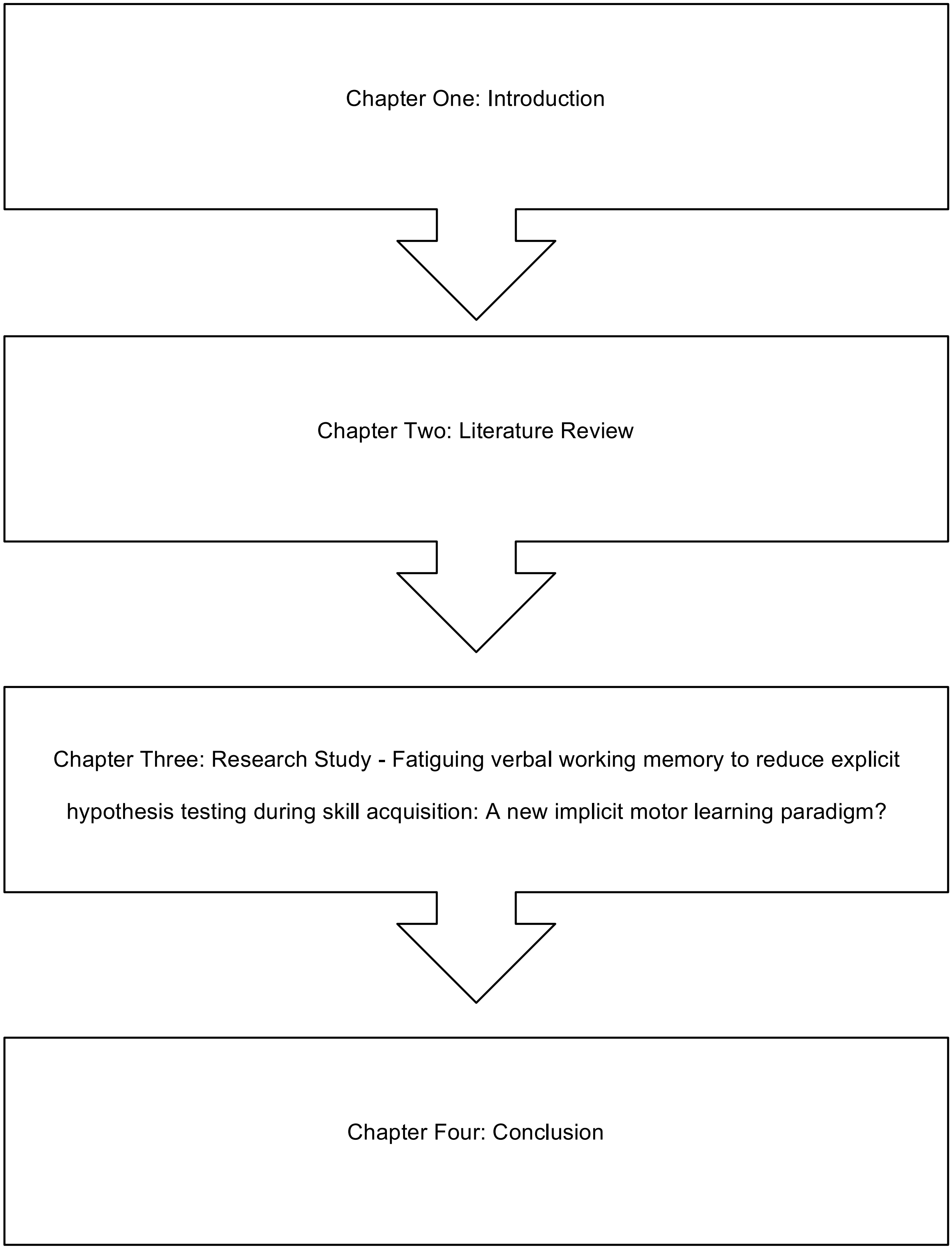

Figure 1. Schematic of the thesis structure.

Chapter 1: Introduction

1.1 Background

There are different ways in which people can learn a new motor skill. Most commonly, people learn explicitly (McMorris, 2014). This form of learning is intentional and requires conscious engagement and effort from the learner (Xie, Gao & King, 2013; Zhu et al., 2015). Explicit learners engage in hypothesis testing and error correction behaviours. These behaviours are employed to resolve outcome errors and aid in developing understanding of the best technique for a successful performance (Maxwell, Capio & Masters, 2017; Steenbergen et al., 2010). Coaches or instructors often provide explicit information and feedback, which must be consciously processed and implemented into practice. These explicit learning processes are conducted utilizing working memory resources and result in the accumulation of declarative knowledge.

The declarative knowledge that is formulated in these primitive stages of motor skill development is comprised of task-relevant rules, which are consciously accessible and can be verbalised by the learner. Learners access such knowledge by retrieving it from storage in memory and then can manipulate the information in working memory to consciously execute motor movements; a process described as reinvestment (Masters, 1992; Masters & Maxwell, 2008). Reinvestment is problematic as it disrupts the automaticity of movements, causing to revert to earlier stages of skill development (Kinrade, Jackson & Ashford, 2010; Malhotra, Poolton, Wilson, Omuro, Masters, 2015; Masters, 1992; Masters & Maxwell, 2008; Masters, Polman & Hammond, 1993; Poolton & Masters, 2010; Uiga, Capio, Wong, Wilson & Masters, 2015).

Research indicates that shifting the extent to which movements are processed implicitly can prevent reinvestment and thus reduce the likelihood of performance breakdown under pressure, for example (Masters & Maxwell, 2008; Maxwell et al., 2000; Maxwell, Masters & Poolton, 2006; Poolton & Masters, 2010). Implicit motor learning paradigms suppress working memory activity during motor skill acquisition, thereby limiting the availability of cognitive resources for explicit learning processes, such as hypothesis testing (Poolton & Masters, 2010; Zhu et al., 2015).

It has been argued that implicit learners also benefit from performing with higher neural efficiency than explicit learners and are better equipped to perform under stress, pressure, fatigue and multitasking situations (Maxwell et al., 2000; Steenbergen et al., 2010; Zhu et al., 2015). Research shows that implicit learners are able to maintain performance under psychological stress and pressure due to having limited explicit knowledge about their movements. This in turn prevents the automatic functioning of their movements from being disrupted by reinvestment (Liao & Masters, 2001; Masters, 1992). Motor performance also remains stable under multi-tasking requirements. This is due to implicit learners having a limited dependence on working memory for motor performance, thereby allowing working memory resources to be utilized to conduct the secondary task. This ability to maintain motor performance under a secondary task load sets implicit learners apart from explicit learners, who are more likely to experience a decline in performance due to being highly dependent on working memory resources for motor performance. The addition of a secondary task load places pressure on working memory resources as they are needed for conducting both the motor movement and the secondary task, which leads to a decline in motor performance (Poolton & Zachry, 2007).

Unfortunately, implicit motor learning paradigms are difficult to implement and not all of the methods effectively bypass working memory. Based on the motor performance benefits, new implicit motor learning paradigms should be formulated. Cognitive fatigue has shown potential in sequence learning. Borragan, Slama, Destrebecqz, and Peigneux (2016) indicate high levels of cognitive fatigue facilitates procedural sequence learning. Borragan et al., (2016) proposed that procedural learning that occurred in a High Cognitive Load (HCL) condition was a result of a reduction in resources assigned to cognitive control, which normally prevent learners from utilizing automatic procedural processes. In this thesis, we aim to determine whether induced cognitive fatigue can be utilized to suppress verbal working memory activity. We hypothesize that by fatiguing verbal working memory we will be able to prevent learners from actively acquiring knowledge about how they move, thereby encouraging implicit motor performance.

1.2 Aims

The overarching aim of this thesis is to identify whether human working memory can be fatigued to prevent learners from actively acquiring knowledge about how they move.

Objectives to achieve this goal are:

1. Induce temporary cognitive fatigue utilizing a Time load Dual-back (TloadDback) task (Borragan et al., 2016).

2. Investigate whether induced cognitive fatigue produces a decrease in verbal working memory capacity post-intervention.

3. Compare the difference in subjective levels of fatigue (VAS-f) between treatment conditions.

4. Investigate whether performance accuracy decreased during the completion of the TloadDback task due to the onset of fatigue.

5. Analyse the difference in motor performance between treatment conditions under a single task and a dual task load.

6. Compare the difference in reported levels of cognitive-motor processing (CMP) between treatment conditions during the single motor task.

7. Assess hypothesis testing by measuring the number of movement adjustments (fidgets) made within each treatment condition during the golf putting task.

8. Compare electroencephalogram (EEG) coherence between groups during the golf putting task to assess whether cognitive fatigue reduces the learners engagement in verbal analytical processes during motor performance.

1.3 Research benefits

Research benefits include:

1. Extending current research concerning the effect of cognitive fatigue on working memory and implicit motor learning.

2. Expanding current research concerning the effectiveness of the TloadDback task as a mechanism for inducing temporary cognitive fatigue.

3. Development of a new tool with which to promote implicit motor learning and performance of motor skills. Significant advantages accompany the acquisition of movement skills without conscious awareness of the knowledge that underlies them. These advantages are particularly obvious in people who have a predisposition to ‘over think’ their movements and could be of benefit in sports, rehabilitation, and medical domains.

Chapter 2: Literature Review

2.1 Chapter framework

This chapter begins by providing a conceptual background to working memory, followed by discussion of the different methods of motor skill learning and the impact these learning techniques have on motor performance. Current research on cognitive fatigue is explored to determine whether it could be a viable method for producing implicit motor learning. The chapter concludes with a summary of findings and suggestions for future research.

2.2 Working memory

Human working memory is a facility within the brain, which acts like a mental workspace enabling us to temporarily store, process and manipulate information (Baddeley, 1986; Baddeley, 2003; Baddeley & Logie, 1999; Gathercole & Alloway, 2008; Holmes, 2012; Reuter-Lorenz, Jonides, Smith, Hartley, Miller, Marshuetz & Koeppe, 2000; Thorn, 2006). Working memory is a multifaceted system comprised of a central executive and three subsystems: the phonological loop, the visuospatial sketchpad, and the episodic buffer (Alloway, Gathercole, Willis & Adams, 2004; Baddeley, 2000; Baddeley, 2003; Dehn, 2008). The primary system, the central executive is the most complex within working memory and is utilized in a variety of cognitive processes including: selective attention and inhibition, coordination and management of concurrent tasks, shifting between retrieval strategies, and interfacing with long-term memory (Alloway et al., 2004; Baddeley, 2012; Dehn, 2008). The phonological loop and visuospatial sketchpad are slave systems to the central executive and provide domain-specific storage (Alloway et al., 2004; Gathercole, Alloway, Willis, & Adams, 2006). The phonological loop is responsible for providing brief storage of auditory and verbal information, in addition to a vocal and subvocal rehearsal mechanism, which is utilized to maintain decaying verbal information (Baddeley, 2003; Baddeley, 2012; Dehn, 2008). Conversely, the visuospatial sketchpad enables the temporary storage of visual and spatial information and is responsible for the formation of visual images, memorizing dynamic spatial information and static visual information (Baddeley, 2012; Dehn, 2008). The final component of working memory, the episodic buffer, is a limited capacity system which utilizes a multidimensional code to integrate information from working memory and long-term memory into a unitary episodic representation (Alloway et al., 2004; Baddeley, 2000).

These working memory processes are crucial for everyday functioning, as they provide moment by moment cognition, allowing us to keep track of where we are and what we are doing (Logie & Morris, 2014). They are also fundamental for completion of a wide range of complex cognitive tasks, including language, reasoning, comprehension, executive attention, problem solving, cognitive control and learning (Baddeley, 1992; Baddeley, 2003; Masters & Maxwell, 2008; Thorn, 2006; Yan, Zhang, Gong & Weng, 2011).

Each individual has an upper limit to their working memory capacity, which dictates the amount of information held and processed at any one time (Gathercole & Alloway, 2008; Holmes, 2012). Through the implementation of complex span tasks, researchers can measure an individual's maximal verbal working memory capacity and visuospatial working memory capacity. These domain-specific measures can be used to predict an individual's academic abilities and performance levels in a variety of higher and lower order cognitive activities (Nadler & Archibald, 2014; Unsworth, 2007; Unsworth & Engle, 2007). Additionally, these capacity measures can be utilized within research to assess changes in working memory following experimental interventions.

2.3 Motor skill learning and performance

Motor skill learning is a targetted intervention, which produces relatively permanent changes to an individual's motor skill movements through goal orientated practice and task experience (McMorris, 2014; Seidler, Bo & Anguera, 2012; Tse, Wong & Masters, 2017; Voelcker-Rehage, 2008). It is an essential and ongoing process, as we are continuously tasked with learning new motor skills throughout our lives for an extensive range of purposes, including work, sport and leisure (Newell, 1991; Seidler et al., 2012; Tse et al., 2017). We also have to relearn and adjust our motor movements and skills during the rehabilitation of an injury or as we age or if our movement abilities regress in response to medical conditions, such as Parkinson’s disease (Masters & Poolton, 2012; Seidler et al., 2012; Voelcker-Rehage, 2008; Zhu et al., 2015). The manner in which we acquire our motor skill movements is fundamental as it can dictate the success of later performance.

The conventional method for learning a motor skill is termed explicit motor learning (McMorris, 2014). Explicit learners engage in numerous verbal analytical processes during repetition or practice, including the implementation of verbal instructions and feedback, formulating and testing hypotheses, making conscious movement adjustments to resolve outcome errors, and utilizing conscious monitoring and control mechanisms (Maxwell, Masters & Eves, 2003; McMorris, 2014; Poolton & Masters, 2010; Zhu et al., 2015). These verbal analytical processes are managed and executed utilizing resources from working memory and are shown to result in the accumulation of declarative knowledge (Poolton, Masters & Maxwell, 2005; Tse et al., 2017; Zhu et al., 2015). This form of knowledge is comprised of task-relevant rules that are encoded verbally, consciously available, and able to be articulated by the learner (Masters, 1992; Maxwell et al., 2003; McMorris, 2014; Poolton & Masters, 2010). Explicit learners utilize accumulated declarative knowledge to guide their motor performance during the motor skill acquisition process. Through the continued reinforcement and application of this knowledge, motor skill movements become automated and explicit control of the movements is gradually released (Maxwell et al., 2000; Maxwell et al., 2003).

Explicit learners are able to readopt these explicit conscious control mechanisms through a process of reinvestment. Reinvestment utilizes working memory resources to retrieve declarative knowledge from storage in long-term memory and to adapt and utilize the retrieved information to consciously control motor movements (Masters & Maxwell, 2008). This self-regulatory behaviour is prone to implementation under pressurized conditions and is particularly evident among high reinvesters, which can include people with Parkinson's disease or stroke, or older fallers – who have been shown to have a greater propensity for reinvestment (Masters, Pall, MacMahon & Eves, 2007; Orrell, Masters & Eves, 2009; Wong, Abernethy & Masters, 2015). Reinvestment can be detrimental to motor performance as it interferes with control mechanisms that are normally automatic (Malhotra et al., 2015; Masters, 1992; Masters & Maxwell, 2008; Poolton & Masters, 2010; Uiga et al., 2015).

An array of literature advises against the active accumulation of declarative rule-based knowledge during motor skill learning because such knowledge increases opportunty for reinvestment (Masters & Maxwell, 2008; Maxwell et al., 2000; Maxwell et al., 2003; Maxwell et al., 2006). Implicit motor learning offers a resolution to this problem, as learners are able to acquire motor skills without conscious movement knowledge being formulated (Maxwell et al., 2000). Implicit motor learning paradigms reduce the role of consciousness in learning (Poolton & Masters, 2010) and function with minimal dependence on working memory resources (Zhu et al., 2015). Researchers have previously formulated implicit motor learning paradigms utilizing approaches such as errorless learning, dual task learning, and analogy learning. Each method suppresses working memory activity, indirectly utilizing differing behavioural interventions (Zhu et al., 2015).

Errorless learning is aimed at limiting error correction behaviours and hypothesis testing by simplifying the motor task to reduce the occurrence of errors and employing fading procedures to gradually increase task difficulty (Maxwell, Masters, Kerr & Weedon, 2001; Poolman & Masters, 2010). Errorless learning has been shown to limit the accumulation of task-relevant knowledge and enables the learner to perform better under pressure (Maxwell et al., 2001; Poolton et al., 2005). An alternative method is dual task learning, during which learners engage in a novel motor task while concurrently completing a secondary task. The implementation of a secondary task during learning reduces the learner's ability to use working memory to form conscious knowledge and has been shown to result in more stable performance under pressure (Masters, 1992). The dual task method has been criticized due to the difficulty in transferring dual task protocols to a normal learning environment (Beek, 2000; Maxwell et al., 2000). In addition, learning tends to be slower than explicit learning (Maxwell et al., 2000; Poolton et al., 2005). In contrast, analogy learning condenses an array of task-relevant rules into a biomechanical metaphor that facilitates learning (Lam et al., 2009; Masters, 2000). Analogy learning minimises the accumulation of task-relevant knowledge and has also been shown to result in stable motor performance under psychological pressure (Liao & Masters, 2001).

While practical for reducing the occurrence of performance breakdown, these learning methods are reported to encounter limitations that hinder practical application (Lam et al., 2009; Zhu et al., 2015). Consequently, Zhu et al., (2015) investigated cathodal transcranial direct current stimulation (tDCS) over the left dorsolateral prefrontal cortex (DLPFC) as a viable method for producing implicit motor learning. In contrast to previous research methods, the researchers aimed to suppress verbal working memory activity directly during the training phase to inhibit learners from utilizing verbal analytical processes to learn. The results of this study indicate that cathodal tDCS over the left DLPFC successfully suppressed the working memory activity of the experimental group. The golf putting performance results showed that participants who received tDCS scored a higher number of successful putts than the control group across the training and testing phase. In addition, the experimental group performed better on a multitasking test, which required participants to complete a golf putting task in conjunction with a secondary tone counting task. This result is consistent with the outcomes from previous research on implicit learning, which have shown that the motor performance of explicit learners deteriorates under pressure, while the motor performance of implicit learners remains stable. Zhu et al., (2015) report that the outcomes of the multi-taking test suggest that the performance of the experimental group was more implicit and automatic than the control group. Overall, the results of this study are promising, as alternative methods of direct working memory suppression need to be explored in order to find alternative implicit motor learning paradigms.

2.4 Cognitive fatigue:

A large corpus of literature has defined cognitive fatigue as a psychobiological state that occurs during or following prolonged periods of demanding cognitive activity (Boksem & Tops, 2008; Borragán, Slama, Bartolomei & Peigneux, 2017; Ishii, Tanaka, Shigihara, Kanai, Funakura & Watanabe, 2013; Ishii, Tanaka & Watanabe, 2014; Marcora, Staiano & Manning, 2009). Cognitive fatigue is commonly characterised by subjective feelings of tiredness, exhaustion, reduced motivation and a lack of energy. Research indicates that when an individual is cognitively fatigued they shift to utilizing a less working memory dependent strategy (Jongman, Meijman & Jong, 1999). This finding suggests the induction of temporary cognitive fatigue prior to motor skill learning could be a viable technique for encouraging learners to adopt implicit processes, due to implicit learning functioning with minimal dependence on working memory. In line with this research, a study by May, Hasher, and Foong (2005) indicates that attempts to consciously process and retrieve information is more successful during peak times of day, when presumably working memory is least fatigued. Additionally, non-optimal times of day are shown to enhance implicit learning, with responses becoming more automatic and unconscious (Delpouve, Schmitz & Peigneux, 2014; May et al., 2005). Further research is needed to explore whether induced cognitive fatigue replicates the effects of non-optimal time of day to produce implicit learning.

In a study conducted by Anguera, Bernard, Jaeggi, Buschkuehl, Benson, Jennett, Humfleet, Reuter-Lorenz, Jonides and Seidler (2011), spatial working memory resources were reduced by utilizing a fatigue-based resource depletion task. This reduction in resources was verified by a decline in performance on a spatial working memory task. The depletion effect was shown to have a domain specific impact on spatial working memory faculties as performance in a digit symbol task was maintained following the depletion protocols. This study draws similarities to the work of Zhu et al., (2015) due to the direct impact both interventions have on working memory resources. Future research should explore whether a depletion task of verbal equivalence would result in the depletion of verbal working memory resources. Based on current implicit motor learning literature the direct depletion of verbal working resources should eliminate the availability of verbal analytical processes necessary for explicit learning, thereby encouraging a shift to implicit motor learning processes.

In other work (Borragan et al., 2016), participants were induced with temporary cognitive fatigue utilizing the Time load Dual-back (TloadDback) task. The TloadDback task combines an N-back task with a decision making task. During this task, participants were presented with a continuous series of digits and letters on the screen for a total of 16 minutes. For each digit that was presented, participants had to determine whether the number was even or odd, pressing 1 or 2 on the numeric keyboard to indicate their answer. Each time a letter was the same as the previous letter, participants had to press the spacebar. The available processing time was set to 85% of the participants maximal capacity in the High Cognitive Load (HCL) and ⅓ slower than the participants 85% maximal capacity in the Low Cognitive Load (LCL) condition.

The induction of cognitive fatigue was assessed subjectively utilizing the Visual Analogue Scale for fatigue (VAS-f) and objectively utilizing the TloadDback performance accuracy scores from four consecutive time intervals (t1, t2, t3 and t4). The subjective results showed that the TloadDback fatigue task produced an increase in self-reported fatigue levels (VAS-f) across both the HCL condition (2.66$\pm$2) and the LCL condition (1.22 $\pm$1.59). Futhermore, participants in the HCL condition reported significantly higher levels of fatigue (VAS-f) than the participants in the LCL condition ($p<.05$). The objective performance accuracy scores showed a main effect of cognitive load, as participants in the LCL condition performed significantly better than the participants in the HCL condition throughout the TloadDback task ($p<.001$). Performance accuracy was shown to decrease between t1 and t4 for all participants (p<.01), however this decrease was more rapid for the participants in the HCL condition.

Sequence learning occurred in both the HCL and LCL conditions, with cognitive fatigue being shown to elicit a facilitating effect on the sequential element of motor sequence learning. Participants within the LCL condition were shown to perform better on the sequence generation task, which indicates participants within the HCL condition had less control over the sequences being learned. Additionally, reaction time scores for the sequential trial blocks were faster in the HCL condition, which suggests the learning in the HCL condition was more automatic.

This study provides further indication that induced cognitive fatigue is a viable method for shifting learning to automatic processes. However, a limitation of this study is the lack of brain activity measurements, which need to be addressed within future studies to provide a clearer assessment of verbal analytical involvement during motor output. Additionally, future research should supplement the current subjective and objective measures used to verify the induction of cognitive fatigue by measuring the pre-post changes in working memory performance.

The TloadDback task was employed by Borragan et al., (2017) in a secondary study, which analysed methods for manipulating cognitive load. The results indicated that cognitive fatigue is triggered by the continuous cognitive effort produced by the pressures of constrained processing time. This study also highlights the importance of individualising cognitive load by manipulating the available processing time. This links with the research conducted by Jongman et al., (1999) indicating cognitive fatigue needs to be individualised as each person is not equally susceptible to fatigue, as individuals with higher working memory capacity are less susceptible to the induction of cognitive fatigue. Future research could explore cognitive fatigue recovery times and the differences in recovery based on cognitive load levels and working memory capacity.

2.5 Chapter summary

The verbal faculties of working memory play an important role in the verbal analytical processes of explicit learning. Researchers promote the use of implicit motor learning paradigms to minimise the utilization of verbal working memory faculties during learning in order to prevent learners from actively acquiring knowledge about how they move. Difficulties exist in implementing implicit learning paradigms into normal learning settings and eliminating working memory activity during learning. Direct working memory suppression is shown to be a beneficial mechanism for producing implicit learning, but further research is required to explore alternative methods for directly manipulating working memory. Cognitive fatigue has been shown to encourage individuals to shift to a less working memory dependent strategy of learning and thus to encourage more automatic responses. Furthermore, visuospatial working memory resources were successfully depleted utilizing a fatigue based depletion task. This evidence suggests that cognitive fatigue could be an effective mechanism for manipulating working memory resources, as it has previously been shown to produce shifts in working memory activity.

Further research is needed to understand the impact of cognitive fatigue on verbal working memory faculties and motor skill learning. To our knowledge, currently no literature exists on the use of cognitive fatigue as a mechanism for fatiguing verbal working memory in order to prevent the occurrence of hypothesis testing. However, present research provides evidence to suggest that the induction of cognitive fatigue prior to motor skill learning will suppress working memory and reduce verbal analytical processes involved in accumulation of task-relevant knowledge.

Chapter 3: Research Study

Fatiguing verbal working memory to reduce explicit hypothesis testing during skill acquisition: A new implicit motor learning paradigm?

3.1 Abstract

Objective: To investigate whether human working memory can be fatigued in order to prevent learners from actively acquiring knowledge about how they move. Methods: Thirty-three healthy adults (women=19, men=14; mean age= 23.3±5.5) were randomly assigned to a treatment condition: control (non-fatigued) or experimental (fatigued). We analysed the impact of induced cognitive fatigue on working memory capacity, motor performance and hypothesis testing, compared to a non-fatigued control group. Results: Participants in the experimental condition reported a significant increase in subjective fatigue (VAS-f) scores following the implementation of a working memory capacity pre-test ($p<.001$) and a Time load Dual-back (TloadDback) fatigue task ($p<.001$). However, this increase in subjective fatigue levels produced by the fatigue task was not reflected by a change in working memory capacity and TloadDback performance. Additionally, the fatigue task did not produce a reduction in hypothesis testing as expected. Discussion: While the cognitive fatigue task successfully altered subjective levels of fatigue, we speculate that fatigue levels were insufficient to alter working memory activity enough to prevent verbal analytical processing during motor learning.

3.2 Introduction

Learners favour the use of verbal analytical processes during motor skill acquisition, choosing to actively engage in hypothesis testing, error correction and conscious control behaviours when the option is available (Poolton & Masters, 2010). By engaging in these explicit processes, the learner accumulates declarative rule-based knowledge and consequently becomes susceptible to reinvestment during motor output. Reinvestment is the process of utilizing working memory resources to retrieve declarative knowledge from storage in long-term memory and to adapt and apply the retrieved information to consciously control movements (Masters & Maxwell, 2008). Research suggests that reinvestment occurs in pressurised situations, interfering with the automaticity of the movements and causing suboptimal motor performance (Masters, 1992; Masters & Maxwell, 2008; Poolton & Masters, 2010). As a consequence, researchers have examined methods for preventing breakdowns in performance caused by reinvestment and have suggested a need to shift learners to implicit processes (Masters, 1992; Masters & Maxwell, 2008; Maxwell et al., 2000; Maxwell et al., 2006; Poolton & Masters, 2010; Poolton, Maxwell & Masters, 2004).

Implicit motor learning paradigms minimise the active role of working memory, thereby preventing learners from enlisting verbal analytical processes during learning (Zhu et al., 2015). This kind of learning promotes low electroencephalography (EEG) coherence between the motor planning region (Fz) and the verbal analytical processing region (T7) (Zhu, Poolton, Wilson, Maxwell & Masters, 2011). EEG coherence measures the degree of association between different regions within the brain (Buszard et al., 2016, p. 248). Low EEG coherence between Fz-T7 is an indicator of regional independence, and limited verbal analytical involvement in movement (Buszard, Farrow, Zhu & Masters, 2016; Zhu et al., 2011). This reduction in verbal analytical processes is also reflected in the number of technique changes made during learning. Research shows that implicit learners make fewer visible adjustments to their motor movements than explicit learners, due to hypothesis testing behaviours being limited (Maxwell & Masters, 2008; Maxwell et al., 2001). Implicit learners also benefit from accumulating procedural knowledge during the learning process. This form of knowledge is consciously inaccessible and can not verbalized by the learner (Steenbergen et al., 2010). Research indicates that limited conscious knowledge is associated with reduced reinvestment and robust performance under pressure, fatigue, anxiety and multitasking requirements (Steenbergen et al., 2010; Zhu et al., 2015). This ability to maintain performance under these stressful conditions is unique to implicitly learned motor skills and is a stark contrast to the performance results produced by explicit learners under identical stress procedures (Steenbergen et al., 2010).

A recent study examined cathodal tDCS over the left DLPFC area, as a method for suppressing working memory activity and inhibiting the use of verbal analytical processes during motor learning (Zhu et al., 2015). Unlike previous implicit motor learning paradigms, the tDCS method was shown to suppress verbal working memory directly. Golf putting performance results showed that the group that received tDCS had higher performance accuracy than the control group, across the training and testing phases. Futhermore, the experimental group had a superior performance on the multi-tasking test, indicating tDCS enabled for a more automatic and implicit performance to occur. These results provide an indication that the direct suppression of working memory may be a more efficient method of producing implicit motor learning than previously employed indirect suppression methods. Indirect suppression methods have encountered limitations in the elimination of working memory activity from the learning process.

As such, we argue that cognitive fatigue could produce a similar effect to tDCS by directly supressing working memory. Research illustrates that cognitive fatigue is capable of modifying working memory strategies (Jongman et al., 1999) and the availability of working memory resources (Anguera et al., 2011). A recent study conducted by Borragan et al., (2016) demonstrates that high levels of cognitive fatigue can facilitate procedural sequence learning. Borragan et al. (2016) suggested that the procedural learning that occurred in a high cognitive load condition was a result of a reduction in resources assigned to cognitive control, which normally prevent the occurrence of automatic procedural processes. The present study aims to examine whether induced cognitive fatigue can deplete working memory resources, thereby minimising a learner's ability to test hypotheses during motor skill acquisition. Based on current literature, we expect that a reduction in hypothesis testing will encourage learners to acquire a novel motor skill implicitly. We hypothesize that participants in the experimental condition will exhibit more stable motor performance under a dual task load, reduced EEG coherence between T7 and Fz, and fewer movement adjustments (fidgets) during motor performance.

3.3 Methods

3.3.1 Participants

Thirty-three healthy adults (women=19, men=14; mean age= 23.3±5.5) volunteered to participate in the study. All participants were classified as novices to golf, having reported limited playing experience (<4 hours). The study was approved by the University of Waikato Human Ethics Committee (Health) and informed written consent was obtained from all of the participants prior to commencing the testing process (See Appendix 3).

3.3.2 Experimental design and procedure

We employed a repeated measures design, as illustrated in Figure 2. Each task was presented in a systematic order to test the effects of induced cognitive fatigue on verbal working memory performance, subjective levels of fatigue (VAS-f), and golf putting performance compared to a normative control. All participants were randomly assigned to a treatment condition before reporting to the motor skill learning laboratory for testing

(Experimental=17; Control=16). Participants were blind to their assigned treatment condition.

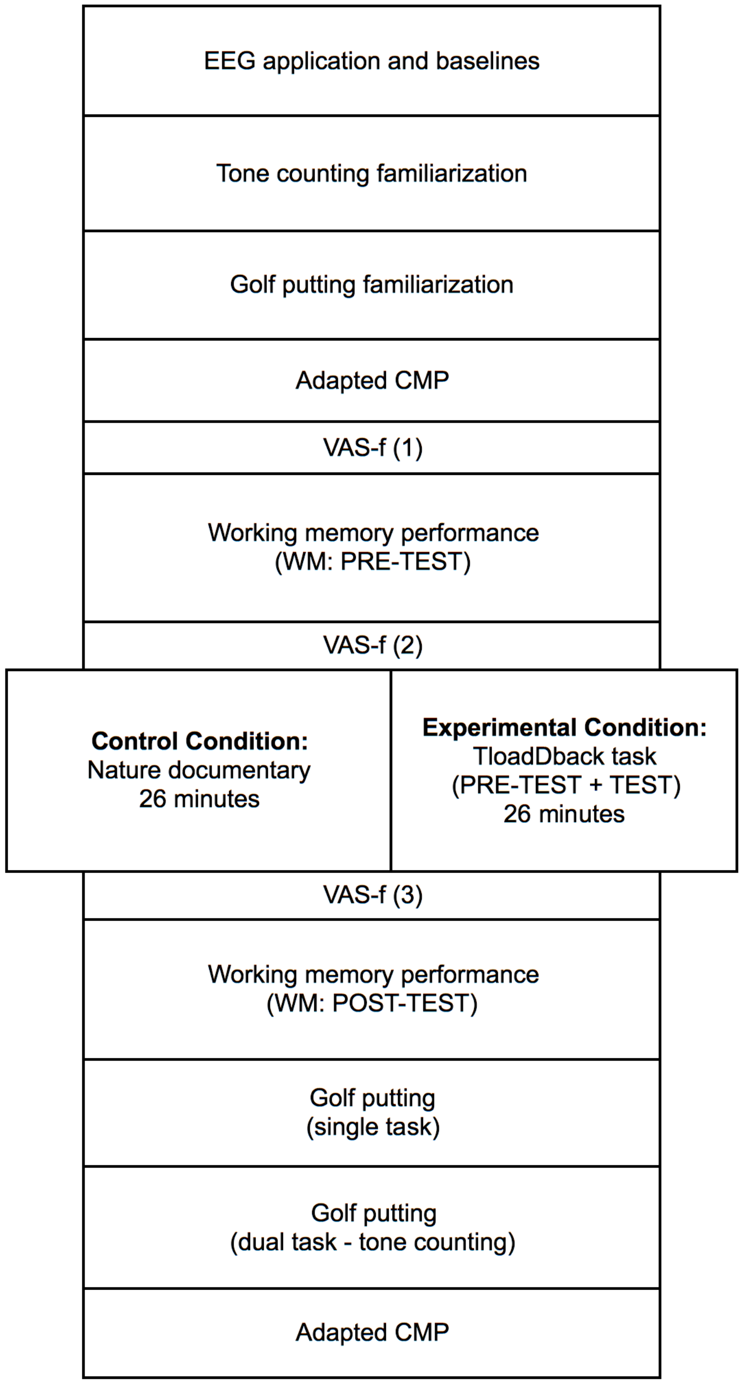

Figure 2. Illustration of experimental design.

Following consent proceedings, the electroencephalography (EEG) application procedure was verbally discussed with the participants. A Neoprene head cap was then fitted, and the electrodes were inserted into the cap across 8 scalp locations (T7, T8, F3, F4, FP1, FP2, Fz, Cz). Conductive gel was syringed into each electrode and the electrode cables were attached. Neurosurfer was then utilized to conduct impedance checks then the EEG recording was started. An initial baseline EEG measurements was taken, during which participants had to sit with their eyes closed for thirty seconds, sit with their eyes open for thirty seconds and stand and hold the golf putter against a ball as if they were going to putt the ball to a target circle for thirty seconds.

Following these baseline EEG measures, a tone counting familiarization protocol was implemented. Participants were required to count the number of low pitched tones that occurred during a set time span. This protocol ensured participants could differentiate between the high and the low pitched tones randomly generated by the computer every second, which is necessary for the dual motor task. Participants then performed two familiarization putts to a marked circle, following the procedures outlined in section 3.3.5.

The learners propensity for conscious motor processing (CMP) was assessed using an adapted version of Masters, Eves and Maxwell's (2005) conscious motor processing subscale from the Movement Specific Reinvestment Scale (See Appendix 6). This questionnaire consisted of five questions relating to the participant's golf putting movements. For each question, participants were require to select an answer on a 6 point Likert scale ranging from strongly disagree to strongly agree. Subjective fatigue scores were then collected using Lee, Hicks and Nino-Murcia's (1991) Visual Analogue Scale for fatigue (VAS-f; See Appendix 7). This questionnaire is composed of four questions, participants were asked to indicate their level of tiredness, cognitive fatigue, efficiency and ability to concentrate on a scale from 1-10. This self-reported measure provided a baseline score for the participants level of cognitive fatigue.

Participants performed a working memory pre-test, as outlined in section 3.3.3, followed by the implementation of the VAS-f questionnaire, which was used to examine the impact of the working memory pre-test on perceived levels of fatigue. Participants assigned to the experimental condition then completed a computerised cognitive fatigue task as outlined in section 3.3.4. In contrast, participants assigned to the control condition watched a nature documentary, which was administered on the same screen utilised in the experimental condition for the fatigue protocols. Each intervention lasted a total of 26 minutes. A final measure of subjective fatigue (VAS-f) was recorded to examine the level of perceived fatigue produced by each intervention. This was followed by a working memory post-test, which measured the impact of each intervention on working memory performance. Participants then performed a single familiarization putt to the target circle, followed by two trial blocks of golf putting, using the protocols outlined in section 3.3.5. The initial block of trials was a single task, composed of ten putts to a target circle. The second block of trials was a dual task. Participants were required to complete ten putts to a target circle, while concurrently counting the number of low tones that were produced by computer software. The testing session was concluded by measuring the participants self reported CMP levels from the single task motor trials. This measure was used to assess whether there were any differences between groups in CMP post intervention.

3.3.3 Working memory assessment

Verbal working memory performance was assessed utilizing an adapted version of the Daneman and Carpenter (1980) original reading span task, and

Unsworth, Spiller and Brewer's (2009) automated complex span task. During each trial, participants were presented with a set of numbers and short sentences in alternating order on the screen. Each number that was presented had to be recalled at the end of the trial. After each number, participants were shown a short sentence and had to process the veracity of the sentence while concurrently remembering the set of numbers. To conclude each trial, participants were asked to recall each of the numbers they were shown in the correct serial position (See Figure 3.). Participants received instant visual feedback on their responses during each trial.

Each trial block was composed of three trials, beginning at span size 2 and increasing incrementally (span 2 - span 9). Participants progressed through the task until errors were made in each trial at a particular level, then the test was discontinued. An error was defined as a number being recalled incorrectly or in the incorrect serial position. In addition, participants were required to get at least one short sentence correct in each trial, or else it was counted as an error as the participant was focusing solely on the memory and recall component of the task.

All participants initially completed a pre-test to establish their maximal working memory capacity. This was followed immediately by a retesting phase, which required participants to perform a second block of trials at their highest achieved level to ensure the baseline measure was correct. During the post-test, participants began the test at two levels below their maximal capacity and progressed through each trial block until they met the discontinuation protocol.

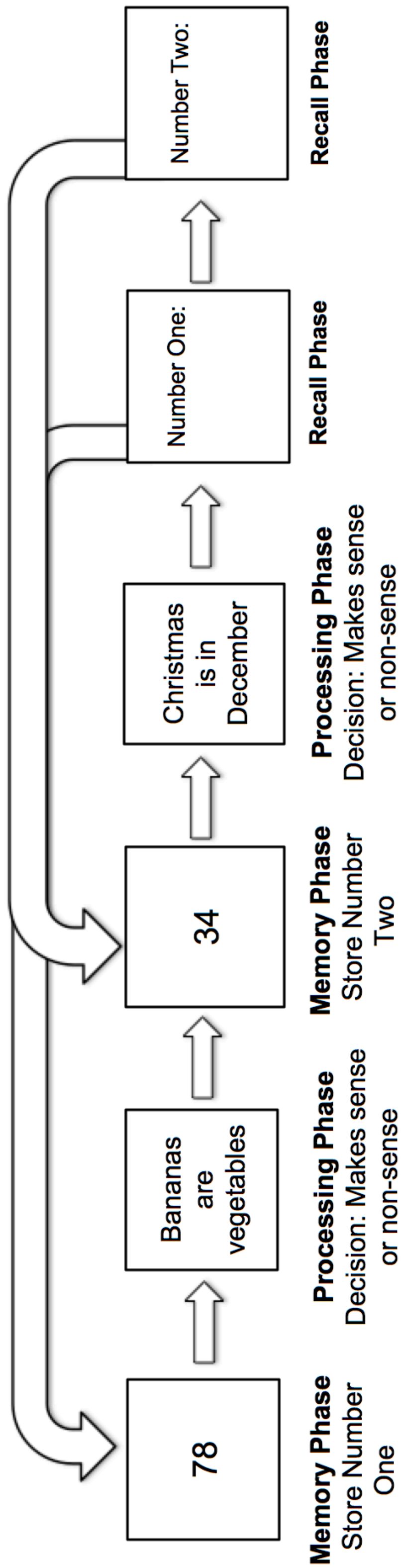

Figure 3. Illustration of the working memory assessment.

3.3.4 Cognitive fatigue task

Participants assigned to the experimental condition performed a Time load Dual-back (TloadDback) task (Borragan et al., 2016), which is comprised of a pre-test and a test. During the task, participants were presented with a continual series of digits and letters in an alternating order on the screen (see Figure 4.). Participants had to decide whether each digit presented was odd or even, and to indicate an even number by pressing “2” and an odd number by pressing “3” on the numeric keypad. Each time the displayed letter was the same as the preceding letter (1-back), participants were instructed to press the spacebar.

During the TloadDback pre-test, the speed at which the digits and letters were presented fluctuated, thereby manipulating the available processing time. The pre-test established the participant's maximal load level and was used to individually calculate the processing time where the participants performed with an 85% performance accuracy on the task.

Immediately after participants were administered the TloadDback test, the pre-test result was used to set the available processing time for each participant. Participants performed the TloadDback task for 16 minutes with the stimulus presented at the participants 85% capacity.

The fatigue protocol lasted a total of 26 minutes. Objective performance measures were collected during the TloadDback test, to assess the evolution of performance accuracy across four consecutive time periods (t1, t2, t3, t4).

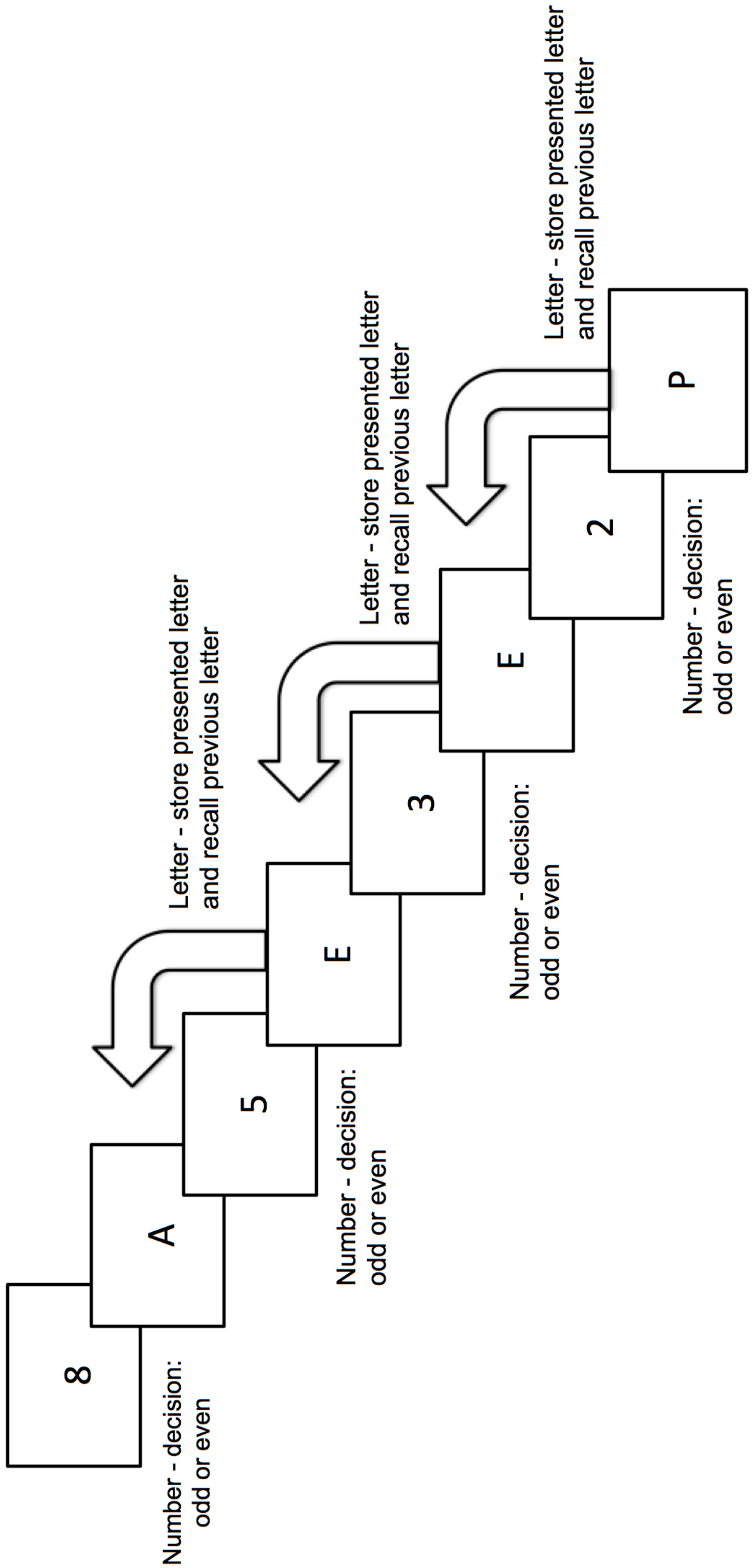

Figure 4. Illustration of the TloadDback assessment.

3.3.5 Golf putting task:

The golf putting task required participants to putt the ball from the marked starting location, across a level artificial green and land the ball on the target circle located 3m away. The size of the target circle replicated a standard sized golf hole (4.25 inch in diameter) and all participants used a 35-inch golf putter and standard white golf balls. Participants performed the golf putting task without any prior knowledge of the task, and no information or demonstrations were provided on how to hold the golf putter.

Participants were instructed not to practice between putts, and to watch the computer screen for visual cues on when to prepare for the movement and when to execute the putting movement. These visual cues were utilized to inform the insertion of markers into the EEG recording and to reduce the disruption to participants during the dual task.

At the beginning stages of the testing session, participants completed two familiarization putts to develop an understanding of the task protocols. Participants were limited to two putts in order to minimise the occurrence of verbal analytical processes prior to the implementation of the fatigue protocols. To begin the motor performance testing phase, participants completed a single familiarization putt to the target circle. Participants then completed two blocks of trials. The first block of trials was under a single task load, requiring participants to complete ten putts to the target circle. During the second block of trials, participants performed ten putts to the target circle, in conjunction with the secondary task of tone counting. The tone counting task required participants to count the number of low tones that occurred throughout their ten putts.

Putting performance accuracy was recorded by measuring distance (metres) to the target. Throughout the golf putting task, movement adjustments (fidgets) were video recorded to measure the amount of hypothesis testing that occurred during motor performance. Movement adjustments were defined as any significant changes in body position, putter position and motor movements made by the participant in an attempt to improve performance accuracy.

In addition, EEG was recorded from 8 scalp locations (T7, T8, F3, F4, FP1, FP2, Fz, Cz) to measure the level of coherence between the different locations. Our primary focus was to measure the coherence between T7 and Fz to test the amount of hypothesis testing occuring during motor performance.

3.4 Results

3.4.1 Subjective fatigue scores (VAS-f)

A two-way analysis of variance was conducted in order to analyse subjective fatigue scores in the two groups (Group; 2 x Test; 3). The results revealed a significant main effect of test ($F(2,62)=28.846$, $p<.001$), which indicates that the participants felt a significant increase in fatigue over time with the implementation of each additional test. A group effect was not evident in the results ($F(2,62)=.589$, $p=.449$), although a Test x Group interaction was evident ($F(2,62)=9.253$, $p<.001$). One-way repeated-measure ANOVA tests were conducted for the two groups separately, with both groups meeting the assumption of sphericity. One-way repeated-measure ANOVA for the experimental group revealed a significant effect for test on VAS-f scores ($F(2,32)=41.541$, $p<.001$). Post-hoc tests using Bonferroni corrections revealed that VAS-f score significantly increased from baseline (14.71±5.86) to both other tests (Post WMC pre-test (19.94±5.19) and Post intervention (26.41±4.65)), and was different between Post WM pretest and Post intervention (all $p<.001$). One-way repeated-measure ANOVA for the control group did not reveal a significant effect for test (F(2,30)=3.048, *p*=.06).

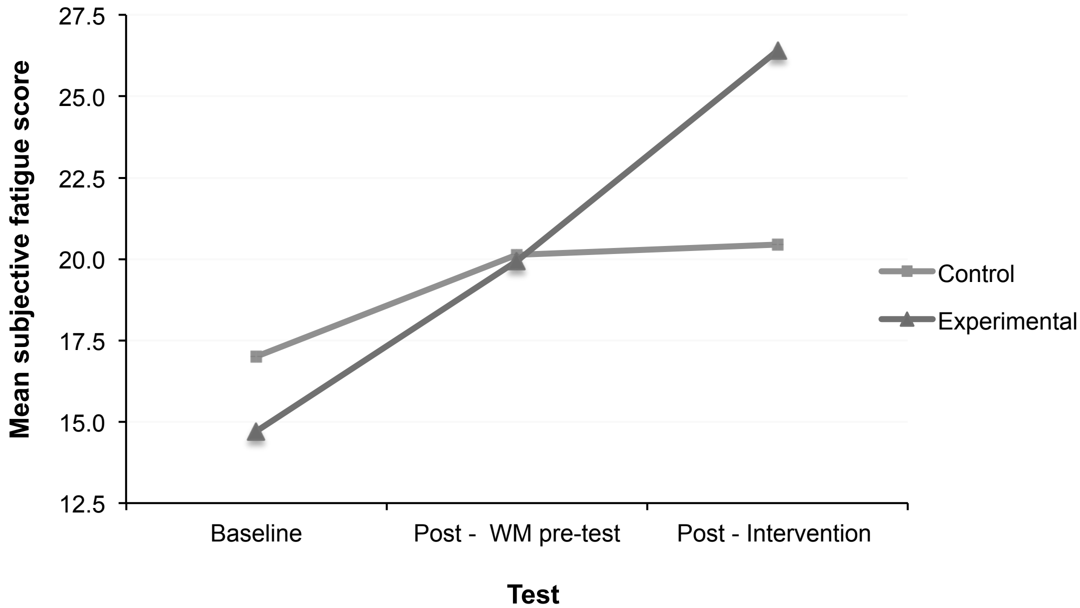

Figure 5. Subjective fatigue scores (VAS-f). Mean perceived fatigue scores for baseline, following the implementation of the working memory (WM) pre-test and following interventions in the experimental and control conditions.

3.4.2 Objective fatigue scores

The mean performance accuracy scores for the TloadDback test over four consecutive time periods were 80% for t1, 77% for t2, 78% for t3, and 79% for t4. Paired samples t-tests with Bonferroni corrections were used to compare the scores at each time period (.05/6 = .008). No significant effects were found, although the difference between t1 and t2 was *p* = .047. These results are illustrated in Figure 6.

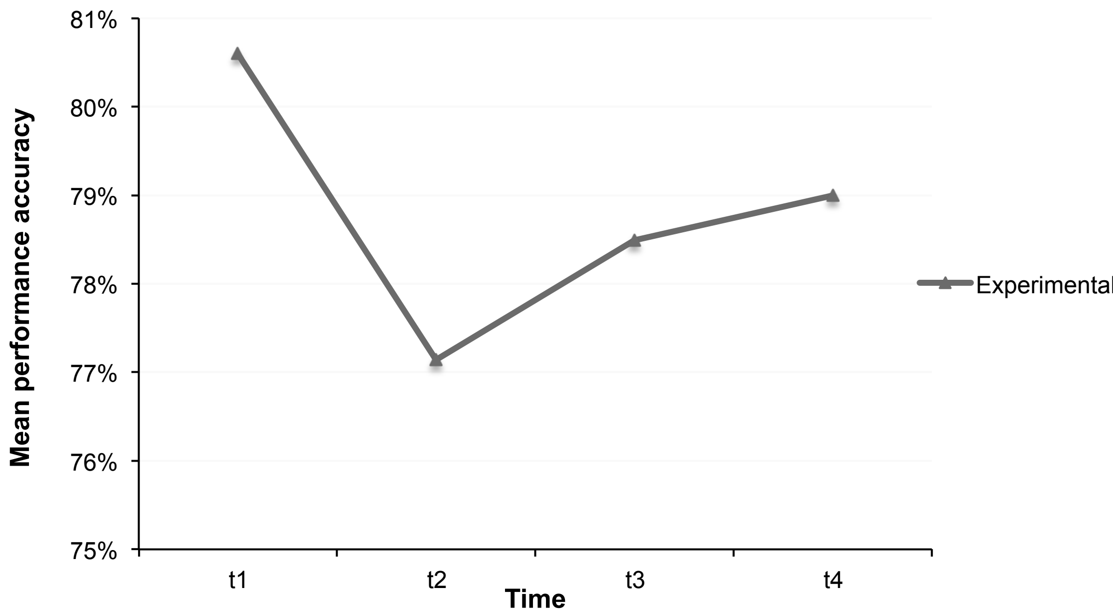

Figure 6. Objective fatigue scores. Mean performance scores over four consecutive time periods during the TloadDback task. Note that no such scores were available for the control condition.

3.4.3 Working memory (WM) performance

We conducted a repeated measures ANOVA to examine working memory performance in the two groups (Group; 2 x Test; 2). A main effect of test was not evident (F(1,31)=0.564, *p*=.458). However, a significant main effect of group was evident (F(1,31)=5.214, *p*=.029), which indicates a significant difference in performance scores between groups even at baseline, despite the participants being randomly allocated to a treatment condition. A Test x Group interaction was not evident (F(1,31)=1.783, *p*=.192). These results are illustrated in Figure 7.

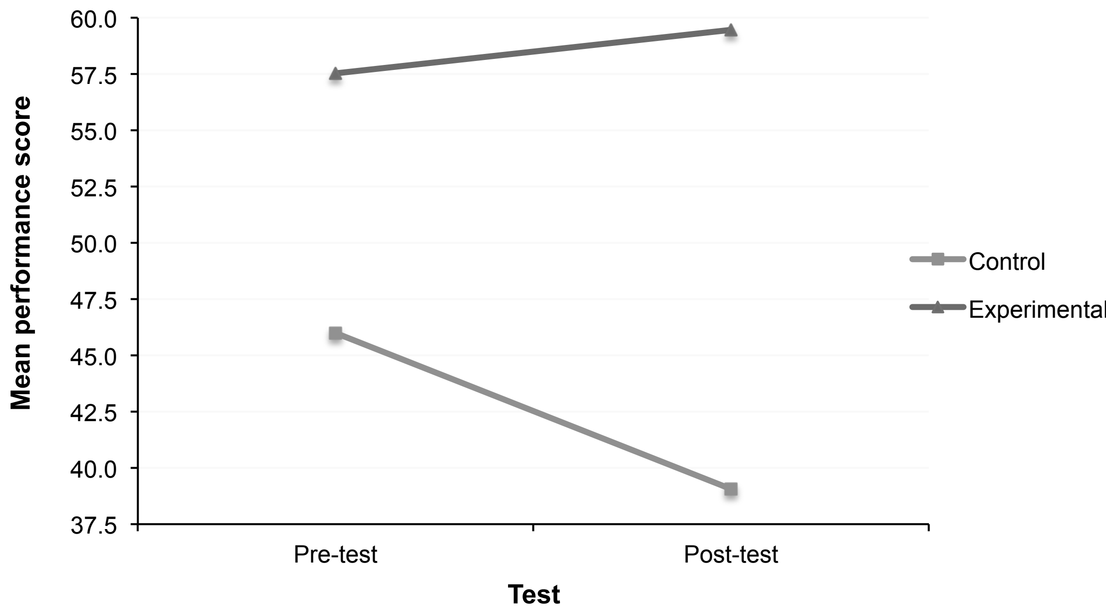

Figure 7. Working memory performance. Mean performance scores for the working memory pre-test and post-test in the experimental and control conditions.

3.4.5 Conscious motor processing

A two-way analysis of variance was conducted in order to analyse conscious motor processing scores in the two groups (Group; 2 x Test; 2). The results indicate no main effect of test ($F(1,31)=.211$, $p=.649$) and no main effect of group ($F(1,31)=1.082$, $p=.306$). In addition no effect in Test x Group interaction was evident ($F(1,31)=2.862$, $p=.101$).

3.4.6 EEG coherence

A two-way analysis of variance was conducted in order to analyse EEG coherence between Fz and T7 Alpha 2 in the two groups during golf putting (Group; 2 x Test; 2). The results indicate no main effect of test ($F(1,31)=.982$, $p=.329$) and no main effect of group ($F(1,31)=.293$, $p=.592$). In addition no effect in Test x Group interaction was evident ($F(1,31)=.940$, $p=.340$).

3.4.7 Movement adjustments

The mean number of adjustments (fidgets) for the experimental group was 3.06, the mean number of fidgets for the control group was 2.88. An independent samples t-test showed no significant difference (p =.807).

3.4.8 Golf putting performance

We ran a repeated measures ANOVA to examine golf performance accuracy in the two groups (Group; 2 x Test; 2). A main effect of test was not evident (F(1,31)= 2.641, p=.114) and a main effect of group was not evident within the results (F(1,31)=.005, p=.528). Additionally, there was no effect of Test x Group interaction (F(1,31)= .408, p=.528). These results are illustrated in Figure 8.

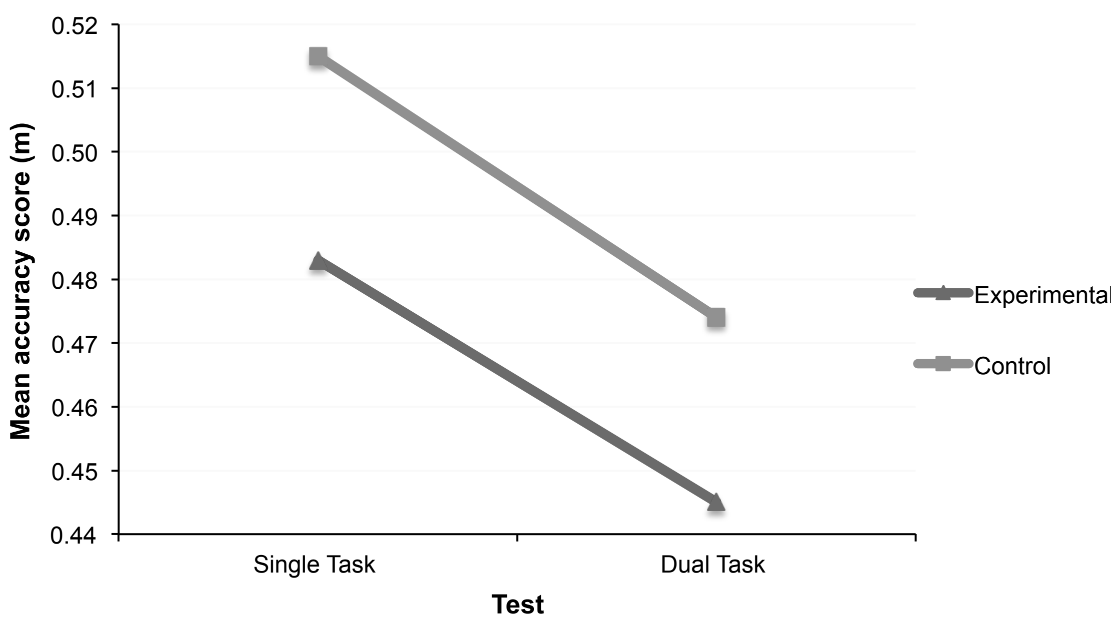

Figure 8. Golf putting performance. Mean accuracy score (m) during the golf putting test for single task and dual task performance in the experimental and control conditions.

3.5 Discussion

This study investigated whether induced cognitive fatigue could be used to fatigue verbal working memory. We hypothesized that fatiguing verbal working memory would prevent novices from generating and testing hypotheses during motor performance, thereby allowing the motor task to be performed implicitly. Participants in the experimental condition were expected to exhibit stable motor performance under a dual task load, limited movement adjustments, and low EEG coherence between T7 and Fz as a result of utilizing implicit processes during motor performance.

The induction of temporary cognitive fatigue was assessed utilizing subjective levels of fatigue (VAS-f), TloadDback performance and working memory performance. The VAS-f results illustrate that participants in the experimental condition reported a significant increase in subjective levels of fatigue following the implementation of the TloadDback task. In contrast, the control condition displayed no significant change in subjective fatigue levels. These results suggest the TloadDback task may have successfully induced cognitive fatigue in the experimental group, while the control group were unaffected by the non-fatiguing protocol.

The objective results of the TloadDback test show performance accuracy declined between t1 and t2, before unexpectedly increasing at t3, and t4. This suggests the experimental participants may not have been adequately fatigued by the TloadDback task, as suggested in the VAS-f results. We suspect the decline in performance accuracy may be influenced by the participant's motivation levels, as the TloadDback test was implemented directly following the pre-test. Interestingly, performance accuracy was below the 85% set level even at t1, which may also be an indicator of reduced motivation levels.

The working memory performance results illustrate that the experimental group experienced no change in performance score following the implementation of the TloadDback task. These findings coincide with the TloadDback performance results, suggesting the TloadDback task was unsuccessful in inducing participants with cognitive fatigue. The control group was shown to have a minor decline (insignificant) in performance accuracy at post-test; however, we are unsure why this was the case. The control group were also shown to have significantly lower performance scores than the experimental group. These differences in performance were unexpected, as the participants were randomly assigned to a treatment condition.

We also assessed the impact of the working memory assessment on VAS-f scores. The results show the participants in both conditions had a visible increase in subjective levels of fatigue (VAS-f) following the implementation of the working memory pre-test. However, this increase was only significant for the participants in the experimental condition. This increase suggests the working memory assessment may have been cognitively fatiguing to some extent. The experimental group scored higher on the pre-test than the control group, which indicates the experimental participantds would have completed a higher number of trials and spans of a higher complexity during the pre-test. Based on this premise, we propose that the differences in the pre-test performance may account for the experimental participants reporting a significant increase in subjective fatigue.

We expected the experimental group to report less conscious motor processing than the control group. However, there were no significant differences between the two groups, which indicates there was no manipulation of verbal working memory resources. Furthermore, the EEG results also displayed no significant reduction in coherence between T7 and Fz among for the experimental group. This also implies we were unable to reduce verbal analytical involvement utilizing the TloadDback fatigue task.

The movement adjustment results show no difference between groups, affirming we were unable to prevent hypothesis testing behaviours during motor performance.

The golf putting performance results reflect the previous findings, as there were no significant differences in motor performance between groups under a dual task load. This further suggests the participants were unaffected by the implementation of the TloadDback task. Participants in both conditions scored slightly better (insignificant) under the dual task load than the single task. We suspect this result is influenced by the limited number of single task trials conducted prior to implementing the dual task trials, as participants would have been still in the early stages of skill development. Notwithstanding, we recognise the number of single task trials needs to be revised in future research to allow for more learning to occur. However, we believe this would have made no difference to the performance outcomes in this study.

Based on the culmination of results found in this study, we propose the fatigue protocol was not able to adequately fatigue the experimental participants. Research indicates individuals with a high working memory capacity are less susceptible to the induction of cognitive fatigue (Jongman et al., 1999). This may have influenced our ability to induce the experimental group with cognitive fatigue, as the participants were shown to score highly in the working memory assessment. However, individualising the available processing time based on performance in the pre-test should have accounted for the variability in working memory capacity. The duration of the TloadDback task may have also influenced the imposed level of fatigue. Alternative cognitive fatigue tasks have been reported to run for 20-30 minutes (Anguera et al., 2011; Tanaka, Ishii & Watanabe, 2014). Borrogan et al., (2017) illustrates the duration of the TloadDback task was arbitrary settled to a 16-minute test and suggests the need for further research into task duration. This indicates the task duration may have been insufficient for inducing high levels of cognitive fatigue. The experimental participants may have also been resilient to the induction of cognitive fatigue thereby requiring a longer protocol. The fatigue protocols need to be revised before further research can be conducted.

In summary, the findings of this study show this fatigue task was capable of producing an increase in self-reported fatigue levels and may have caused some cognitive fatigue for the experimental participants. However, the level of fatigue that was induced was probably trivial and therefore was unable to suppress working memory activity. It remains inconclusive whether cognitive fatigue can be utilized as a mechanism for fatiguing verbal working memory and provoking implicit motor performance.

Chapter 4: Conclusion

In this thesis, we conducted an experimental research study to test the viability of induced cognitive fatigue as a mechanism for manipulating working memory activity. We hypothesized that exhausting working memory would reduce the learner's ability to employ hypothesis testing, thereby encouraging implicit performance of the motor task. The experimental group was expected to be able to maintain their motor performance under a dual task load, due to having limited dependence on working memory involvement during motor output. Additionally, the experimental group was expected to display low EEG coherence between T7 and Fz, limited movement adjustments and report minimal conscious motor processing, as a result of verbal analytical processes being limited by suppression of working memory.

The fatigue protocols were shown to have an effect on the learners subjective evaluation of fatigue; however, the objective performance scores did not support this, suggesting that the TloadDback task was unable to induce the experimental participants with cognitive fatigue as intended. These results were reflected in the working memory performance results, as the experimental group had no change in performance from pre-test to post-test. This indicates the fatigue protocols that were implemented were ineffective for manipulating working memory activity. There were no significant differences in EEG coherence, CMP levels, movement adjusts and motor performance when comparing the experimental and control groups. This is unsurprising as there was no manipulation of working memory and therefore no change in the learner's engagement in verbal analytical processes.

From the results of our experimental research, we can conclude that the fatigue protocol was unsuccessful in inducing the participants with cognitive fatigue and therefore did not manipulate working memory activity and motor performance. We suspect this may be attributable to the experimental participants having high working memory capacity, as research indicates individuals with high working memory capacity are more difficult to induce with cognitive fatigue (Jongman et al., 1999). In line with this notion, the test duration may need to be revised to ensure it accounts for individuals with high working memory capacity. Extending the task duration may increase the task difficulty for participants, thereby encouraging cognitive fatigue to occur. Additionally, the utilization of a shortened pre-test may have resulted in the available processing time to be set incorrectly, making the test to weak to produce cognitive fatigue. In order to combat this issue, the full pre-test should be conducted opposed to the shortened protocol. A longer pre-test will help to ensure the correct processing time is selected for the test.

An alternative view is that the shortened pre-test may have resulted in the available processing time being set higher than the participants actual 85% processing capacity. If the processing time is set too fast for the participant, they will find the test too challenging to respond therefore become disengaged from the task. The participants need to be actively engaged in the task for the task to induce cognitive fatigue. In order to prevent learners from disengaging from the fatigue test due to the processing time being set too high, the full pre-test should be run opposed to the shortened version.

We suspect participants may have lost motivation during the TloadDback fatigue test due to the test being conducted directly after the TloadDback pre-test and the working memory assessment. The subjective fatigue measures show the experimental participants perceived the working memory assessment as fatiguing, which may have lead to their disengagement from the fatigue task. To address this issue, a two-day protocol should be employed. The initial day should be composed of the working memory assessment (pre-test), followed by a recovery period, then the TloadDback pre-test. The second day should begin with the TloadDback fatigue test, therefore ensuring there was no disengagement due to the order of assessments.

We also encountered issues with the working memory assessment being conducted as a repeated measure. Participants were unfamiliar with the working memory task at pre-test; however, by the post-test some participants had reported building methods for conducting the task. By separating the assessments over two separate days would enable a washout period.

The motor task would benefit from the employment of a two-day protocol as it would allow us to increase the number of single task trials, without making the session length too long for the participants. Additionally, the motor task should be conducted in a larger space, as we encountered issues with the golf ball hitting the back wall of the laboratory. We were unable to measure the real distance to the target for some putts, as hitting the wall would have caused the ball to decelerate providing us with an incorrect distance.

Overall, we were unable to induce significant cognitive fatigue, so it remains inconclusive whether cognitive fatigue can be used to suppress working memory activity and influence motor performance. Further research is initially required to find fatigue protocols that are capable of inducing participants with cognitive fatigue and to suppress verbal working memory. We remain optimistic that fatiguing working memory may provide benefits to motor performance, that could be transferred to clinical and sporting domains.

An extension of the current research would be to investigate whether induced cognitive fatigue can be used to fatigue verbal working memory and enable implicit motor learning to occur. Research could also investigate the differences between induced cognitive fatigue and the fatigue caused by non-optimal time of day as methods for producing implicit motor learning.

While the experimental research conducted in this thesis solely focused on novices, future research should also investigate the effects of induced cognitive fatigue on the motor performance of experts with a high propensity for reinvestment. Unlike novices, the motor movements of experts are already proceduralized from their practice and experience of repeatedly performing the motor skill (Masters, 1992). However, the automaticity of their movements can be revoked when experts employ reinvestment to consciously control their movements during motor output. Research indicates this loss of automaticity among expert performers is commonly observed within sporting environments when performers encounter pressurised situations and is particularly evident among people with a high propensity for reinvestment (Masters, 1992). Therefore, we suspect that by fatiguing verbal working memory with a cognitively challenging task, we will be able to prevent high reinvestors from engaging in reinvestment whilst having minimal effect on their proceduralized movements.

Future possibilities beyond this kind of fatigue could be natural fatigue that might occur at altitude. Cognitive functions are reported to be compromised by the decrease in arterial blood oxygen saturation at altitude (Peng, Zhang, Hai-Yan, Ran & Yu-Qi, 2012; Yan et al., 2011). Research indicates the verbal working memory of children and adolescents is impaired by acute short-term exposure to high altitude (Rimoldi, Rexhaj, Duplain, Urben, Billieux, Allemann, Romero, Ayaviri, Salinas, Villena, Scherrer & Sartori, 2015). Similar impairments to verbal working memory were shown to occur among college students residing at high altitudes. Yan et al. (2011) reported a significant difference ($p=0.001$) in verbal working memory performance between two groups, with a high altitude group shown to have delayed reaction times and reduced accuracy compared to a sea level group. Research should assess whether short-term acute hypoxic training in an environmental chamber can be used to supress verbal working memory, thereby allowing subsequent motor tasks to be performed implicitly.

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Appendices

Appendix 1 - Ethics approval

The University of Waikato
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Human Research Ethics Committee
Julie Barbour
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Email:julie.barbour@waikato.ac.nz

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

25th May 2017

Ko-Tahi-Ra Boaz-Curry
Merel Hoskins

Prof. Rich Masters

Dear Tahi,

UoW HREC(Health)#2017-18: Fatiguing verbal working memory to reduce explicit hypothesis testing during skill acquisition: A new implicit motor learning paradigm.

Thank you for submitting your amended application HREC(Health)#2017-18 for ethical approval. We are now pleased to provide formal approval for your project including:

- EEG monitoring of 75 participants drawn from the University of Waikato student population, in either a control group or an experimental group during:
    - a computer based brain activity task
    - a novel motor task (golf-putting)
    - a temporary mental fatigue task
- Participants will also complete a series of short written surveys (Working Memory, The Movement Specific Reinvestment scale, and VAS-F)

We understand that the project is intended to provide data for Ko-Tahi-Ra's Masters thesis, and that it may contribute to Merel Hoskin's PhD thesis, along with other published outcomes. Dr. Tim Buszard will provide training and support for the data collection process.

Please contact the committee 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.

Regards,

Julie Barbour PhD
Chairperson
University of Waikato Human Research Ethics Committee

Appendix 2 - Participant information sheet.

The Faculty of Education
The University of Waikato
Private Bag 3105
Hamilton, New Zealand

Phone +64 7 838 4500
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THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Project Name: Temporary mental fatigue, motor learning and motor performance.

Investigators: Ko-Tahi-Ra Boaz-Curry (Masters Student), Merel Hoskens (PhD student), Dr. Tim Buszard and Prof. Rich Masters.

Participant Information Sheet:

Purpose:
The purpose of this research is to determine the impact of temporary mental fatigue on our ability to perform a novel motor task.

Participant Requirements:
To participate in this study, it is required that:
1) You are a novice at golf putting.
2) You are right handed.
3) You wash your hair the night before the testing session, and don't put any products (such as sprays or gels) in your hair on the day of the test.
4) You do NOT drink any coffee on the day of the test.

What will you have to do and how long will it take?
You will be asked to visit the motor learning laboratory at the University of Waikato Faculty of Education (TT0.10) for a testing session.

During this session, you will complete:

- Short questionnaires – Basic information sheet, reinvestment scale and subjective level of fatigue scale
- A computer based brain activity task – this task requires you to (1) store a series of digits and then recall the digits in the correct order, and (2) decide whether the short sentence presented to you on the computer screen makes sense or is non sense.
- A novel motor task - golf-putting to a target
- A computer based attention task, which requires you to (1) remember letters that are presented to you on a computer screen and respond if they were the same as the previous letter, and (2) decide whether the numbers presented to you on the computer screen are odd or even (using the keyboard).

We will be analysing

- The number of successful putts
- Level of temporary mental fatigue
- Brain activity using Electroencephalography (EEG) - you will be wearing an EEG neoprene cap with sensors on it, as shown in the figure. This cap is worn so we can measure which areas of your brain you use during the motor task.

Figure 1. EEG neoprene cap

Retrieved from "http://www.neuroelectrics.com" http://www.neuroelectrics.com/products/enobio/

The duration of the study will be approximately 1.5 - 2 hours and you will be paid a $25 New World Voucher for volunteering your time, which you will receive at the end of the testing session.

Potential risks or discomfort
The risks involved in participating in this study are minimal. For part of the experiment you will be wearing a neoprene cap with sensors on it. These are completely harmless. Occasionally they can feel uncomfortable, but they do not cause any pain. The surface electrodes used to monitor brain activity can cause short-lasting minor skin irritation to participants with sensitive skin. However, this is unlikely. You will have a small amount of gel on some spots on your head after your experiment.

What will happen to the information collected?
The information collected in this study may contribute to or inform theses written by Ko-Tahi-Ra Boaz-Curry (Masters) or Merel Hoskens (PhD). An electronic copy of the theses will become widely available, as the University of Waikato requires that a digital copy of Master's and Doctoral theses be lodged permanently in the the University's digital repository: Research Commons. In addition, we will use the information to produce peer-reviewed research articles, conference presentations and/or popular media dissemination (e.g., columns, blogs as requested by journalists). Only the research team will have access to the raw data and participant information. No participants will be named in the publications and every effort will be made to disguise identities.

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: Ko-Tahi-Ra Boaz-Curry [redacted] Merel Hoskens [redacted] or Professor Rich Masters [redacted]

Appendix 3 - Informed consent.

The Faculty of Education
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THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Project Name: Temporary mental fatigue, motor learning and motor performance.

Investigators: Ko-Tahi-Ra Boaz-Curry (Masters Student), Merel Hoskens (PhD student), Dr. Tim Buszard and Prof. Rich Masters.

Informed Consent:

I have read the Participant Information Sheet for this study and the details of the study have been explained to me. My questions about the study have been answered satisfactorily, and I understand that I may ask further questions at any time.

I understand that a coding system will be used to ensure that my identity is not revealed and that my data or responses remain confidential. I am aware that the data will be included in scientific publications, presentations, teaching, and student theses. Every effort will be made to ensure confidentiality and anonymity; although, I understand that anonymity cannot be guaranteed.

I also understand that I am free to withdraw from the study at any point with no repercussions. I understand I can withdraw any information I have provided up until three weeks following my participation in the research.

I agree to provide information to the researchers under the conditions of confidentiality set out on the Participant Information Sheet.

I agree to participate in this study under the conditions set out in the Participant Information Sheet.

If you would like to receive a copy of the summary of findings from the study when it is concluded, please fill out your preferred contact email below.

Participant Contact Email: ____

Participant Name: ____________________________ Participant Number: __________

Participant Signature: __________________________ Date: ___________________

By signing below, I acknowledge that I have received my participant voucher.

Participant Signature: __________________________ Date: ___________________

Researchers Name: ____________________________

Researchers Signature: __________________________ Date: ___________________

Appendix 4 - Receipt of voucher acknowledgement

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

Date:

Receipt of Voucher Acknowledgement

Fatiguing verbal working memory to reduce explicit hypothesis testing during skill acquisition: A new implicit motor learning paradigm?

Dear ____________________________

For your participation in the 'Fatiguing verbal working memory to reduce explicit hypothesis testing during skill acquisition: A new implicit motor learning paradigm?' research experiment, the University is pleased to offer you the enclosed $25 New World voucher. In accordance with University financial reporting policy, we are required to obtain your acknowledgement of your receipt of this voucher.

Please provide your acknowledgement in writing below.

Name: ____

Signature: ____

Date: ____

Thank you for your participation.

Regards
Professor Rich Masters
Health, Sport and Human Performance
University of Waikato

Appendix 5 – Basic information sheet

Project Name: Temporary mental fatigue, motor learning and motor performance.

Investigators: Ko-Tahi-Ra Boaz-Curry (Masters Student), Merel Hoskens (PhD student), Dr. Tim Buszard and Prof. Rich Masters.

Purpose: The purpose of this research is to determine the impact of temporary mental fatigue on our ability to perform a novel motor task.

Basic Information Sheet **Participant No**. ___________________________

First Name:
Family Name:
Date of Birth: Age:
Gender (circle) : Male / Female
Handedness (circle): right hander / left hander
Golf experience (check boxes or fill in): **I know what these sports are:** ▫ Golf ▫ Unihockey / Floorball ▫ Field hockey ▫ Ice hockey ▫ I have never played golf before ▫ I have played golf a few times ▫ I have played a lot of golf ▫ I have played a golf (any type) match _____ times ▫ I have had ____________ golf lessons (including high school PE classes etc) ▫ I play(ed) golf regularly __________ hours a week during ___________ years ▫ I have never played anything like floorball / field hockey / unihockey / ice hockey ▫ I have played floorball / field hockey / ice hockey/ unihockey a few times ▫ I have played a lot of floorball / field hockey / ice hockey

Appendix 6 - The Movement Specific Reinvestment Scale (adapted version)

Project Name: Temporary mental fatigue, motor learning and motor performance.

Investigators: Ko-Tahi-Ra Boaz-Curry (Masters Student), Merel Hoskens (PhD student), Dr. Tim Buszard and Prof. Rich Masters.

Purpose: The purpose of this research is to determine the impact of temporary mental fatigue on our ability to perform a novel motor task.

THE MOVEMENT SPECIFIC REINVESTMENT SCALE

Participant No. ______________________________ Date _____________________

DIRECTIONS: Below are a number of statements about your movements in general. Circle the answer that best describes how you feel for each question.

1 I remember the times when my movements have failed me.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

2 If I see my reflection in a shop window, I will examine my movements.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

3 I reflect about my movement a lot.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

4 I try to think about my movements when I carry them out.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

5 I am self conscious about the way I look when I am moving.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

6 I sometimes have the feeling that I am watching myself move.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

7 I am aware of the way my body works when I am carrying out a movement.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

8 I am concerned about my style of moving.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

9 I try to figure out why my actions failed.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

10 I am concerned about what people think about me when I am moving.

strongly disagree | moderately disagree | weakly disagree | weakly agree | moderately agree | strongly agree

Appendix 7 - Visual Analogue Scale for Fatigue

Project Name: Temporary mental fatigue, motor learning and motor performance.

Investigators: Ko-Tahi-Ra Boaz-Curry (Masters Student), Merel Hoskens (PhD student), Dr. Tim Buszard and Prof. Rich Masters.

Purpose: The purpose of this research is to determine the impact of temporary mental fatigue on our ability to perform a novel motor task.

Visual Analogue Scale for Fatigue (VAS-F):

Participant Number : ______________________ **Date:** ____________________________ **(PRE)**

DIRECTIONS: You are asked to circle a number on each of the following lines to indicate how you are feeling RIGHT NOW.

For example, suppose you have not eaten since yesterday. What number would you circle below?

Not at all hungry 0 1 2 3 4 5 6 7 8 9 10 Extremely hungry

You would probably circle a number closer to the "extremely hungry" end of the line. This is where I put it:

Not at all hungry 0 1 2 3 4 5 6 7 8 9 10 Extremely hungry

NOW PLEASE COMPLETE THE FOLLOWING ITEMS:

1) not at all **tired** 0 1 2 3 4 5 6 7 8 9 10 extremely **tired**

2) not at all **fatigued** 0 1 2 3 4 5 6 7 8 9 10 extremely **fatigued**

3) not at all **efficient** 0 1 2 3 4 5 6 7 8 9 10 extremely **efficient**

4) **concentrating** is no effort at all 0 1 2 3 4 5 6 7 8 9 10 **concentrating** is tremendous chore

Project Name: Temporary mental fatigue, motor learning and motor performance.

Investigators: Ko-Tahi-Ra Boaz-Curry (Masters Student), Merel Hoskens (PhD student), Dr. Tim Buszard and Prof. Rich Masters.

Purpose: The purpose of this research is to determine the impact of temporary mental fatigue on our ability to perform a novel motor task.

Participant Number : ____________________ **Date:** _________________________ **(POST WM)**

DIRECTIONS: You are asked to circle a number on each of the following lines to indicate how you are feeling <u>RIGHT NOW</u>.

1) not at all **tired**	0	1	2	3	4	5	6	7	8	9	10	extremely **tired**
2) not at all **fatigued**	0	1	2	3	4	5	6	7	8	9	10	extremely **fatigued**
3) not at all **efficient**	0	1	2	3	4	5	6	7	8	9	10	extremely **efficient**
4) **concentrating** is no effort at all	0	1	2	3	4	5	6	7	8	9	10	**concentrating** is tremendous chore

Participant Number : ____________________ **Date:** ___________________ **(POST TREATMENT)**

DIRECTIONS: You are asked to circle a number on each of the following lines to indicate how you are feeling <u>RIGHT NOW</u>.

1) not at all **tired**	0	1	2	3	4	5	6	7	8	9	10	extremely **tired**
2) not at all **fatigued**	0	1	2	3	4	5	6	7	8	9	10	extremely **fatigued**
3) not at all **efficient**	0	1	2	3	4	5	6	7	8	9	10	extremely **efficient**
4) **concentrating** is no effort at all	0	1	2	3	4	5	6	7	8	9	10	**concentrating** is tremendous chore