The Effects of Fatigue on Manual Dexterity

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Abstract

Humans are uniquely adept at manipulating objects in their environment. Our ability to use our hands for dextrous skilled movements is unique in the animal kingdom and fundamental for us to successfully perform a myriad of everyday tasks. Even a seemingly simple task such as turning off an alarm clock is the result of a complex and dynamic interplay of sensory, cognitive, and physiological processes. Dextrous behaviours in young, healthy adults are well-characterised, but research has so far failed to establish how fatigue affects manual dexterity in this population. In this thesis, a series of studies was performed with the aim of revealing insights into how mental and neuromuscular fatigue affect the sensorimotor system in the context of dextrous actions. Three studies explored and critically examined existing paradigms for inducing mental fatigue, which were found to have numerous limitations. To address these limitations, study four validated a novel method to induce mental fatigue using a combination of subjective and behavioural measures. This novel method was then used in study five to investigate the effects of mental fatigue on a battery of dexterity tasks. The outcomes from this study indicated that mental fatigue has specific effects on dextrous behaviour which appear to be mediated through cognitive processes. Study six examined participants' performance in the same three dexterity tasks after undergoing a neuromuscular fatigue intervention. Like study five, study six also found task-specific effects on dextrous behaviour, with the perceptual effects of neuromuscular fatigue appearing to have particular importance. Together, these studies show that the sensorimotor processes underlying manual dexterity are affected in specific ways by fatigue and that these effects are highly dependent on the origin of that fatigue. These novel findings extend prior research and provide a foundation for future research into how different types of fatigue could meaningfully impact the outcomes of dextrous tasks.

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Contents

Page

List of Figures

List of Tables

Abbreviations

ATP Adenosine Triphosphate

AX-CPT A-X Continuous Performance Test

BIS Balanced Integration Score

BRUMS Brunel Mood Scale

CNS Central Nervous System

EMG Electromyography

GABA Gamma-aminobutyric Acid

GET Gas Exchange Threshold

GFR Grip Force Rate

LFR Load Force Rate

MRI Magnetic Resonance Imaging

MVC Maximum Voluntary Contraction

N Newtons

N/s Newtons per Second

NASA-TLX National Aeronautics and Space Administration Task Load Index

NMJ Neuromuscular Junction

PCr Phosphocreatine

RCP Respiratory Compensation Point

RPE Rating of Perceived Exertion

RT Reaction Time

RTV Reaction Time Variability

SD Standard Deviation

SWI Size-Weight Illusion

TMS Transcranial Magnetic Stimulation

W Watts

pGF Peak Grip Force

pGFR Peak Grip Force Rate

pLF Peak Load Force

pLFR Peak Load Force Rate

tPGF Time to Peak Grip Force

tPLF Time to Peak Load Force

Chapter 1: Introduction

1.1 Dexterity

One of the most fundamental and unique skills of humans is the ability to dextrously manipulate objects in the environment around us (Flanagan & Johansson, 2002). From drinking from a cup of coffee, to buttoning a jacket, to doing the washing up, we rely on efficient and accurate dextrous manipulation of items in our surroundings throughout many of the activities that are essential to our daily lives. Manual dexterity is a highly complex skill requiring the interaction and co-ordination of numerous systems in the human body. There are a whole host of dynamic sensory and cognitive processes underlying dextrous manipulation of objects which must work in tandem to maximise efficiency by minimising time costs, energy expenditure, and error.

The human hand is a remarkable instrument comprising 27 bones, 41 muscles, and up to 25 degrees of freedom (Brochier et al., 2009; Jeannerod, 2009; Sobinov & Bensmaia, 2021). Controlling the hand is a highly complex skill (Wing & Lederman, 2009), and is supported by a vast array of sensory and motor systems which span the whole body, from skin receptors, to muscle fibres, to neurons, to cortex. Indeed, a considerable and disproportionate amount of the brain is dedicated to functions which support dextrous movements (Sobinov & Bensmaia, 2021). Primary motor regions have been found to connect directly to the motor neurons that control hand movements and fingertip force generation (Sobinov & Bensmaia, 2021), whilst a variety of other 'premotor' areas have been shown to activate during different types of sensory and motor events (A. M. Smith, 2009). Vast swathes of cortex are also devoted to sensory systems for vision, proprioception, and touch, which perform critical functions in dextrous movements, providing continuous high-resolution feedback about hand and object position (Sobinov & Bensmaia, 2021).

Planning is a fundamental aspect of dextrous movements, because it allows movement to be driven by feedforward processes as opposed to being driven by reactive feedback. The acquisition and processing of sensory information is slow in comparison to the speed with which humans and other objects move (Vaillancourt & Russell, 2002), and the information acquired through sensory systems contains noise which can result in error (Franklin & Wolpert, 2011). If humans were reliant on feedback to drive movement, those movements would be slower, less accurate, and consequently less efficient (Flanagan & Johansson, 2002). Generating plans facilitates feedforward processes. Rather than solely reacting to changes in the environment or state of the body, predictions are made about features of objects and the environment and about how those features may change. For example, prior to lifting an object, a prediction is made about how heavy that object will be, how much force should therefore be used to grasp and lift that object, and how fast the object should move whilst being lifted with the appropriate amount of force (Hermsdörfer et al., 2011). Humans are extremely accurate in these predictions, with feedforward plans generated using prior experience with individual objects or other objects in that category (Nowak et al., 2004). In daily life, we use feedforward processing to lift many objects throughout the day with minimal error and with minimal conscious thought. It is only when a box is unexpectedly light or a kettle unexpectedly empty that we may become aware of such processes and how they can be mistaken.

Whilst dexterity is driven largely by feedforward processing, feedback (i.e. reactive) processes are nonetheless absolutely essential to monitor dextrous manipulations and to minimise and/or correct errors (Flanagan & Johansson, 2002; Scott, 2012). A whole host of different sensory systems feed back relevant information to support dextrous object interaction. Vision can be used to monitor the location of the object in the environment in relation to the body and other objects, proprioception provides information about the relative location of the limbs in space, mechanoreceptors feed back information about how hard an object is being grasped, and haptic feedback gives continuous information about the weight and balance of the object in the hand. All of this sensory information is combined and compared with the motor plan to generate corrections to ongoing movements in a dynamic manner (Vaillancourt & Russell, 2002), using a host of different brain regions such as the cerebellum (Raz et al., 2005), basal ganglia (Seidler et al., 2010), frontal cortices (R. Peters, 2005; Seidler et al., 2010), and motor cortices (Seidler et al., 2010). Without these processes, errors in the feedforward plan would be uncorrected, possibly resulting in failure of the plan, e.g. dropping an object, missing a throw, or colliding with obstacles.

Critically, feedback and feedforward processes occur in a continuous loop. Sensory information is continuously sent to the brain where it is dynamically decoded, interpreted, integrated with other information (such as prior knowledge), and used to form ongoing predictions, which are then used to update the motor signals that are sent to the rest of the body so that it moves appropriately for its environment and goals (de Lange et al., 2018; Enoka et al., 2011; Mahoney et al., 2011; Saccone & Chouinard, 2018). Altogether, these processes ultimately facilitate intention to be translated into action.

The processes underlying sensorimotor control have been investigated extensively. Prior research therefore provides a rich insight into the sensorimotor system, which is now well-characterised in normal healthy adults. This research forms a basis from which the effects of a variety of different conditions, such as developmental coordination disorder (Arthur et al., 2021), attention-deficit hyperactivity disorder (Neely et al., 2016), and stroke (Nowak, 2008), can be examined. The effects of a transient state such as fatigue, however, are yet to be investigated in-depth. Fatigue is a common everyday occurrence which disproportionately affects some individuals due to their health or occupational status, with potentially detrimental effects on their quality of life and ability to live safely and independently (Latash & Johnston, 2012). Fatigue is, therefore, of great importance for the general population, those in demanding work environments, and some clinical groups who may be more susceptible to fatigue.

1.2 Fatigue

Defining fatigue

The word ‘fatigue’ means many different things to many different people. Whilst most people will have their own understanding of what fatigue is, fatigue is a multifaceted concept, manifesting in many ways and under many different circumstances. Fatigue can be short-lived or chronic; have clinical, physical, psychological or even unknown origins; and have systemic, perceptual, and physiological effects.

There are many different definitions of fatigue available. The word ‘fatigue’ has been attributed to a broad range of phenomena alluding to different characteristics and origins of fatigue such as “a failure to maintain the required or expected force” (Edwards, 1981), “any exercise-induced reduction in the ability to exert muscle force or power, regardless of whether or not the task can be sustained” (Bigland-Ritchie & Woods, 1984), and “a subjective feeling of tiredness resulting from prolonged periods of cognitive activity that diminishes cognitive performance over time” (Inzlicht et al., 2014). Consequently, there is ongoing debate in the literature about how best to define fatigue (Behrens et al., 2022; Skau et al., 2021; Venhorst et al., 2018). Behrens et al. (2022) provide a general definition of fatigue as “psychophysiological condition characterized by a decrease in motor or cognitive performance (i.e. motor or cognitive performance fatigue, respectively) and/or an increased perception of fatigue (i.e. perceived motor or cognitive fatigue).”

Whilst this provides a general definition of fatigue, the work presented in this thesis has two main focuses: mental fatigue, and neuromuscular fatigue. To increase specificity and agreement with prior closely-related literature, the definition of mental fatigue will be taken as a “psychobiological state caused by prolonged periods of demanding cognitive activity and characterized by subjective feelings of ‘tiredness’ and ‘lack of energy”’ (Marcora et al., 2009). This definition has been chosen because a) it is widely-used in the relevant literature, and b) there are clear ways to operationalise demanding cognitive activity and subjective feelings (see Chapter 4). Additionally, the tiredness component of the definition provided by Marcora et al (2009) accords with the Skau (2021) definition of fatigue as “the sensation of feeling the need for rest”, whilst theoretical discussion about the nature and effects of mental fatigue by Marcora and colleagues regularly includes the perception of mental fatigue with reference to concepts similar to Skau’s “mismatch between effort expended and actual performance” component. Neuromuscular fatigue will be defined as an adaptation which occurs progressively during exercise resulting in a reduction in the ability to produce force or power (Amann, 2011; Cairns et al., 2005; Enoka & Stuart, 1992; Gandevia, 2001).

1.2.1 Mental fatigue

Development of mental fatigue

According to Marcora et al. (2009), mental fatigue develops when a task is cognitively challenging, the sense of effort from the task increases, a compensatory reduction in task performance is elicited, and the task is eventually voluntarily terminated. Research has found that the subjective experience of mental fatigue as increased effort on a task is associated with alterations in brain activity (Barwick et al., 2012; Shortz et al., 2015; Tanaka, Shigihara, et al., 2012; Van Cutsem et al., 2022).

Numerous neurotransmitters and metabolites have been implicated in mental fatigue development. Early research indicated a possible role of serotonin in both neuromuscular and mental fatigue (Newsholme & Blomstrand, 1996), though this has since been refuted (Meeusen et al., 2006). More recent evidence indicates that mental fatigue is associated with an accumulation of adenosine (which regulates sleep; Martin et al., 2018), and an inhibitory effect on dopamine (which regulates mood, and is also critical for motor control; Martin et al., 2018). Research suggests that demanding cognitive activity results in the accumulation of adenosine, which increases perceptions of effort (Meeusen et al., 2021). This increase in adenosine is associated with a decrease in dopamine, which is necessary to sustain effort and motivation during task performance (Meeusen et al., 2021). The link between mental fatigue and adenosine has been supported through research into the effects of caffeine supplementation. Caffeine blocks adenosine receptors in the brain, and has consistently been found to mitigate the effects of mental fatigue (Proost et al., 2022). There is therefore growing evidence implicating adenosine and dopamine in mental fatigue development, but it is yet to be determined whether there are other neurotransmitters or metabolites which contribute to mental fatigue development.

Mental fatigue may affect exercise performance by impeding muscle function, but there is limited evidence for this relationship. Ferris et al. (2018) investigated whether mental fatigue would affect the intensity of exercise that an individual was able to sustain without having to increase muscle recruitment - the electromyographic fatigue threshold. They found that whilst the production of power was no different between the fatigued and non-fatigued exercise bouts, there was a significant decrease in the electromyographic fatigue threshold when participants were fatigued. That is, participants had to work harder to recruit their muscles and produce power when mentally fatigued. This finding indicates that mental fatigue somehow affects the activation of motor units within the muscle, and this inhibited muscle activation might be why endurance performance and strength can be affected by mental fatigue.

In contrast with Ferris et al. (2018), other research has found that mental fatigue has no effects on muscle function. Instead, other research indicates that exercise performance is affected due to increased perceived exertion (RPE). Pageaux et al. (2013) assessed participants' endurance performance and neuromuscular function in a submaximal strength task following either a challenging or easy cognitive task (90 mins duration). They found that following the challenging task, participants' endurance was reduced, but their muscle function was unaffected - activation of motor units within the muscle during endurance exercise was similar, they were able to voluntarily produce similar levels of maximal force, and electrical stimulation of the muscle produced similar levels of electromyographic activity and similar levels of force. Participants' performance decrement was therefore not associated with any alterations in muscle function, but was instead associated with a significantly higher RPE. Similar results were found in Pageaux et al. (2015), where neuromuscular function in a work-matched cycling task was unaffected by mental fatigue, despite an increase in RPE.

The idea that perceived exertion can increase in the absence of physiological alterations that would affect exercise performance is supported in the findings of a meta-analysis by Chen, Fan, and Moe (2002), which found that perceived exertion does not consistently correlate with physiological measures of fatigue (heart rate, blood lactate concentration, respiration rate). Overall, the evidence supports the notion that mental fatigue affects subjective perception of effort, which subsequently results in participants' decision to reduce their effort to a more comfortable level (Marcora et al., 2009), and that this can occur in the absence of any physiological effects (Van Cutsem et al., 2017).

Effects of mental fatigue

The evidence regarding the effects of mental fatigue on physical tasks provides some insight into how mental fatigue may affect dexterity. Mental fatigue has been found to primarily affect strength- and skill-based performance (Halperin et al., 2015), with participants producing less force and performing worse at technically challenging athletic tasks when mentally fatigued (M. R. Smith et al., 2016). Mental fatigue has also been found to affect endurance performance (Marcora et al., 2009; Pageaux et al., 2015; Van Cutsem et al., 2017) by increasing perceived effort, reducing power production, and reducing the voluntary duration of exercise. The effects of mental fatigue on exercise outcomes, however, have not always been replicated. A meta-analysis by Holgado et al. (2020) found that current research does not provide conclusive support for the effects of mental fatigue on exercise performance. In Clark, Vanhatalo, et al. (2018), time-trial performance was unaffected by mental fatigue, and there were also no changes in neuromuscular responses to exercise when participants were mentally fatigued, with Holgado et al. (2023) finding similar null effects.

Nonetheless, various meta-analyses and reviews (Brown et al., 2019; Holgado et al., 2020; Martin et al., 2018; McMorris et al., 2018; Silva-Júnior et al., 2016; Van Cutsem et al., 2017) have found that, despite there being mixed evidence, there are likely to be some small effects of mental fatigue on motor outcomes. There is relatively little focus on precision movements in these analyses, however, and where the effects of mental fatigue on precision movements have been considered, the focus has been on actions such as kicking or hitting a ball (Le Mansec et al., 2017; M. R. Smith et al., 2016).

There is some research which examines the effects of mental fatigue on outcomes which are more closely related to dexterity. The most consistent finding amongst this research is that mental fatigue reduces isometric grip endurance (Bray et al., 2008; Muraven et al., 1998; Murtagh & Todd, 2004) though there is also strong evidence to the contrary (Xu et al., 2014). These contradictory findings are mirrored in literature with an ageing focus, with some studies finding an effect (Pereira et al., 2018; Shortz and Mehta, 2017; Voelcker-Rehage et al., 2006), and others not (Bray et al., 2011; Guillery et al., 2017).

Given the contradictions found in the literature, it is difficult to ascertain what effects mental fatigue could have on dexterity. The literature does however indicate that precision motor movements such as those used during object lifting could be affected. Since 2015, three papers examining mental fatigue and dexterity have been published (Budini et al., 2022; Duncan et al., 2015; Valenza et al., 2020), with mixed findings. These findings are explored and furthered in Chapter 5.

1.2.2 Neuromuscular fatigue

Development of neuromuscular fatigue

Neuromuscular fatigue is an adaptation which occurs progressively during exercise resulting in a reduction in the ability to produce force or power (Amann, 2011; Cairns et al., 2005; Enoka and Stuart, 1992; Gandevia, 2001). There are two different types of neuromuscular fatigue: peripheral, and central. The locus of these types of fatigue are determined with reference to the neuromuscular junction (NMJ), the point at which the motor neurons meet the muscle. Peripheral fatigue occurs at or distal to the neuromuscular junction, whilst central fatigue occurs proximal to the neuromuscular junction (Gandevia, 2001).

Muscular contraction is the result of a series of events. Primary motor cortex propagates a motor command through the central nervous system (CNS) to the motor neurons (Gandevia, 2001). When this motor command arrives at the NMJ an action potential is sent along the t-tubules and into the muscle tissue, resulting in a depolarisation of muscle cells and a release of calcium ions (Ca^{2+}) into the sarcoplasm of the muscle cells. The released Ca^{2+} then binds with the troponin C protein, exposing the myosin binding sites on the actin filaments. Cross-bridge cycling then occurs: actin and myosin filaments bind; a power stroke moves the actin filament inwards, shortening the sarcomere (i.e. contracting the muscle); the cross-bridge is broken by adenosine triphosphate (ATP); and actin and myosin filaments bind again at a new site. Repeated cross-bridge attaching and breaking (cross-bridge cycling) continues to contract the muscle until the motor command is ceased. Ceasing results in repolarisation of the muscle cells, reuptake of Ca^{2+}, and relaxation of the muscle (Allen et al., 2008).

Muscular contraction therefore relies on activation of the primary motor cortex, propagation of the motor command to the motor neurons, transmission of the command at the neuromuscular junction, availability of sodium (Na^{+}) and potassium (K^{+}) ions for the conduction of action potentials, availability of Ca^{2+} for exposure of myosin binding sites, the creation of an effective cross-bridge link between actin and myosin, and availability of ATP. All of these processes are affected by neuromuscular fatigue.

Peripheral fatigue development

Peripheral fatigue occurs when exercise is extreme enough that the environment within the muscle is destabilised (Poole et al., 2016), resulting in an increase in metabolites which interfere with contractile function, and depleting the necessary substrates for muscle contraction. Adenosine triphosphate (ATP) is a critical molecule which is utilised to fuel sustained or continued muscular contractions. It is, however, in limited supply within the muscle, and so must be resynthesised during exercise. The process of ATP re-synthesis relies on the availability of the phosphocreatine (PCr), glycogen, and oxygen. As re-synthesis continues within the muscle the availability of these substrates declines, until the capacity to re-synthesise ATP is not able to match the rate at which it is being used. This results in a reduction in the rate of ATP re-synthesis, and consequently the reduced availability of ATP for cross-bridge cycling (Ament & Verkerke, 2009; Fitts, 1994; Jones et al., 2008; Westerblad et al., 2002a). Additionally, when exercise is more extreme, the rate of ATP utilisation is higher and so ATP must be re-synthesised at a higher rate for muscular contractions to continue. This re-synthesis is achieved through multiple different pathways which all produce different metabolites, resulting in the accumulation of inorganic phosphate (Pi), hydrogen ions (H^+), and K^+. These metabolites subsequently interfere with muscle contractile function by inhibiting cross-bridge cycling, limiting Ca^{2+} release, reducing cellular Ca^{2+} sensitivity, and inhibiting the transmission of action potentials (Allen et al., 2008). This process is exacerbated when oxygen availability can not meet demand, resulting in higher rates of PCr and glycogen utilisation and faster accumulation of Pi (Ipata & Balestri, 2012; Westerblad et al., 2002b).

Central fatigue development

Central fatigue occurs when exercise results in reduced neural drive - the motor signal that is propagated from the motor cortex. Neural drive can be altered due to changes within the brain which cause motor signals to be produced at a lower intensity or reduced frequency. It can also be altered due to changes in the rest of the CNS which result in ineffective propagation of the motor command through the motor neurons (Gandevia, 2001). This means that, whilst the muscle may be capable of producing higher levels of force, the CNS downregulates the activation of the muscle so that voluntary production of force is reduced (Gandevia, 2001). There are numerous theories as to how and why central fatigue develops, though no definitive mechanism has yet been established (Shei and Mickleborough, 2013). Feedback from the muscles has been theorised as having multiple potential effects, either by being used by a subconscious intelligent system to predict and prevent a disruption to homoeostasis (Noakes, 2011), having a directly inhibiting effect on CNS drive (Amann and Dempsey, 2008), or being consciously used to determine when exercise has exceeded the voluntary limit of effort (Marcora, 2008). The accumulation and depletion of certain neurotransmitters and other molecules have also been implicated in central fatigue. The serotonin hypothesis proposes that the accumulation of serotonin, a neurotransmitter implicated in sleep regulation, can result in increased lethargy and reduced neural drive (Boyas and Guével, 2011; Meeusen et al., 2006). Neural levels of dopamine, noradrenaline, glutamate, acetylcholine, adenosine, GABA, ammonia and glucose have all been suggested to be involved in the development of central fatigue, but the roles of each of these is still unclear (Meeusen et al., 2006). Whilst the mechanisms may be unclear, the conditions under which central fatigue develops have been well-established (Burnley and Jones, 2018), as are the methods used to assess its development (Gandevia, 2001). Whilst the debate around how central fatigue develops continues, it is still possible to elicit fatigue, identify the presence or absence of physiological correlates of fatigue, and consequently assess its effects on subsequent outcomes.

Effects of neuromuscular fatigue

Efficient and accurate dexterity relies on the brain producing appropriate signals from the motor cortex, the CNS propagating that signal effectively, the muscles responding to the signals that they receive, and the return of accurate perceptual information to the brain. Fatigue can disrupt all of these processes. Fatigue of the arm muscles results in a decline in maximal force production, primarily as a consequence of peripheral fatigue development (J. L. Smith et al., 2007). Whilst we may not need to produce maximal force in routine interactions with the environment, the effect of fatigue on maximal force is indicative of an alteration in the ability to produce force in general. This is supported by the findings of Singh et al. (2013), who found that fatigue induced by repetitive thumb exercise resulted in both a decline in the maximal forces applied by the thumb in a maximal voluntary contraction and the submaximal forces applied by the thumb during interaction with an object.

Movement accuracy can also be affected by fatigue (Knicker et al., 2011), due to an alteration in the way that motor units are recruited (Boyas and Guével, 2011). Fatigue elicited in the arms reduces the coordination of muscular contraction (Missenard et al., 2008), which consequently reduces movement accuracy (N. Forestier and Nougier, 1998; Jaric et al., 1999). Fatigued individuals may, however, modify their behaviour when fatigued, so that their fatigue does not affect the accuracy of their movements (Gates and Dingwell, 2008; Huffenus et al., 2006; Selen et al., 2007).

The effect of physiological fatigue on perception of effort has been thoroughly discussed in the literature (Knicker et al., 2011; Marcora, 2008). How fatigue may affect the perception of the sensory information which is then used to guide actions is, however, unclear. Burgess and Jones (1997) found that participants in a fatigued state experience a dissociation between their perception of effort and force. This dissociation indicates that fatigued individuals process and integrate sensorimotor feedback differently, which could affect the subsequent generation of feedforward signals. This change in perception of effort could also be related to an alteration in proprioception (Gandevia, 2001), which may result in fatigued individuals misperceiving the location of their limbs or digits, contributing to movement inaccuracy (Proske, 2019).

1.3 Aims

Dexterity is a complex skill which relies on a number of neural and physiological processes to operate accurately and efficiently. Both mental fatigue and neuromuscular fatigue have been found to affect these processes, but there is a lack of research into the effects of transient fatigue on dexterity in healthy adults in tasks which might reflect tasks of daily living. Whilst more recent papers have started to investigate mental and neuromuscular fatigue and dexterity, the behavioural and functional consequences of fatigue on dexterity remain unknown.

The broad aim of the thesis is to establish if and how different types of transient non-clinical fatigue affect dexterity, with the intention of gaining a better understanding of how the human sensorimotor system is affected by and functions under conditions of fatigue.

Chapter 2 outlines the different approaches available for investigating how fatigue may affect dexterity. The broad research approach is discussed, as well as the specific methods for inducing mental and neuromuscular fatigue. Different methods for assessing dexterity are outlined. The specific tasks selected to assess dexterity and what those tasks can elucidate are then discussed in-depth.

Chapter 3 explores existing paradigms for inducing mental fatigue, and investigates the possible effects of mental fatigue arising from these paradigms on some basic dexterity-related tasks. Given the limited research in this area and the variability in methods and outcomes previously used in the mental fatigue literature, pilot work was necessary to develop suitable methodologies for inducing mental fatigue, and for measuring dexterity and related outcomes. Chapter 3 outlines this pilot work across three studies, providing context for the further methodological development in Chapter 4.

Chapter 4 outlines the limitations of extant mental fatigue induction paradigms, and describes a novel method which was developed to induce mental fatigue which addresses these limitations. Chapter 5 subsequently uses this novel method to investigate the effects of mental fatigue on behaviour, perception, and performance in three different tasks assessing manual dexterity - the Purdue Pegboard Test, an object lifting task, and a force matching task.

Chapter 6 aimed to investigate the effects of neuromuscular fatigue on the same tasks used in Chapter 5. Given the various central contributions to dexterity, Chapter 6 chose methods to maximise central fatigue development using a long-duration heavy-intensity cycling intervention to induce neuromuscular fatigue. By examining the behaviour, perception, and performance of participants who have undergone such exercise, this final experimental chapter elucidates how neuromuscular fatigue induced through exercise may affect dexterity.

Finally, Chapter 7 summarises the key outcomes of the work, with key conclusions and suggestions for future research into fatigue and dexterity.

Chapter 2: Methodology

There were various challenges in choosing the methodology for the research presented in this thesis. Firstly, the broad experimental paradigm had to be selected. Dual-task paradigms are sometimes used in similar research (e.g. Shortz and Mehta (2017) and Wagenblast et al. (2023). This approach was, however, considered undesirable for a number of reasons. Firstly, dividing attention across two different tasks may affect dexterity (Beurskens et al., 2020), or may interact with fatigue (Wagenblast et al., 2023). Secondly, dual-task paradigms typically involve two simple tasks where more complex dexterity tasks were desirable in the current research. Additionally, the current research employed multiple different dexterity tasks which place differing demands on participants, and a dual-task paradigm would have required participants to remember different instructions simultaneously, considerably increasing the complexity of the tasks at hand. Finally, practical constraints hinder the ability to simultaneously fatigue participants and perform the dexterity tasks. Consequently, a subsequent-task paradigm was chosen: fatigue was induced, and its effects on a subsequent task were assessed. This approach is commonly used in the literature and thus the results generated from this approach are more easily compared to extant literature (Duncan et al., 2015).

2.1 Mental fatigue

The difficulties of inducing mental fatigue are manifold. Mental fatigue development and the effects of mental fatigue on subsequent tasks can be influenced by individual state and trait characteristics such as cognitive abilities (O’Keeffe et al., 2020), and motivation (Herlambang et al., 2019). It is also unclear whether there are effects of different task characteristics and durations (Holgado et al., 2020), and there is no consensus on which are the most appropriate methods for inducing mental fatigue. Alongside these difficulties, there are definitional issues regarding the nature of mental fatigue (Behrens et al., 2022; Skau et al., 2021; Venhorst et al., 2018), and this had lead to researchers adopting different ways of operationalising mental fatigue (Pageaux et al., 2014; M. R. Smith et al., 2019; Tanaka et al., 2014). Hence, multiple existing approaches were trialled in Chapter 3, ultimately leading to a novel method being developed in Chapter 4.

2.2 Neuromuscular fatigue

Neuromuscular fatigue encompasses a range of physiological changes that can occur to different extents in a variety of different circumstances. One challenge of the current research was to select a fatiguing activity that would have relatively consistent and predictable effects between participants, with minimal effects from participants' individual differences in sex, fitness, or age. Furthermore, the method chosen to induce neuromuscular fatigue needed to be highly controllable and repeatable, with effects that would not dissipate either during or prior to conducting the subsequent dexterity tasks. The selected method also needed to be achievable for a broad range of participants to minimise the likelihood of participants dropping out of the research, and to maximise the representativeness of the sample for the general population. To reduce the burden on participants i.e. from taking biological samples, it was also important to select a fatiguing task with known quantified effects on the various physiological variables underlying fatigue development

Consequently, a paradigm used by (Clark, Vanhatalo, Thompson, Joseph, et al., 2019; Clark, Vanhatalo, Thompson, Wylie, et al., 2019; Clark, Vanhatalo, et al., 2018) was selected. This approach has been shown to induce measurable fatigue in participants and is tailored to participants' individual fitness levels. This paradigm should also maximise central fatigue development (which should not recover rapidly post-exercise) as opposed to peripheral fatigue development (which recovers quickly with rest; Clark, Vanhatalo, et al., 2018). The specifics of this method are further discussed in Chapter 6.

2.3 Dexterity

As discussed in Chapter 1, dexterity is a complex behaviour which relies on a dynamic interplay between predictive feedforward processes and reactive feedback sensory processes. For movement to be successful, the CNS must successfully propagate signals from cortex to muscle and back, and the muscle must be able to contract accordingly. Given the wide array of different processes involved in even apparently simple movements, such as reaching, dexterity has been studied extensively using a wide range of methods, with each approach providing different insights into dexterity.

At the behavioural level, measuring fingertip force control is a prominent method that has been used for many years to better understand the sensorimotor processes underlying dexterity (Hermsdörfer, 2009). To date, single digit, precision grasp, and multi-digit grasps have all been investigated thoroughly, often in tandem with other methods, to generate a rich understanding of the sensorimotor processes underlying force control (Hermsdörfer, 2009; T. Schneider & Hermsdörfer, 2016; Zatsiorsky & Latash, 2009). Examining force production from different numbers of digits in different types of task provides different insights into dexterity. For example, maximum voluntary contraction measured from squeezing the whole hand can be used as a measure of strength, whilst precision grip during object lifting can provide indices of sensorimotor prediction (Hermsdörfer, 2009). Multi-digit grasps can also provide information into the computational processes underlying the coordination of force control when there are multiple points of contact between the hand and the object (Zatsiorsky & Latash, 2009).

Kinematic behaviour during reaching and grasping has also been widely studied, and has given unique insights into sensorimotor control (Jeannerod, 2009). Kinematic measurements can be taken from multiple body parts to measure different aspects of movement. The kinematics of the wrist, for example, can be useful for assessing whether movement is degraded by being slower or less accurate (Cicerale et al., 2014). In contrast, the precision kinematics of the fingertips during reaching can give an insight into the underlying cognitive processes of grasp preparation (Castiello & Ansuini, 2009; Gentilucci, 2002). These different types of insights can be useful in understanding general underlying processes in all adults, as well as in understanding how to assess and treat conditions where movement impairments are prominent, such as in stroke patients (Nowak, 2008).

Electromyography (EMG) has been used to investigate dexterity in animals, but has limited applications in humans where it is more suited to more gross movements. Invasive EMG - which uses a combination of subcutaneous or intramuscular needles, wires, and patches - has been used in animal models to examine muscle activation during both finer dextrous movements and gross reaching movements (Brochier & Lemon, 2009). Whilst invasive EMG can be used in humans it is better suited to examining the extrinsic muscles of the hand which control grosser grasping movements. (Brochier & Lemon, 2009). Such invasive methods are also onerous for participants, with a risk that discomfort from intramuscular wires could cause participants to alter their movements. Surface EMG - where patches are placed on the surface of the skin - is more suitable for use in humans as it is not invasive. Surface EMG recordings are, however, subject to noise from other nearby muscles, and this challenge is greater for the relatively small intrinsic hand muscles. Consequently, there is little research using EMG to examine dexterity in healthy humans, and so the EMG patterns which reflect normal behaviour in different types of dextrous movements remain unknown (Silva et al., 2017). Instead, EMG is often used to investigate differences in grosser movements between clinical and non-clinical populations (K. M. Peters et al., 2018), or in healthy individuals, between different experimental conditions (W.-L. Chen et al., 2010). Comparing muscle activation patterns for gross movements may be useful to aid treatment of specific clinical populations for whom gross movements may be impaired. It is difficult, however, to understand how muscle activation patterns for gross movements relate to the quality of fine dextrous movements, and therefore difficult to make meaningful inferences about healthy adults' performance in dextrous tasks from surface EMG recordings of broad movements.

Whilst there is a breadth of different methods available, the different insights provided by each as well as the practical implications of implementation must all be considered carefully to decide which is the most appropriate approach for the given focus on fatigue. For the purposes of the research described in this thesis, three main aspects were prioritised. The first was that at least one of the outcomes needed to be easily interpretable so that meaningful conclusions could be generated with implications for naturalistic behaviours. The second was that the procedures needed to be fast to implement, as mental fatigue and neuromuscular fatigue could recover over longer periods of time. Third, it was considered desirable to use methods which provided outcomes which could provide different insights into similar aspects of dextrous movements. Three different tasks were selected that met these criteria.

2.3.1 Dexterity assessment

To assess dexterity more generally, the Purdue Pegboard Test (Tiffin & Asher, 1948) was selected. This task is described in detail in Chapter 5 methods. Briefly, the test requires that participants place as many small metal pins, circular disks, and cylinders as they can within a set time. There are different subtests which use both the dominant and non-dominant hands in unimanual and bimanual tasks, each with specific instructions. Participants are instructed to be as quick and accurate as possible and are given a simple score from counting the number of items successfully placed in each trial. The test takes approximately 15 minutes to administer in full. The Purdue Pegboard Test originated as a test of dexterity for employees seeking industrial jobs (Tiffin & Asher, 1948), and has since been used extensively in research, proving to be reliable and valid for use in a range of healthy and patient populations (Yancosek & Howell, 2009). The simplicity of the outcome measure makes it easy to distinguish whether differences are arising between experimental conditions, and means that the implications are clearly interpretable: if scores differ between conditions, the lower score would reflect fewer items being assembled successfully, which reflects detrimental changes in speed and/or accuracy in that condition. If mental fatigue, for example, resulted in worse performance in the Purdue Pegboard Test, it would indicate that there were underlying mechanisms that could have meaningful real-world implications for similar tasks. At the time of study conceptualisation, the Purdue Pegboard Test has not been used to investigate the effects of mental or neuromuscular fatigue on dexterity. It was, however, later adopted by Budini et al. (2022), with a similar task also used by Valenza et al. (2020) (see Chapter 5).

2.3.2 Fingertip force control

To further enhance insights into how dexterity may be affected by fatigue, two additional tasks were chosen which examined fingertip force control.

Object lifting

An object lifting task was selected to examine sensorimotor prediction and perception. Object manipulation has been extensively characterised in prior research (Hermsdörfer, 2009) and is considered a 'hallmark' of skilled motor behaviour (Flanagan & Johansson, 2002). The task is simple to implement, typically involving presenting participants with a series of objects differing in size and/or weight, and asking them to lift them and report their weight. During the task, the forces applied to the object can be continuously measured, resulting in a variety of different dependent variables. The task is fast to implement, uses equipment which is sensitive enough to detect small changes, and can provide insights into multiple aspects of sensorimotor control.

By examining participants' perceptual reports of object heaviness and the forces they apply to the objects in both illusory and non-illusory lifting paradigms, researchers have generated a rich insight into sensorimotor behaviour during this simple task. Both predictive (Flanagan & Johansson, 2002; Hermsdörfer et al., 2011) and reactive processes (Buckingham & Goodale, 2010; Scott, 2012) can be examined (Nowak & Hermsdörfer, 2004), and these can give an insight into the cognitive processes underlying the movements (Brooks & Thaler, 2017; Nowak & Hermsdörfer, 2003). Additionally, by examining both perception and action, it is possible to identify where participants may have erroneous perceptual beliefs, which again can reflect differences in sensorimotor processes (Buckingham, 2014). Behavioural and perceptual outcomes in object lifting tasks have been investigated extensively in clinical and non-clinical populations (Arthur et al., 2020, 2021; Buckingham et al., 2018; Cole, 1991; Diermayr et al., 2011; Nowak & Hermsdörfer, 2004). Given this extensive body of research, it is possible to generate appropriate predictions and make meaningful inferences from object lifting tasks.

Force matching

A force matching task was selected to examine participants' *conscious* control of forces, complementing the examination of *automatic* force control during the object lifting task. Object lifting is typically used to examine predictive processes (Flanagan & Johansson, 2002), whilst a force matching task can be used to more closely examine perception and sensorimotor integration (Abolins et al., 2020). The task can be implemented very quickly, uses highly sensitive force transducers which can detect very small fluctuations in force (such as in tremor), and is focused closely on the muscles involved in precision grip.

Force matching tasks involve either matching force to a constant level (Abolins et al., 2020; Neely et al., 2016) or to a level which fluctuates during each trial (Kriz et al., 1995; Wagenblast et al., 2023). The level of force that is matched is typically relative to individual strength, with different proportions of maximal strength placing different demands on participants (Noble et al., 2011). There are many variations of force matching tasks which target different muscle groups. Some of the muscle groups investigated so far are related to dexterity, with single digit (Abolins & Latash, 2022; Vaillancourt et al., 2001), precision grip (Kriz et al., 1995; Voelcker-Rehage et al., 2006), wrist (Wagenblast et al., 2023), and elbow force matching all having been investigated (Selen et al., 2007). Whilst these tasks often use a single limb, bimanual tasks have also been developed (Abolins et al., 2020). Research has also investigated the effects of varying vision, with vision being made unavailable partway through the duration of the force-matching trial (Abolins & Latash, 2022; Abolins et al., 2020).

Behaviour in force matching tasks has been examined in multiple different populations such as older adults (Noble et al., 2011; Voelcker-Rehage et al., 2006), people with attention deficit hyperactivity disorder (Neely et al., 2016), and Parkinson's patients (Vaillancourt et al., 2001), often using young healthy adults as control populations. Normal behaviour is thus well-established, and researchers have generated a good understanding of how different dependent variables can provide insights into memory (Vaillancourt & Russell, 2002), perception, and sensorimotor integration (Abolins et al., 2020).

Chapter 3: Investigating Mental Fatigue

This chapter explores and critically examines established ways of inducing mental fatigue through three separate studies. The possible effects of mental fatigue induced through these methods on different aspects of dexterity are also examined, with the aim of elucidating further research pathways. Study 1 examined commonly-adopted n-back and Stroop paradigms, and how mental fatigue induced from these affects grip strength endurance. Study 2 examined the letter-crossing paradigm to explore how mental fatigue affects fingertip forces and weight perception during object lifting. Study 3 focused solely on mental fatigue development, examining how mental fatigue develops from a single extended-duration task. The limitations of these approaches are discussed, with suggestions as to how they could be addressed.

3.1 Introduction

A common approach in studies which examine the effects of mental fatigue on other tasks is to induce fatigue by having participants engage in a demanding cognitive task which requires limited cognitive resources (e.g. response inhibition or self-regulation) for an extended period of time. Two of the most commonly-used tasks are the Stroop colour-word test (Pageaux et al., 2015; M. R. Smith et al., 2016; Thompson et al., 2020), and variations of the n-back task (Clark, Goulding, et al., 2018; Shortz et al., 2015).

The Stroop (Stroop, 1935) and n-back (Kirchner, 1958) tasks are well-characterised having been used extensively in numerous research areas (see Jaeggi et al., 2010; MacLeod, 1991; Owen et al., 2005 for overviews). In the Stroop task, participants are presented with a serial string of colour terms, which are presented in a colour that is either congruent or incongruent with the word itself. Typically, participants will either be asked to report the name of the colour that the word is presented in, or the colour that the word says. For example, the word ‘green’ presented in the colour red could require either the response ‘red’ or the response ‘green’. There are numerous variations of ways that the task is presented and that participants can be asked to respond. For example experimenters can serially present flash cards with colour words on them with participants required to respond verbally, or a computer can be used to present colour words with participants either pressing coloured buttons or letters on a keyboard corresponding to certain colours (e.g. r for the response ‘red’). In the mental fatigue literature, the Stroop is used for an extended period of time, with participants responding using a keyboard to indicate the colour that the word is in. When performed in this way, the incongruent version of the task requires participants to inhibit automatic processing of the semantic meaning of the colour-word in order to successfully respond with the colour that the word is in.

In the n-back task, participants are presented with a serial stream of items and are required to respond with whether the current item is the same or different to the one *n* repetitions prior to the current item: a *1*-back version of the task requires participants to verify whether the current item is the same as the one immediately prior to it; a *2*-back version of the task requires participants to verify whether the current item is the same as the item which appeared 2 items ago, etc. To complete this task participants must use working memory to remember and continuously update a list of items, control attention to monitor the ongoing stream of stimuli, and must successfully inhibit/elicit the appropriate response to the stimuli presented on the screen.

Ego depletion can be considered a sub-type of mental fatigue (Baumeister, 2020; Habay et al., 2023), and so ego depletion methods were considered for use in inducing mental fatigue. In ego depletion, the ‘ego’ is considered as a precious limited resource which, when depleted, results in altered task behaviour (Baumeister, 2019). The ego depletion approach considers the mind as similar to a muscle which tires through use and can recover through rest (Maranges and Baumeister, 2016). In the ego- and self-control depletion literature, the letter-crossing task and variations (e.g. Sripada et al., 2014) have been extensively used to elicit a state of ego depletion. The task is considered by leaders in the field as one of the best methods to induce ego depletion (as discussed in Hagger et al., 2016).

3.2 Study 1

3.2.1 Purpose

Mental fatigue can result in neurochemical alterations and changes in brain activation (Barwick et al., 2012; Dietrich, 2006; Martin et al., 2018; Shortz et al., 2015). These changes may reduce neural drive – the signals being sent from the brain to the muscles – and affect the level and accuracy of force production. There is limited research into the effects of mental fatigue on endurance force maintenance, particularly in the arm muscles. If mental fatigue affects the control or maintenance of force output from the muscles in the arm, then this could affect dextrous manipulation. Inaccurate or inefficient control of arm muscles could result in hazards such as an increased likelihood of dropping objects or could affect quality of life by making interactions more effortful and more tiring.

Shortz and Mehta (2017) investigated how mental fatigue and concurrent cognitive demands may affect grip force endurance. They tested participants' ability to maintain force output during repeated 15 second long intermittent contractions at 30% of their maximum voluntary contraction (MVC) under three different conditions: control, sequential fatigue, concurrent fatigue. In the control condition, participants watched a documentary before producing the intermittent contractions. In the sequential fatigue condition, participants engaged in two cognitively demanding tasks for a total of one hour before producing the intermittent contractions. In the concurrent fatigue condition, participants conducted a cognitively demanding task whilst producing intermittent contractions. Their study with 20 females found that 10 older participants had lower endurance and higher variability under concurrent fatigue than in either the control or sequential fatigue conditions. The 10 younger participants did not show this effect. The authors concluded that concurrent fatigue affects grip force endurance and that this is exacerbated by ageing (Shortz and Mehta, 2017).

The Shortz and Mehta (2017) study may be subject to a confounding interaction between the endurance task demands and ageing. Older adults have higher force variability at lower levels of force (Castronovo et al., 2018; Voelcker-Rehage et al., 2006), use greater cognitive resources to generate appropriate force outputs (Buckingham et al., 2018) and have reduced cognitive capacity (Park et al., 2002). In the Shortz and Mehta (2017) study, older adults may have had to use a higher cognitive resources to maintain the same force rates a younger adults. Older adults would therefore find the concurrent fatigue task disproportionately challenging due to having to simultaneously use their limited cognitive resources for both the challenging cognitive task and monitoring their grip force. In comparison, younger adults would be able to allocate more cognitive resources to the cognitive task. This age difference in subjective task difficulty would not have existed in the sequential fatigue condition because the tasks were not conducted at the same time and so were not competing for the same cognitive resources. The results of Shortz and Mehta (2017) study could therefore be due to the interaction between task demands and ageing as opposed to being due to mental fatigue.

This study aimed to further clarify this phenomenon in younger adults using a sequential as opposed to concurrent task paradigm, and an endurance task which required maintenance of force rates at a higher proportion of participants' MVC (55%). The hypothesis was that when participants were fatigued, their 1) endurance, and 2) force variability would be different to when they were not fatigued.

3.2.2 Methods

Materials

The mental fatigue tasks chosen were the Stroop (Stroop, 1935) and n-back (Kirchner, 1958) tasks. These were selected for their previous use in inducing mental fatigue (Shortz and Mehta, 2017; Van Cutsem et al., 2017) and because they are established psychological testing paradigms. The tasks were conducted on a laptop screen using an external keyboard. The tasks were run in PsyToolKit (Stoet, 2010, 2017) on Microsoft Edge browser. The tasks (Kirchner, 1958; Stroop, 1935) were adapted from those found in the PsyToolKit library (PsyToolKit, 2018a, 2018b).

Grip force endurance and variability were measured using a Jamar Smart Plus Hand Dynamometer. Grip force was recorded using the Jamar Smart Plus application (v1.6.0) on an Apple iPad (6th gen). Endurance time was additionally measured using a stopwatch.

Participants

A convenience sample of eight students and staff at the University of Exeter were recruited via posters on campus and email. There were five males and three females with mean age 26 ± 3 years. All participants reported being free of neurological impairments, physical impairments in the dominant limb, and uncorrected visual impairments. Participation was voluntary. All procedures were approved by the Sport and Health Sciences Ethics Committee at the University of Exeter (Reference 190311/A/03).

Procedures

The full procedures are outlined in Figure 3.1. Participants visited the lab on three separate occasions. On all visits, participants sat comfortably in a chair with a desk in front of them for the duration of the visit. The first visit lasted approximately 15 minutes. Participants gave their informed consent. The procedure for the MVC test was then explained. Participants then held their dominant arm at an approximately 45 degree angle and held the dynamometer in their dominant hand, as determined by self-report. The dynamometer grip was set to position 2 and was held so that the handle rested in the crook of the thumb (Figure 3.2). The experimenter said “Ready. Two, one, go”. Participants squeezed the dynamometer as hard as they could for around three seconds whilst verbal encouragement was provided by the experimenter. One minute of rest was given and this procedure was then repeated two more times. The highest of these three measurements was taken as the MVC value for each participant. One participant’s MVC was taken from the higher of two measurements due to their arm deviating from the 45 degree angle whilst gripping the dynamometer during one of the three measurements.

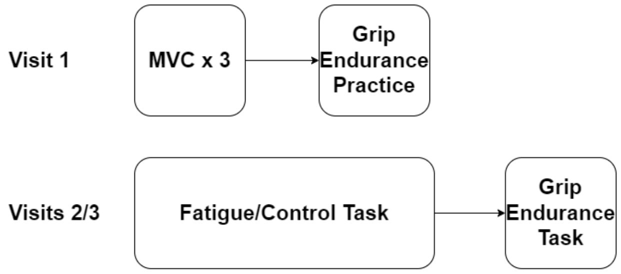


Figure 3.1: Schematic of Overall Study Procedures.

Figure 3.2: The Grip Force Dynamometer

Participants were then familiarised with the endurance protocol. Participants held the dynamometer in their dominant hand as in the MVC task. Participants were shown the tablet screen which showed the amount of grip force being exerted in pounds (lbs). Participants were instructed to consistently maintain this level at a value equal to 55% of their MVC for as long as possible, with the exact value in pounds provided to participants. The experimenter said “2, 1, go” and the task was performed once. Once participants’ grip force output reduced below 50% of their MVC for 10 seconds, failure was deemed as having been reached. At this point, participants were instructed to stop gripping the dynamometer. One participant was stopped at a point where they were unable to maintain their force above 50% of their MVC without their arm deviating from the 45 degree angle.

The second and third visits lasted approximately 1 hour and 15 minutes. Participants engaged in a mental fatigue task or control task and were blinded to the purpose of the tasks. The order of these was counterbalanced such that four participants did the mental fatigue task in their second visit and four in their third visit. Participants were randomly allocated to an order using a random number generator in Microsoft Excel. In the control task, participants watched one hour of a neutral documentary (Flesher, 2012) on a tablet placed on the desk in front of them.

The mental fatigue task consisted of two different tasks performed sequentially on a computer, with responses given via a keyboard. The two tasks were conducted in a randomly allocated counterbalanced order such that four participants conducted the Stroop colour-naming task (Stroop, 1935) first and four conducted the n-back task (Kirchner, 1958) first. Following the mental fatigue/control task, participants underwent the grip force endurance task as described previously. At the end of their final visit, participants were debriefed.

The mental fatigue tasks were conducted as follows. In the Stroop (Stroop, 1935) task, participants were presented with a series of colour words on a screen. Some words were congruent with their colour, for example the word “blue” coloured in blue. Some were incongruent, for example the word “blue” coloured in red. Participants were asked to respond with the colour of the presented word using a keyboard - “r” for red, “g” for green, “b” for blue and “y” for yellow. A description of the procedure for each of the tasks can be seen below. In each trial, a fixation point was shown for 200ms, a blank screen for 100ms, single coloured word for up to 2000ms, blank screen 500ms. Five practice trials were conducted, followed by 30 minutes of task. This was arranged in three blocks of 10 minutes in duration with a short ($<$ 1 minute) break in between blocks. In the n-back task (Kirchner, 1958), participants were presented with a series of letters which they were instructed to remember. In each trial, a letter was shown for up to 2000ms, a blank screen was shown for 500ms and another letter then appeared. At random intervals, participants were asked whether the current letter was the same as the letter which had been presented two letters previously (a 2-back task). Whilst Shortz & Mehta (2017) used a 1-back task, a 2-back task was selected in the current study due to it being more challenging and thus more likely to make participants mentally fatigued. Participants provided “yes” or “no” responses using a keyboard - “m” for yes, “n” for no. Two letters were presented with no response required, five practice trials were conducted, followed by 30 minutes of the task. This was arranged in three blocks of 10 minutes in duration with a short ($<$ 1 minute) break in between blocks.

Analyses

The independent variable condition was treated as a within-subjects factor of two levels: fatigue, control.

Endurance time was measured as the time in seconds until failure to maintain grip force at 55% of their MVC. Once participants' grip force output reduced below 50% of their MVC for 10 seconds, failure was deemed as having been reached.

Grip force variability was measured as the coefficient of variance (CoV). This was calculated as:

$$\mathrm{CoV} = \frac{\mathrm{SD}_{\mathrm{force}}}{\mathrm{MEAN}_{\mathrm{force}}}$$

with the values for force taken as those from the endurance trial until the point of failure.

Balanced Integration Score Throughout the Stroop and 2-back tasks, participants' responses (correct/incorrect) and reaction time (in milliseconds) were recorded. This information was used to calculate a Balanced Integration Score (BIS; Liesefeld and Janczyk, 2019). The BIS is an integrated measure of reaction time and accuracy which has shown to be less affected by speed-accuracy trade-offs than other measures (Liesefeld and Janczyk, 2019). The BIS is a standardised score, meaning that a score of 0 reflects the average performance of the group, with positive scores being above-average performance and negative scores being below-average performance. BIS scores were calculated separately for the Stroop and N-Back tasks, with separate scores calculated for 3 x 10 minute bins of each 30-minute task.

Data processing and analyses were conducted in the Jamar Smart Plus application and in RStudio (RStudio Team, 2016) using the following packages: dplyr (Wickham et al., 2017), lattice (Deepayan, 2008), psych (Revelle, 2018), tidyr (Wickham and Henry, 2018), ggplot2 (Wickham, 2016), nortest (Gross and Ligges, 2015), car (Fox and Weisberg, 2011), ggpubr (Kassambara, 2018).

The data were inspected for erroneous values before analyses were conducted. For all parametric tests used the assumptions were checked using visual inspections of the data, descriptive statistics, and Shapiro-Wilk tests. Any violations of these assumptions are reported within the results. The alpha level was set at .05 for all analyses.

3.2.3 Results

Visual inspection of the BIS outcomes shown in Figure 3.3 indicates that participants' performance in the Stroop and N-Back tasks improved throughout the tasks. The data were not normally distributed as determined by significant (p > .05) Shapiro-Wilk tests, and so two Wilcoxon Signed Rank tests were performed to compare performance in the 2-back and stroop tasks from the first block to the last block of each task. A Wilcoxon Signed Rank Test with time point (block 1/block 3) as the independent variable and n-back BIS score as the dependent variable revealed a significant increase in BIS score, $z = -2.66$, $p = .007$, 95% CI [-2.54, -.063], $r = .94$. Participants' performance significantly improved from the first to the last block of the n-back test. A Wilcoxon Signed Rank Test with time point (block 1/block 3) as the independent variable and stroop BIS score as the dependent variable revealed a significant increase in BIS score, $z = -1.92$, $p = .054$, 95% CI [-.98, .003], $r = .68$. Participants' performance did not significantly change from the first to the last block of the Stroop test.

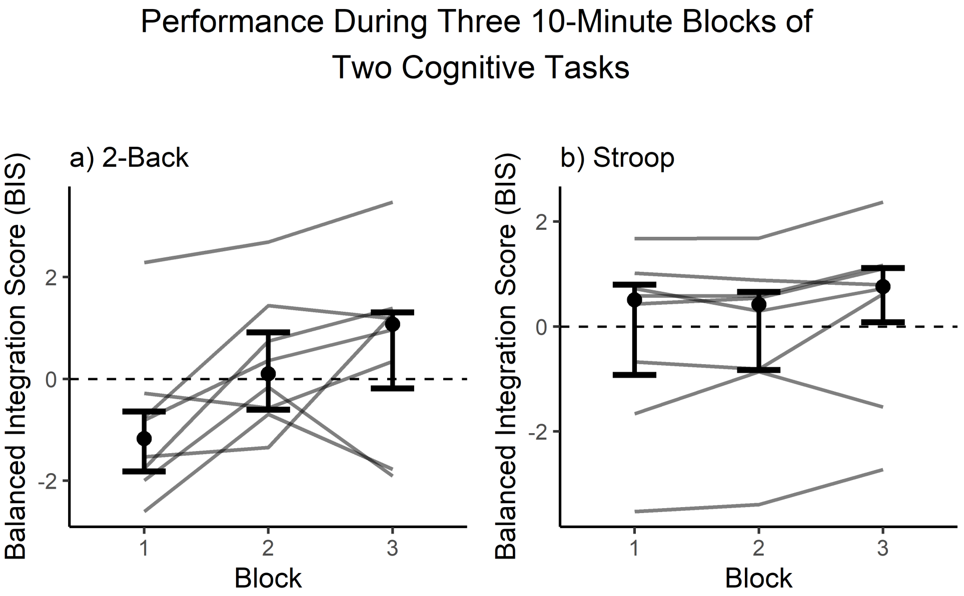


Figure 3.3: Performance in the a) N-Back and b) Stroop tasks (n = 8, with 4 participants completing N-Back prior to Stroop and vice versa). Individual responses are represented by thin grey lines, with the black dots representing the median. The upper and lower horizontal lines indicate the first and third quartiles (25th and 75th percentiles).

Two repeated-measures t-tests were conducted comparing participants' 1) endurance (seconds) and 2) force variability (coefficient of variance) in a submaximal endurance hand grip task following either a control documentary-watching task or two mentally fatiguing cognitive tasks (the Stroop and 2-Back). The results showed no significant difference in endurance time between the fatigue and control conditions, *t* (7) = -0.86, *p* = .418, 95% CI [-34.65, - 16.15], *d* = .30 (Figure 3.4). There was also no significant difference in force variability between the fatigue and control conditions, *t* (7) = -0.59, *p* = .572, 95% CI [-0.16 - 0.09], *d* = .21 (Figure 3.4). Thus, there was no evidence that mental fatigue affected participants' performance in an endurance grip task.

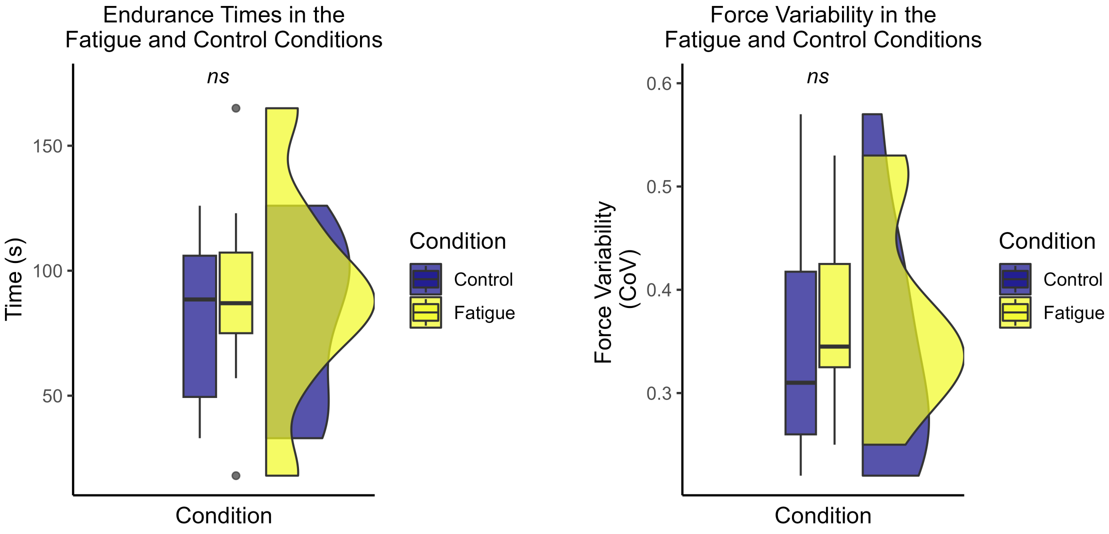


Figure 3.4: Endurance Times and Force Variability in a Submaximal Handgrip Task (n = 8). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. *ns* denotes non-significance ($p \geq .05$).

3.2.4 Discussion

The grip endurance results replicate those of Shortz and Mehta (2017). Younger adults' grip endurance time and force variability were no different following two mentally fatiguing cognitive tasks than following a control documentary. This indicates that mental fatigue does not affect endurance hand grip performance.

There is, however, a major limitation to this work. It is not clear whether the null finding is due to the fact that mental fatigue does not affect hand grip performance, whether it is because the mental fatigue manipulation was not successful in inducing mental fatigue, or due to the sample size being too small to detect a small effect. Participants' performance as measured by the BIS improved over the 30-minute time period of the 2-back task, and appeared unaffected during the Stroop task. If participants were becoming mentally fatigued throughout the duration of the two tasks, their performance would be expected to either stay the same or decline. Thus there is no objective evidence that participants were mentally fatigued by the intervention. Subjective reports of mental fatigue were not taken, and so there is also no evidence to assess whether participants felt mentally fatigued.

In conclusion, the results of this study, whilst in support of Shortz and Mehta (2017) findings, may be due to a failure of the mental fatigue manipulation. This is discussed further in section 3.5.

3.3 Study 2

Given the apparent failure to induce mental fatigue in study 1, this study used an alternative existing paradigm - the letter-crossing task - to induce mental fatigue, to investigate the effects of mental fatigue on dexterity in a naturalistic object lifting task. Data collection and conceptualisation of this study was performed in part by an undergraduate dissertation student and a research assistant.

3.3.1 Purpose

As outlined in section 3.1, the letter-crossing task has been used extensively in the mental fatigue-allied ego/self-control depletion literature. This study applied an existing naturalistic object lifting paradigm in a novel way to investigate whether the mental fatigue induced by the letter-crossing task would affect indices of sensorimotor control during object lifting.

The object lifting protocol has potential benefits as a method for investigating the effects of mental fatigue on dexterity. Firstly, subtle changes in motor control are the most likely to be affected by mental fatigue (Brown et al., 2019; Pereira et al., 2018) and these can be accurately detected in fingertip force control due to the precise nature of the required movement and the high sensitivity of the measurement techniques used. Secondly, lifting an object is a naturalistic task that most people do hundreds of times every day, and has been extensively characterised in prior research (Flanagan & Johansson, 2002). Using a novel approach in this way may reveal previously undiscovered effects of mental fatigue.

Given the findings of previous research (Bray et al., 2008, 2011; Shortz and Mehta, 2017; Shortz et al., 2015), it is plausible that grip force (the force applied to an object in order to securely grasp it) will be reduced in participants who are mentally fatigued compared to in those who are not. Load force (the force applied to an object in order to lift it) may be similarly affected if mental fatigue reduces neural drive to the muscles used in generating upward force to lift objects. This could affect perceptions of object weight. The way an object is perceived throughout the duration of an interaction with it is an important aspect of motor control. Whilst interacting with objects, the perception of features of those objects such as their weight can lead us to alter our movements in accordance with what is being perceived. For example, the perception that an object is unusually heavy given its size will lead to an increase in the amount of force applied through the fingertips in order to grip the object (Buckingham, 2014). The alteration of perception by mental fatigue could result in object interactions being less accurate and less efficient, potentially leading to dangers such as dropping objects. Mental fatigue may also affect perception of object weight due to its effects on neural drive. Whilst the force output required to lift the object would be the same as if not mentally fatigued, the amount of neural drive required to achieve the exertion of that amount of force would be higher, resulting in a perception that the force required to lift the object is greater (Marcora et al., 2009; Martin et al., 2018; Pattyn et al., 2018; M. R. Smith et al., 2016).

Weight perception can be studied in the context of the size-weight illusion (SWI). In the SWI a smaller object will feel as though it weighs more than an equally-weighted larger object (Buckingham, 2014). The SWI is universal and cognitively impenetrable: almost all adults experience it even when they know that the objects weigh the same amount (Buckingham, 2014). One theory of why the SWI occurs is that our expectation about how much something will weigh does not match with how heavy it feels. We expect a smaller object to be lighter, so it feels unexpectedly heavy, and we expect a larger object to be heavier, so it feels unexpectedly light (Buckingham, 2014). If mental fatigue affects perceptions of the effort required to lift objects, being mentally fatigued may affect the SWI. Smaller objects would be perceived as even more unexpectedly heavy due to the increased perceived effort required to lift them. However, the effect would be slightly different for larger objects. Larger objects are generally expected to require more force to lift and so the increased effort required to lift them would be more in line with the prediction about the weight of the object. Larger objects would therefore still be perceived as unexpectedly light but this would be to a lesser extent than when not fatigued. As a result, weight ratings would be comparatively much higher for smaller objects in the fatigue condition whilst only being somewhat higher for larger objects. These differences in weight ratings for different sized objects would affect the magnitude of SWI. The SWI magnitude is calculated as the difference between weight scores for smaller vs larger objects. With a much higher weight rating for smaller objects but only a somewhat higher weight rating for larger objects, the magnitude of the SWI would be larger in participants who were fatigued than in those who were not. Previous research supports that being physiologically fatigued makes objects appear to be heavier (Burgess and Jones, 1997). It remains to be determined whether this will be the case with mental fatigue and how this will affect the SWI.

The hypotheses were that 1) mentally fatigued participants' reports of object weights would be different compared to non-fatigued participants' reports, and 2) mentally fatigued participants would use different force rates to grasp and lift objects in comparison with non-fatigued participants.

3.3.2 Methods

Materials

The letter-crossing task comprised five short stories which were approximately 300-600 words in length. Each story was presented in a different font style and size. This task has been demonstrated to effectively elicit a mentally fatiguing effect. Participants' performance on the task reduces over time and increased effort is required to maintain levels of task performance, regardless of individual working memory capability (Arber et al., 2017; Hagger et al., 2016).

For the object lifting task, four objects differing only in diameter and weight were used (Figure 3.5). Each object was a 3D printed black plastic cylinder which was 10cm in height. There were two different diameters (5cm diameter, 10cm diameter) and two different weights (355g, 490g). To achieve the desired weight, each object was filled with small lead balls and foam to prevent any rattling. The objects also had foam pads attached to the bottom so that they did not make a noise when placed on a surface.

Each object had a mount on top onto which a force transducer (Nano17, ATI Industrial Automation, Apex, NC) was attached prior to each lift. The force transducer acted as a handle for participants to grasp when lifting the objects. Forces were sampled at a rate of 500Hz.

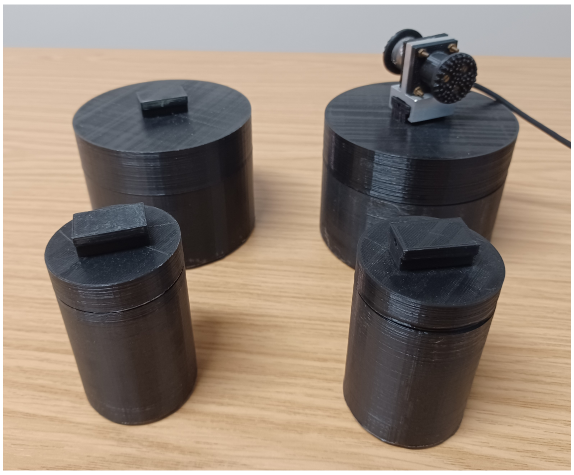


Figure 3.5: The objects used in the experiment. L-R 355g, 490g. Top right object has force transducer attached as it was prior to each lift.

Participants

55 students and staff at the University of Exeter were recruited via posters on campus and email. Two participants were excluded from analysis due to their pre-existing familiarity with the task. Of the remaining 53 participants, there were 25 males and 28 females with mean age 24 ± 7 years. All participants were untrained and reported being free of neurological impairments, physical impairments in the dominant limb and uncorrected visual impairments. Participants were paid £10 for their time. This was approved by the Sport and Health Sciences Ethics Committee

at the University of Exeter (Reference 190619-A-01).

Procedures

Full study procedures are outlined in Figure 3.6. Participants visited the lab once in a visit lasting approximately 40 minutes. Throughout the duration of the visit, participants sat comfortably in a chair with a desk in front of them and the objects which were not currently being lifted concealed from view. The experimenter sat on the opposite side of the desk facing the participant. Participants read an information sheet and signed a consent form.

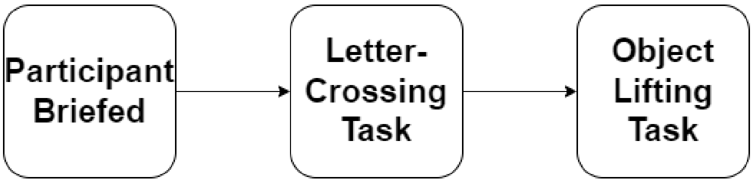


Figure 3.6: Schematic of Overall Study Procedures.

The overall procedure was explained to participants, followed by a detailed explanation of the SWI task. Participants rested their hands on the table in front of them with their eyes closed. The experimenter quietly placed an object on top of a force plate in front of the participant. A beep was played which signalled to the participants to open their eyes, reach forwards with their dominant hand, and grasp the object with their thumb and forefinger using the force transducer as a handle. Participants lifted the object upwards in a smooth motion and held it in place at the top of the lift, approximately 10cm above the force plate. After three seconds another beep signalled to the participants to place the object back down onto the force plate. Participants gave a numerical indicator of the perceived weight of the object, placed their lifting hand back on the table, and closed their eyes. Participants' weight reports were on a scale of their choosing, with large numbers indicating heavier and small numbers indicating lighter perceived weights (absolute magnitude estimation; Zwislocki and Goodman, 1980). The experimenter demonstrated a lift and participants practised approximately five times with an object which on its own did not elicit the SWI.

The letter-crossing task was then conducted. Participants were provided with a blank copy of the stories and a pen. Participants were told they had 10 minutes to complete the task. They were instructed to either circle every “e” (control condition, low difficulty) or circle every “e” which was next to a vowel which was not an “i” (fatigue condition, high difficulty; Hagger et al., 2016). Participants had the opportunity to ask any questions, and were then asked to start the task. Once 10 minutes had elapsed, participants were instructed to stop the task.

Immediately following the letter-crossing task, the SWI task was conducted. Participants then completed a payment form, and were debriefed and thanked for their time.

Analyses

The independent variable *condition* was treated as a between-subjects factor of two levels: fatigue, control.

The independent variable *object size* was treated as a within-subjects factor of two levels: small (5cm diameter), large (10cm diameter).

The independent variable *object mass* was treated as a within-subjects factor of two levels: light (355g), heavy (490g).

The dependent variable *weight report* was calculated per participant as a z-score. It is centred around zero with positive numbers indicating that objects were rated as heavier, and negative numbers indicating that objects were rated as lighter.

The dependent variable Peak Grip Force Rate (pGFR; N/s) was calculated from grip force, defined as force applied orthogonally to the force transducer. Peak Load Force Rate (pLFR; N/s) was calculated from load force, defined as the vector sum of the vertical and lateral forces applied to the force transducer. To attain the rate for each of these measures, the force data was filtered through a 14-Hz 4th-order Butterworth filter and differentiated using a 5-point central difference equation. The peak of these rates was then automatically selected using custom MATLAB code. This ‘peak’ was visually verified by the experimenter and modified where necessary to make sure that the correct peak had been identified. Trials where the force data did not show a clear peak, or where the experimenter had marked down an error during the trial, were manually removed as erroneous. For both force rates, the value represents how quickly a participant is increasing (positive values) or decreasing (negative values) the amount of force applied to the transducer. Force rates were only analysed for the first two experimental trials for each participant (i.e. the first lift of the large heavy and small heavy objects). This allowed for an assessment of sensorimotor prediction in the different conditions as well as a comparison of absolute changes in grip force magnitude (Buckingham and MacDonald, 2016).

Statistical analysis and data visualisation was conducted in RStudio using the following packages: plyr (Wickham, 2011), sjstats (Lüdecke, 2019), DescTools (Signorell, 2019), ggplot2 (Wickham, 2016), psych (Revelle, 2018), dplyr (Wickham and Henry, 2018), data.table (Dowle and Srinivasan, 2019), gtools (Warnes et al., 2018).

The data were inspected for erroneous values before analyses were conducted. Any values ± 3 SD away from the mean were removed as outliers. For all parametric tests used the assumptions were checked using visual inspections of the data, descriptive statistics, and Shapiro-Wilk tests. Any violations of these assumptions are reported within the results. The alpha level was set at .05 for all analyses.

For all boxplots, the upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Where there are no outliers, the upper and lower whiskers extend to the full range of the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line or dot showing the median. All density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. Where there are multiple lines or dots, these display individual responses within the relevant category. Non-significant results are highlighted *ns*, with significant results' associated *p* value displayed on the figure.

3.3.3 Results

A mixed ANOVA was conducted with pGFR (N/s) as the outcome variable and condition (control/fatigue), and size (small/large) as the predictors. pGFR was log normalised due to a severe violation of the parametric assumption of normality. Three participants' data were removed from the analysis due to missing values. The analysis found no main effect of condition, *F* (1, 49) = 0.586, *p* = .447, 95% CI [-0.28, 0.10], η^2 = .008. There was a main effect of size, *F* (1, 49) = 13.046, *p* < .001, 95% CI [-0.44, -0.06], η^2 = .064, indicating that participants initially used lower grip forces to lift smaller objects than larger objects. The interaction between condition and size was not significant, *F* (1, 49) = 0.623, *p* = .434, η^2 = .003. Participants scaled their grip force based on the expected weight of objects, as indicated by their size, and this behaviour was unaffected by mental fatigue (Figure 3.7).

There was no main effect of condition on pLFR, *F* (1, 49) = 0.93, *p* = .34, 95% CI [-10.57, 2.75], η^2 = .013, supporting the null hypothesis. There was a main effect of size, *F* (1, 49) = 7.184, *p* = .01, 95% CI [-13.26, 0.05], η^2 = 0.037, indicating that participants initially used higher load force to lift smaller objects than they did to lift larger objects. The interaction between condition and size was not significant, *F* (1, 49) = 2.411, *p* = .127, η^2 = .012. There was no difference in peak load force rate between the two conditions but participants did scale their force based on object size, using higher load forces for larger objects (Figure 3.7).

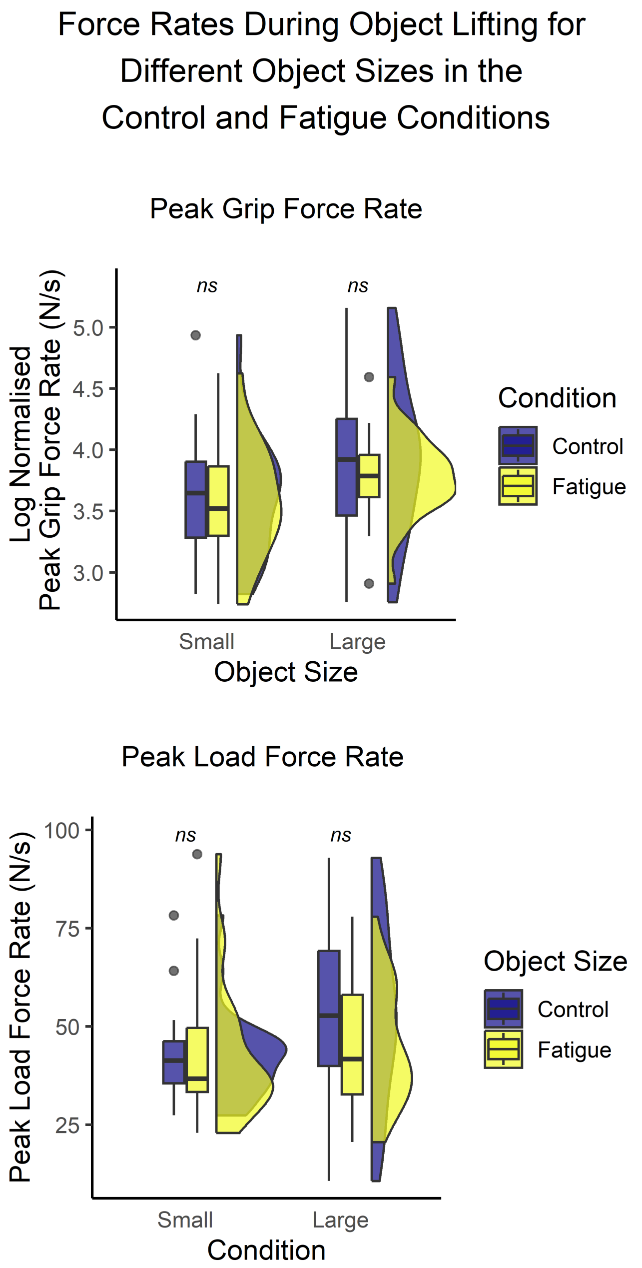


Figure 3.7: Peak Grip and Load Force Rates During Object Lifting for Different Object Sizes in the Control and Fatigue Conditions (control n = 25, fatigue n = 26). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. *ns* denotes non-significance ($p \geq .05$).

A mixed ANOVA was performed with condition (control/fatigue), size (small/large), and mass (light/heavy) as the predictors and normalised weight rating as the outcome. The results of this analysis are shown in Table 3.1. There was no main effect of condition, indicating that participants' perception of object weight was not generally affected by fatigue. Significant main effects were found for size and mass indicating that participants' weight reports were affected by both illusory weight differences (size) and real ones (mass). There were no significant interactions found between condition and size or condition and mass, indicating that the differences in weight reports between objects of difference sizes and masses were no different between conditions, i.e. participants did not report more extreme weight differences based on either size or mass when they were fatigued. There was no evidence for an effect of mental fatigue on weight perception, with participants reporting similar magnitudes of illusory and real weight differences between conditions (Figure 3.8).

	Effect	*df*	*F*	η^2_p	*p*
1	Condition	1, 51	0.50	.010	.481
2	Size	1, 51	429.62	.894	**.001**
3	Mass	1, 51	1803.00	.972	**.001**
4	Condition x Size	1, 51	1.86	.035	.178
5	Condition x Mass	1, 51	0.05	.001	.821
6	Size x Mass	1, 51	1.41	.027	.241
7	Condition x Size x Mass	1, 51	0.15	.003	.697

Table 3.1: Results of a 2 (Condition) x 2 (Size) x 2 (Weight) Mixed ANOVA with Normalised Weight Report as the Dependent Variable. Bold ***p*** values are significant at the $p < .05$ level.

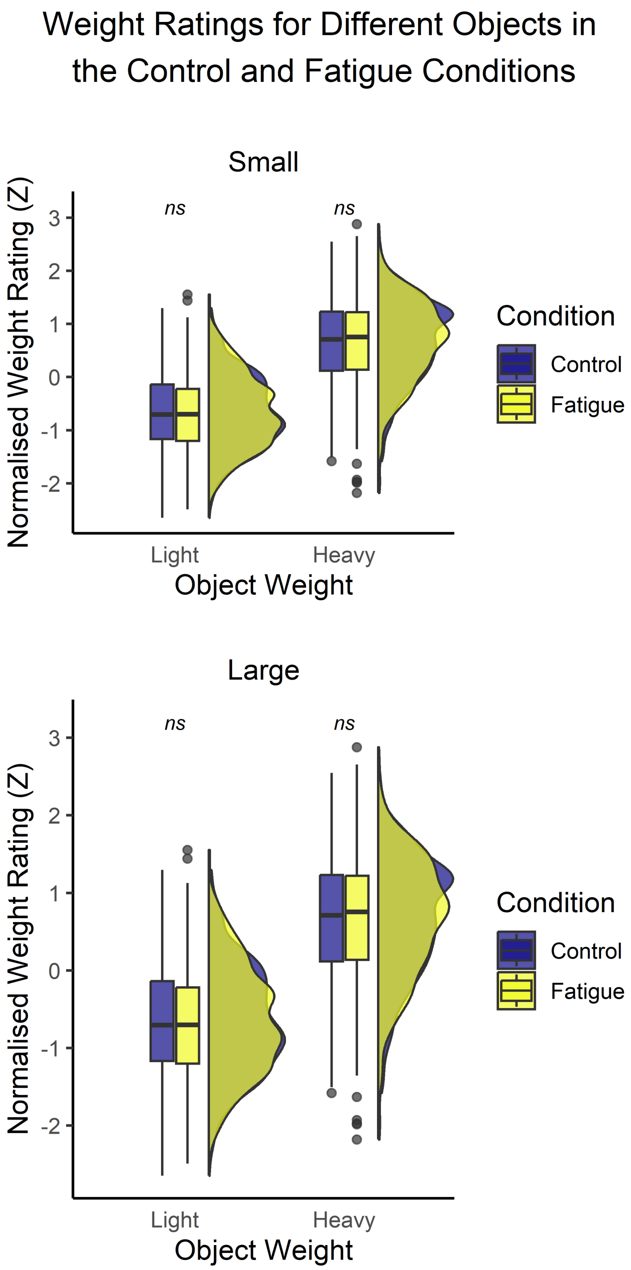


Figure 3.8: Weight Ratings for Small and Large Objects in the Control and Fatigue Conditions (control n = 25, fatigue n = 26). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. *ns* denotes non-significance ($p \geq .05$).

3.3.4 Discussion

Study 2 found no evidence for an effect of mental fatigue on perceptual reports or grip and lift behaviour during object lifting. Regardless of whether they were fatigued or not, participants experienced a size-weight illusion and were also able to discriminate real differences in object weight. Participants in the mental fatigue condition also used predictions to generate similar grip and load force rates to participants in the control condition. Thus, mental fatigue does not appear to affect dexterity when examined using an object lifting task.

There is a major limitation, however, in this study. Manipulation checks were not performed to test whether the letter-crossing task had successfully induced mental fatigue: neither subjective reports of mental fatigue nor performance data for the letter-crossing task were collected. When the study was designed, the letter-crossing task had been used extensively to induce ego depletion, which can be considered a sub-type of mental fatigue (Baumeister, 2020; Habay et al., 2023). It was therefore considered a suitable manipulation. Despite this, the suitability of the letter-crossing task for inducing ego depletion, the nature of carry-over effects from the letter-crossing task, and the cognitive processes/effects of the letter-crossing task have fallen under great scrutiny. This has led to extensive debate in the ego depletion literature and casts doubt on its viability as a mental fatigue-inducing measure. A many-labs replication by Hagger et al. (2016) found that, in 23 participating labs and with a total of 2141 participants, the effect of ego depletion as induced by the letter-crossing task on reaction time (RT) and reaction time variability (RTV) in a subsequent task was very small and that the 95% confidence intervals surrounding the effect included zero (RT and RTV *d* = .04, RT CI -.07, .14, RTV CI -.07, .15). This was taken as a null effect for ego depletion (Hagger et al., 2016), thus indicating that the letter-crossing task is unsuitable to induce ego depletion in a sequential-task paradigm like study 2.

This replication by Hagger et al. (2016) was, however, heavily criticised for using a computerised version of the letter-crossing task and for not following established procedures in the letter-crossing task which make it ego depleting (Baumeister & Vohs, 2016). Further publications by Baumeister and colleagues emphasised the specificity of the methods which they had previously used to induce ego depletion, arguing that failure to find effects of ego depletion on subsequent tasks was not due to a null effect of ego depletion but due to a failure to properly elicit ego depletion (Baumeister, 2019, 2020). Other authors also explored the high task specificity of ego depletion and found various mixed outcomes (C. Forestier & Chalabaev, 2020; C. Forestier et al., 2022; Radel et al., 2019; Wimmer et al., 2019). A more recent many-labs replication by Vohs et al. (2021) used both the letter-crossing task and a writing task to investigate the effects of these tasks on performance in two subsequent tasks. In 36 labs with 3531 participants, no ego depletion effect was found on subsequent tasks.

Whilst the letter-crossing task therefore may be suitable for inducing ego depletion, this can only be achieved under very specific circumstances (Baumeister, 2020). Ego depletion also does not consistently affect subsequent tasks (Hagger et al., 2016; Vohs et al., 2021). The letter-crossing task is therefore unsuitable for inducing mental fatigue in examining the effects of mental fatigue on dexterity, and so alternative methods must be sought.

3.4 Study 3

Given the limitations identified in studies 1 and 2, study 3 aimed to closely investigate the development of mental fatigue. As the Stroop, n-back, and letter-crossing task did not prove to be reliable methods for inducing mental fatigue, a mental rotation task was chosen, with the aim to investigate how a task with different cognitive demands may affect different indices of mental fatigue. The data collected in this study was collected as part of an undergraduate dissertation.

3.4.1 Purpose

Given the lack of evidence for mental fatigue having been induced in study 1, and the possible limitations of using the letter-crossing task as discussed in study 2, an alternative approach to inducing mental fatigue was sought. Many studies use a single long-duration cognitive task to induce mental fatigue in participants, with the Stroop and n-back having been used extensively (Clark, Goulding, et al., 2018; Pageaux et al., 2015). As identified in study 1, however, participants do not always show behavioural decrements in performance in these tasks. If participants' performance in a cognitive task declines over time, then this could indicate the development of mental fatigue, as it would show a difficulty to maintain performance under high cognitive demand. If participants were to show a behavioural performance decrement, this would provide additional evidence beyond subjective measures that they were experiencing mental fatigue.

As the Stroop and n-back tasks proved unsuitable for meeting the criterion of causing a performance decrement in the cognitive task in study 1, study 3 aimed to test whether a single long-duration mental rotation task (Shepard & Metzler, 1971) would be a suitable alternative. The mental rotation task places different cognitive demands on participants than the Stroop and n-back tasks. Whilst the Stroop and n-back tasks test response inhibition, working memory, and sustained attention (Kirchner, 1958; Stroop, 1935), the mental rotation task tests participants' spatial reasoning. Study 3 therefore sought to discover whether a task which placed different types of demands on participants would have differing effects with regards to participants' behavioural performance.

To compare the effects of the mental rotation task on mental fatigue with the effects identified in other research, two measures were adopted. Firstly, a simple rating of perceived exertion was taken to provide a measure of participants' subjective feelings of fatigue. Secondly, in line with Marcora et al. (2009), an AX-CPT task was used to measure response time and accuracy. Despite the prevalence of the AX-CPT task in the mental fatigue literature, performance in the task is often simplified to either reaction time or accuracy (e.g. Marcora et al., 2009). This does not, however, account for speed-accuracy trade-offs: where reaction time increases, this could be characterised as worsening performance when it may alternatively demonstrate an alternative strategy being applied by a participant. Therefore, an integrated measure of reaction time and accuracy was used to test participants' performance in the AX-CPT.

The hypotheses were that 1) participants would report a change in mental fatigue from before to after a 40-minute duration mental rotation task, and 2) participants' performance in the AX-CPT (as measured using an integrated measure of reaction time and accuracy) would be different from before to after a 40-minute duration mental rotation task.

3.4.2 Methods

Materials

A custom program was developed in PsychoPy3 (v2020.2.4, Peirce et al., 2019) and designed to run full-screen in browser in Pavlovia (https:%pavlovia.org accessed February 2021). The program was designed to be used on a laptop or desktop computer with participants responding using a keyboard, with the full-screen design intended to hide distracting information such as the time or computer notifications. Once participants had given informed consent, they were sent a link to the custom program so that they could complete the study procedures in a time and place of their choosing. Study procedures took a total of approximately one hour, and response values and reaction times were collected throughout.

Participants

30 healthy adults aged 18-65 were recruited via email, social media, and word of mouth. All participants reported no cognitive or visual impairments that may affect their ability to take part in the study. The sample size was determined by feasibility - data collection was completed under time constraints for an undergraduate dissertation. Participation was voluntary and informed consent was obtained from all study participants. This study was approved by the University of Exeter Sport and Health Sciences Ethics Committee (Reference 2020-006).

Procedures

A schematic of the procedures can be seen in Figure 3.9. First, participants were asked to give RPE by rating their “current level of fatigue” on a discrete scale of 1 to 10, where 1 = not fatigued at all, 5 = moderately fatigued, and 10 = extremely fatigued.

Participants then completed a ten-minute AX-CPT task, with procedures following those in Marcora et al. (2009). Detailed instructions were provided at the beginning of the task with no time restriction on reading the instructions. The AX-CPT itself comprises multiple trials each of which comprise a continuous series of four letters - cue, distractor, distractor, probe. When the cue is A and the probe is X (target trials; 70% of trials), the correct response is to press the letter ‘k’. For any other combination of letters (non-target trials; 30% of trials), the correct response is to press the letter ‘d’. This procedure is described in more detail in 4.1.2.

Following the first AX-CPT task, participants were shown detailed instructions for a mental rotation task (Shepard & Metzler, 1971) using stimuli developed and validated by Ganis and Kievit (2015). Briefly, in the mental rotation task, participants are shown two 3D shapes where one may be rotated to differing degrees in relation to the other. Participants must “mentally rotate” the items to determine whether they match. Half of the trials included matching shapes, with the correct response being to press the letter ‘k’, and half contained non-matching shapes, with the correct response being to press the letter ‘d’. A subset of 160 of Ganis and Kievit (2015) stimuli were chosen for this study, such that all eight variations of 20 different shapes were included. The stimuli were presented in a pseudorandom order such that all of the 160 stimuli were displayed before any were repeated. Assuming average response times as in Ganis and Kievit (2015), participants would see each individual image approximately three times over the course of 40 minutes. This procedure is described in more detail in 4.1.2.

Immediately following the mental rotation task, participants completed another RPE, followed by another ten-minute AX-CPT task.

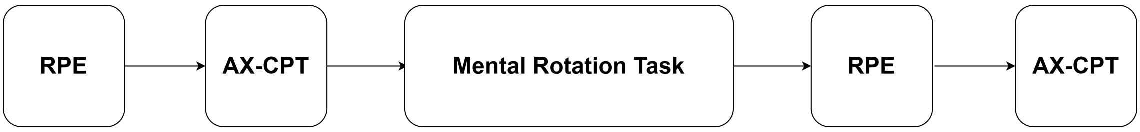


Figure 3.9: Schematic of Study 3 Procedures.

Analyses

Both analyses used *time point* (pre/post) as the independent variable. The dependent variables were *RPE* (1-10) and *Balanced Integration Score* (BIS) (-1 to 1).The BIS was calculated as described in subsubsection 3.2.2 (Liesefeld & Janczyk, 2019).

Data cleaning, visualization, and analysis was performed in RStudio (RStudio 2023.09.1+494 “Desert Sunflower” Release) using the here (Müller & Bryan, 2020), dplyr (Wickham et al., 2017), stats (Team, 2022), data.table (Dowle & Srinivasan, 2019), psych (Revelle, 2018), ggplot2 (Wickham, 2016), tidyr (Wickham & Henry, 2018), gridExtra (Auguie & Antonov, 2017), grid (Team, 2022), reshape (Wickham, 2007), and lsr (Navarro, 2015) packages.

The data were inspected for erroneous values before analyses were conducted. Any values ± 3 SD away from the mean were removed as outliers. For all parametric tests used the assumptions were checked using visual inspections of the data, descriptive statistics, and Shapiro-Wilk tests. Any violations of these assumptions are reported within the results. The alpha level was set at .05 for all analyses.

For all boxplots, the upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Where there are no outliers, the upper and lower whiskers extend to the full range of the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line or dot showing the median.

3.4.3 Results

To analyse the change in participants' perceived fatigue from before to after the mental rotation task, a paired t-test was performed with RPE as the dependent variable and time point (pre/post) as the dependent variable. This found that there was a significant increase in RPE from before to after the mental rotation task, $t(29) = -10.48$, $p = < .001$, 95% CI [-3.15, -2.12], $d = 1.91$, with 29 of the 30 participants reporting higher perceived fatigue following the mental rotation task (Figure 3.10).

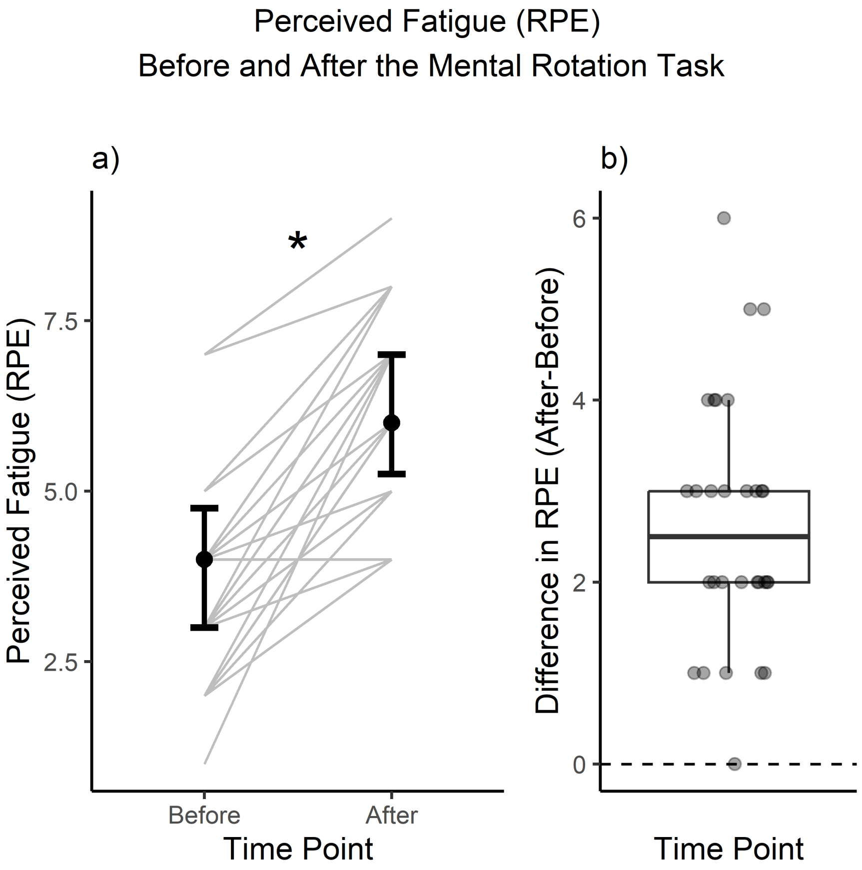


Figure 3.10: Perceived Fatigue (RPE) Before and After the Mental Rotation Task (n = 30). For a), top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle dot showing the median. The values in b) are calculated as post-pre, meaning that values above zero indicate participants who reported higher feelings of fatigue at the end of the mental fatigue battery than they did at the beginning. For b), the upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. * indicates significance at the $p < .05$ level.

The data were not normally distributed according to a Shapiro-Wilk test, p < . 001). To analyse the change in AX-CPT performance from before to after the mental rotation task, a paired Wilcoxon Signed Rank test was therefore performed with BIS as the dependent variable and time point (pre/post) as the dependent variable. This found that there was no significant difference in BIS over time, $z = -0.14$, $p = .887$, 95% CI [-.45, .4], $r = .03$. There was no change in participants' AX-CPT performance from before to after the mental rotation task, with only 16 out of 30 participants showing a reduced performance (Figure 3.11).

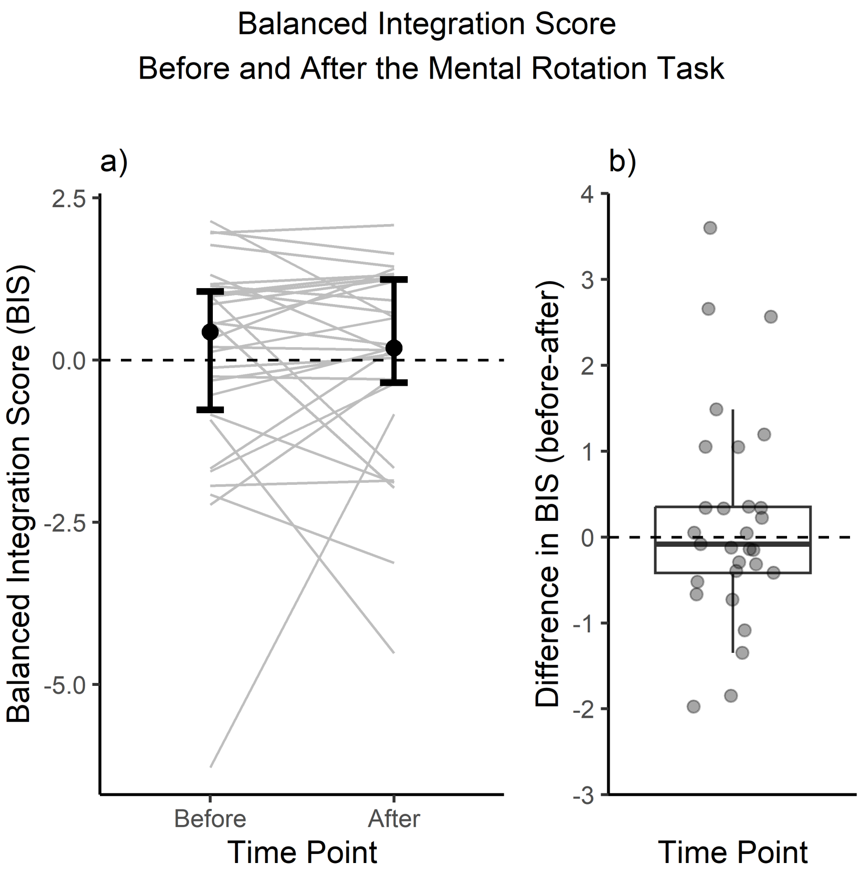


Figure 3.11: AX-CPT BIS Before and After the Mental Rotation Task (n = 30). For a), top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle dot showing the median. The values in b) are calculated as pre-post, meaning that values above the zero line are participants who performed worse at the end of the mental fatigue battery. For b), the upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data.

3.4.4 Discussion

The hypothesis that participants would report a change in mental fatigue from before to after the 40-minute duration mental rotation task was confirmed. Participants' RPE significantly increased from a mean of 3.77 (±1.52) before the mental rotation task to 6.4 (±1.4) afterwards. The mental rotation task thus successfully induced subjective feelings of mental fatigue.

There was, however, no significant difference in AX-CPT performance as measured by the BIS from before to after the mental rotation task. Approximately half of the participants (14/30) showed an improvement on the AX-CPT from before to after the 45-minute mental rotation task. The hypothesis that participants' performance would differ from before to after the mental rotation task was therefore rejected. Whilst some participants' performance did decline, this effect was not sufficiently consistent to be significant at the group level, and so the task was deemed to be unreliable for the purposes of inducing performance alterations which would objectively support the presence of mental fatigue.

Overall, these results suggest that the mental rotation task in itself is not suitable for inducing mental fatigue, due to the lack of objectively measurable changes in performance in the AX-CPT task. This does not appear to be an issue of sample size or low statistical power to detect an effect, as considering individual performance differences, almost exactly half of the participants showed an *improvement* in AX-CPT performance, where a decrement would be expected in mental fatigue.

3.5 Conclusions

Neither study 1 nor 2 found evidence for an effect of mental fatigue on dexterity or related outcomes. It is unclear whether this is a genuine lack of effect, or due to a failure to elicit mental fatigue. Study 3 looked more in-depth at inducing mental fatigue used a similar approach to prior literature, but failed to elicit mental fatigue objectively even though participants did report a subjective increase in mental fatigue. Of the three approaches - one hour comprising two different commonly-used tasks, ten minutes of a single letter-crossing task, and 40 minutes of a single mental rotation task - none appear to be suitable for furthering research into mental fatigue and manual dexterity. An alternative approach therefore appears to be necessary.

Chapter 4: Development of a Novel Method to Induce Mental Fatigue

Given the limitations identified in Chapter 3, a carefully considered approach to inducing mental fatigue is necessary before the possible effects of mental fatigue on indices of dexterity can be examined. This chapter adapts and extends Hassan, E. K., Jones, A. M., & Buckingham, G. (2023). A novel protocol to induce mental fatigue. *Behavior Research Methods*. https://doi.org/10.3758/s13428-023-02191-5 which is under a Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/). The aim of the published study was to develop a novel method of inducing mental fatigue which addresses the limitations of the methods used in prior literature.

4.1 Study 4

4.1.1 Introduction

The concept of mental fatigue is one which is intuitively understood from a lay perspective. For many people, mental fatigue may be familiar as a sensation experienced occasionally at the end of a particularly challenging day. For others who work in jobs which are routinely demanding such as surgeons, those in the military, or air traffic controllers, mental fatigue may be much more commonplace. It is important to understand how mental fatigue may affect our lives. However, researchers across multiple disciplines do not yet agree on a scientific definition of mental fatigue and, crucially, how it should be induced experimentally.

Research into mental fatigue and allied concepts (e.g. cognitive fatigue, ego depletion, self-control exertion) has taken numerous different conceptual approaches (Pattyn et al., 2018) leading to differences in understanding between researchers in different disciplines (Baumeister, 2020; C. Forestier and Chalabaev, 2020). For example, mental fatigue has been conceptualized both as having a variety of effects (Lorist and Faber, 2011), and as being highly task-specific (e.g. Tanaka, Ishii, et al., 2012). Some researchers consider ego depletion as a type of mental fatigue (e.g. Habay et al., 2023), whereas others argue that they are separate phenomena (e.g. C. Forestier and Chalabaev, 2020). There are similar differences in opinion about the relationship between boredom and mental fatigue (e.g. Pattyn et al., 2008; M. R. Smith et al., 2019). Pattyn et al. (2018) describe these differing accounts of mental fatigue as “mainly semantic”. By operationalizing mental fatigue using different definitions, researchers limit the value of their research and put researchers in other disciplines are at risk of “reinventing the wheel” (Skau et al., 2021).

Consequently, the methods used to induce mental fatigue are highly varied (Pitts and Bhatt, 2023; Sun et al., 2021; Tran et al., 2020; Van Cutsem et al., 2017). Some researchers use simple tasks such as the Stroop colour-word test, where participants must exercise inhibition to overcome semantic interference (Pageaux et al., 2015; M. R. Smith et al., 2016; Thompson et al., 2020) or variations of an n-back task, which require participants to remember differing lengths of sequences of items (numbers, letters, or images) whilst monitoring incoming stimuli (Clark, Goulding, et al., 2018; Shortz et al., 2015). Other more complex tasks have also been used to try to induce mental fatigue. For example, O’Keeffe et al. (2020) compared a ‘TloadDBack’ task, designed to maintain alertness whilst challenging each participant at an individualized level of difficulty, with the A-X Continuous Performance Test (AX-CPT), designed to test memory. O’Keeffe et al. (2020) demonstrated that the nature of the mental fatigue that is induced by these two tasks differs. They found that participants’ physiological arousal was affected by task choice, with participants showing significantly greater galvanic skin response and lower heart rate variability during the TloadDback than during the AX-CPT. Subjective effects also differed, with participants reporting significantly lower sleepiness, higher end-point motivation, and significantly higher vigour after the TloadDBack compared to after the AX-CPT. Mental fatigue responses also differed, with participants reporting higher mental fatigue after the TloadDBack when measured by a visual analogue scale, but higher mental fatigue after the AX-CPT when measured by the Brunel Mood Scale (Terry et al., 2003). These results highlight the importance of task choice when inducing mental fatigue, and it is reasonable to assume that this issue extends beyond the tasks tested in their study.

Differences in the tasks used by researchers to induce mental fatigue may partly explain the varying results in the literature (Holgado et al., 2020). The issue of task specificity is already the subject of extensive debate in the allied ego depletion literature, where failed replications and reduced effect sizes have been attributed to the failure by researchers to select tasks which generate the motivational conflict required to induce ego depletion (Baumeister, 2019, 2020; C. Forestier and Chalabaev, 2020; C. Forestier et al., 2022). The duration of mental fatigue-inducing tasks also varies greatly – from 4 minutes (Bray et al., 2011) to 100 minutes (Budini et al., 2014) – which could affect the outcome of the manipulation (MacMahon et al., 2021). Research into this issue has so far been inconclusive, with some researchers proposing shorter tasks as more appropriate for inducing mental fatigue (O'Keeffe et al., 2020), and others deeming it necessary to use longer tasks, with Van Cutsem et al. (2017) notably excluding short-duration tasks from their meta-analysis. Research focusing on the differing influences of tasks of different durations is ongoing (Dallaway et al., 2022). Whilst the implications of using different task durations are not as easily apparent as the implications of using different tasks, introducing methodological heterogeneity in this way is only likely to make it more difficult to elucidate the nature of mental fatigue (Arber et al., 2017).

Despite the various conceptual and methodological approaches in the literature examining the origins, characteristics, and effects of mental fatigue, two main limitations are apparent. The first limitation is an over-reliance on subjective measures of fatigue at the expense of other measures. By adopting the definition of mental fatigue as a "psychobiological state caused by prolonged periods of demanding cognitive activity and characterized by subjective feelings of 'tiredness' and 'lack of energy'" (Marcora et al., 2009), we can determine whether participants are experiencing mental fatigue by subjecting them to a demanding cognitive activity and taking subjective measures. Subjective measures alone are, however, problematic due to the potential for participants to respond to experimenter demands (Thompson et al., 2019). Additionally, tiredness and a lack of energy are not unique markers for a sense of mental fatigue and could be conflated with boredom or other sensations (Pattyn et al., 2008), including physical fatigue. Rather than relying on subjective measures alone, for participants to be mentally fatigued there should be concurrent evidence that a high cognitive demand has been placed on participants. One way of determining whether a cognitive activity is demanding is to examine performance in the cognitive activity. If participants' performance declines over time, then this shows that the task is demanding enough that participants fail to maintain task performance as time progresses. It is crucial to use both types of measures concurrently, as examining one measure at the exclusion of another risks oversimplifying mental fatigue (M. R. Smith et al., 2019) as well as risking error if bias can affect the measure (for alternative perspectives on these criteria, see Pageaux et al., 2014 and Van Cutsem et al., 2017). In line with this perspective, researchers have employed various subjective, physiological, and behavioural measures in an effort to better understand how mental fatigue is manifested (Dallaway et al., 2022; Tanaka et al., 2014).

The second major limitation in the current literature is that the paradigms which are most frequently used have low ecological validity (Gantois et al., 2021). Tasks such as the Stroop, n-back, and AX-CPT were specifically designed to target a limited number of cognitive processes in order to understand those processes better. For example, the Stroop task was designed specifically to test semantic interference (Stroop, 1935), which would not typically be experienced with great repetition or at great length as a part of daily life. When we think about the subjective experience of a few hours of challenging work, it it is qualitatively different to the subjective experience of doing a single specific and repetitive cognitive test for 30, 60, or 90 minutes. Rather, doing multiple different types of tasks and having to switch between them is more reflective of the demands of a typical day. Task-switching between multiple short-duration tasks also places additional demands on participants, increasing the likelihood that they will experience mental fatigue (Dang et al., 2013).

Without addressing these two weaknesses and moving towards a consistent way of inducing mental fatigue, researchers in all disciplines who are interested in elucidating the nature, origins, and effects of mental fatigue are likely to produce and build upon heterogenous outcomes (Holgado et al., 2020) which cannot be interpreted in a way that is meaningful for real-world applications. This will hinder our understanding of mental fatigue and its effects, which is problematic given the importance for certain populations, such as athletes, night-shift workers, emergency services, pilots, and those working in other demanding environments e.g. the armed forces.

The aim of this study was to develop a novel and more ecologically-valid method for inducing mental fatigue which causes performance decrements as well as a subjective increase in fatigue. To this end, a task battery was developed based on a number of cognitive tests. The hypotheses were that completing two hours of this cognitive task battery would cause both (a) an increase in subjective feelings of fatigue, and (b) a decrement in cognitive task performance.

4.1.2 Methods

Materials

Cognitive tasks Two custom programs were developed in PsychoPy3 (v2020.2.4; Peirce et al., 2019) and designed to run full-screen in browser in Pavlovia (https://pavlovia.org/; accessed February 2021). One program was a training program, designed to familiarize participants with the experimental procedures. The other program was a testing program, designed to elicit and assess mental fatigue. Both programs were designed to be used on a laptop or desktop computer with participants responding using a keyboard, with the full-screen design intended to hide distracting information such as the time or computer notifications. The files containing code and materials for each program can be found at https://osf.io/357un/ and are free to use under a General Public License v3.0 (https://psychopy.org/about/index.html,https://github.com/psychopy/psychopy/blob/release/LICENSE).

Both programs consisted of four different tasks: the AX-CPT, an n-back task, a visual search task, and a mental rotation task. The tasks were selected based on their prior use in the mental fatigue literature, and in order to maximise the breadth of executive functions which would be challenged: the AX-CPT task requires participants to engage their short-term (working) memory and inhibit their responses (Barch et al., 1997); the n-back task requires participants to continuously update the information stored in working memory and sustain attention (Kirchner, 1958); the visual search task requires participants to control spatial attention (Horowitz & Wolfe, 1998); and the mental rotation task requires spatial reasoning (Ganis & Kievit, 2015). Whilst the Stroop task is commonly used in the mental fatigue literature as previously outlined, it was not included as the primary functions which it challenges – response inhibition, semantic interference, and attentional control – are all challenged in other tasks selected. The Stroop task also requires different types of responses to the other tasks selected which would have added additional complexity to the task with unknown effects on the Stroop task itself and any task that immediately followed it.

AX-CPT The AX-CPT has been used extensively to induce mental fatigue and was designed in line with Marcora et al. (2009). In each trial, participants saw a series of four letters consisting of a cue, two distractors, and a probe. The cue was shown in red and could be any letter other than K or Y. Distractors were shown in white and could be any letter other than A, K, X, or Y. The probe was shown in red and could be any letter other than K or Y. There were four different types of trial. In target trials, A was the cue and X was the probe. The three non-target trials followed a B-X, A-Y, or B-Y cue-probe sequence, where B and Y represent any possible letter other than A or X. As in Marcora et al. (2009), 70% of trials were target trials and 30% were non-target trials (10% of each type). The correct response was ‘k’ in target trials and ‘d’ in non-target trials. Target and non-target trials were presented in a pseudorandom order, where in each 10 trials, seven were target trials and there was one of each type of non-target trial. Each letter was shown centrally on a grey background and was normalized to 7.5% of the height of the participant’s screen. The letters were each shown for 300 ms with a 1200 ms interval immediately afterwards, during which a blank screen was shown. After the probe had been presented and either participants had responded or 1200 ms had elapsed, feedback was given in yellow text. If participants responded correctly, “Correct” was shown for 1000 ms. If participants failed to respond in time or responded incorrectly, “Incorrect” was shown for 1000 ms. After a 1200 ms blank screen, a new cue was shown (Figure 4.1).

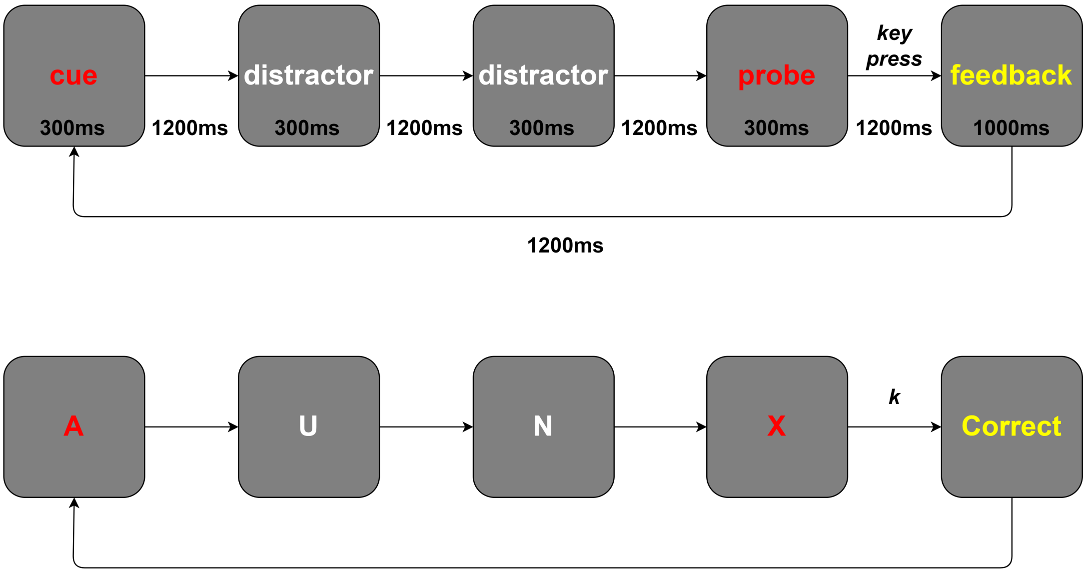


Figure 4.1: AX-CPT procedures and example target trial with correct response ('k').

N-back In the n-back task, participants are shown a series of items and are required to indicate whether the current item is the same as the item shown n items previously (Kirchner, 1958). Here, a 3-back task was used where participants had to indicate whether the current letter was the same as the letter shown 3 letters ago. Participants responded 'k' if it was the same (30% of trials) and 'd' if it was not (70% of trials). Trials were presented in a pseudorandom order, where in each 10 trials, three were target trials and seven were non-target trials. Each letter was presented for 2000 ms, followed by 1000 ms of feedback and a 1200 ms interval as in the AX-CPT task (Figure 4.2). All of the letters were shown in a white font on a grey background at the same height as the letters in the AX-CPT task. Whilst prior research has often used the 2-back version of the n-back, the more demanding 3-back was chosen to maximise the cognitive demands of the task battery in order to induce fatigue. Additionally, the findings of study 2 indicated that participants did not find the 2-back challenging when performed continuously for 30 minutes.

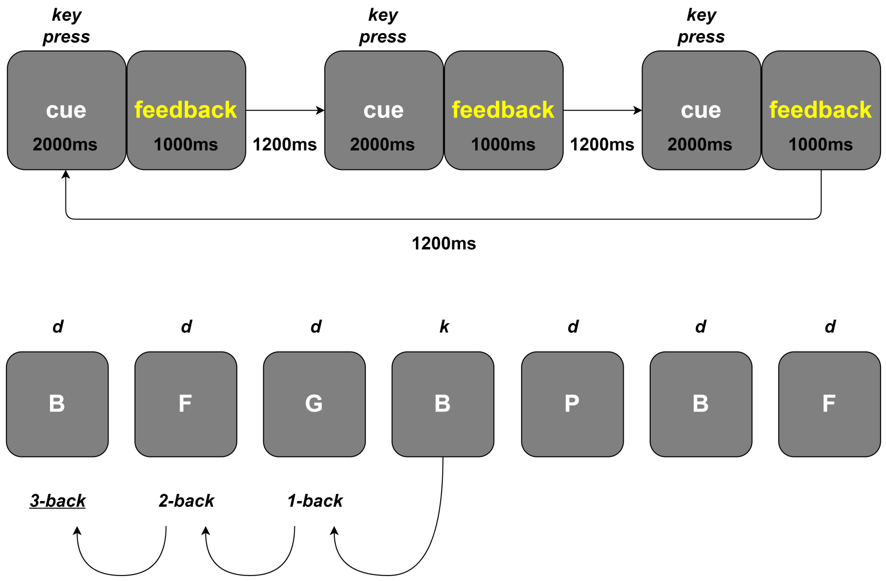


Figure 4.2: N-Back procedures and example series of letters with correct responses indicated above.

Visual search task A visual search task based on that used by Horowitz and Wolfe (1998) was used. In this task, participants were shown 11 letters on a screen which could be rotated either 0, 90, 180, or 270 degrees. The letters could appear in any space on an invisible 4 x 4 grid. The grid was centred and the size was normalized so that it would leave a border of 25% of the participants' screen size on all sides. Every trial consisted of at least 10 letter 'L's. Half of the trials were target trials where a letter 'T' was also present in the grid in a random orientation and position (Figure 4.3a). The other half of the trials were non-target trials where an additional letter L was present (Figure 4.3b). Trial order was pseudorandomized so that in every 10 trials, five were target trials and five were non-target trials. Participants were told to press 'k' when the T was shown and 'd' otherwise. There was no time limit for participants to respond. Once they had responded, 1000 ms feedback and a 1200 ms interval were shown as in the AX-CPT and n-back tasks. Letters were presented as in the n-back task.

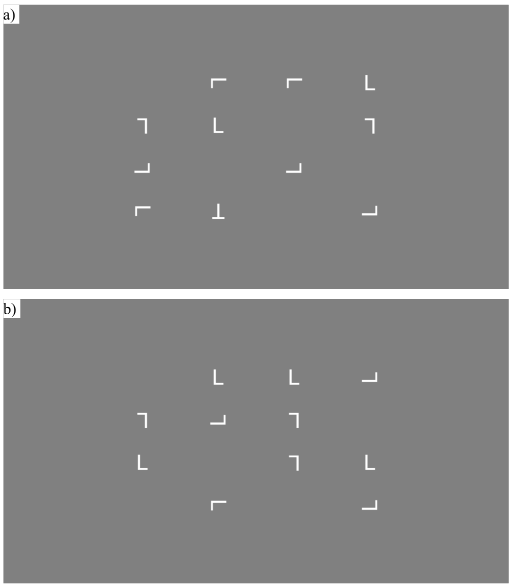


Figure 4.3: Examples of the a) target and b) non-target visual search trials, with a) showing T in the bottom row and rotated by 180 degrees.

Mental rotation task In mental rotation tasks, participants are presented with an image of two items and asked to determine whether the items match. One item may be rotated in relation to the other, requiring participants to visualize and "mentally rotate" one or other of the items to complete the task (Shepard & Metzler, 1971).

A set of stimuli developed and validated by Ganis and Kievit (2015) was used. In Ganis & Kievit's (2015) stimuli, the left-hand shape is always oriented in the same way, with the right differing by 0, 50, 100, or 150 degrees around a vertical axis (25% of the set differs by each amount). Half of the stimuli show matching shapes (Figure 4.4a) and half show non-matching shapes (Figure 4.4b). The non-matching shapes are pseudo-mirror images which are made of the same number of cubes and have the same configuration of arms as the matching shapes. The same subset of 96 stimuli as Ganis and Kievit (2015) used in their validation study was chosen. With the subset of 96 stimuli, a mean response time of 3000 ms (the largest mean response time in Ganis and Kievit, 2015) would mean that each trial would take 5.2 s allowing for each participant to complete at minimum 115 trials. As the stimuli were presented in a pseudorandom order requiring that every stimulus had been presented at least once before any could be presented again, a participant would see each of the 96 stimuli at least once in 115 trials. Stimuli were presented centrally at 50% of the width and 25% of the height of the participant's screen. Participants were presented with each stimulus for 7500 ms and required to respond with 'k' if the shapes matched and 'd' if they did not. As in the other tasks, participants received written feedback for 1000 ms, followed by a 1200 ms interval (Figure 4.4c).

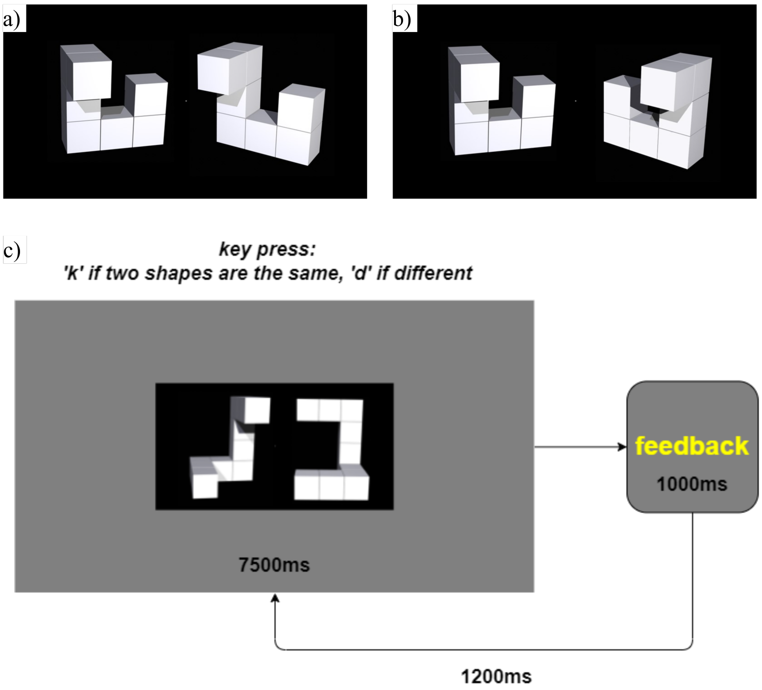


Figure 4.4: Example stimuli and procedures in the mental rotation task. a) shows example matching stimulus, with shape on the right rotated by 50 degrees on the vertical axis relative to the shape on the left (stimulus '1_50' from Ganis & Kievit, 2015). b) shows example non-matching stimulus, with pseudo-mirror shape on right rotated by 50 degrees on the vertical axis relative to the shape on the left (stimulus '1_50_R' from Ganis & Kievit, 2015). c) shows procedures.

Brunel Mood Scale (BRUMS) Questionnaire To assess the subjective experience of fatigue, a computerized version of the BRUMS (Terry et al., 1999, 2003) was developed. The BRUMS comprises 24 items with descriptors such as "bitter", "active", and "uncertain" which can be divided equally onto six subscales – anger, confusion, depression, fatigue, tension, and vigour. Participants reported how they were feeling at that moment by rating each item from 0 (Not at all) to 4 (Extremely) using a mouse to select one of five points distributed equally along a horizontal line. The total score for each subscale was calculated by adding up the numbers selected for each item, giving a possible range for each subscale from 0 to 16.

Participants

71 participants over the age of 18 who self-reported being free from cognitive and/or visual impairments were recruited. The sample size was determined by feasibility constraints – namely the financial cost of remunerating participants, and the availability of researcher(s) to run the study. Data collection ceased when the budget for the study was nearly depleted and when the research team no longer had capacity to run the study. Informed consent was obtained from all study participants. This study was approved by the University of Exeter Sport and Health Sciences Ethics Committee (Reference 201021-A-07) and was conducted in line with the Declaration of Helsinki. Participants were paid £20 to compensate them for their time taking part in the study.

Of the 71 participants recruited, 12 participants withdrew (five failed to complete the initial training session and seven failed to complete the testing session). Five of these participants withdrew due to technical errors during data collection which led to a failure to complete the task or save the data.

Nine participants were excluded due to poor data quality. The parameters for what constituted poor data quality were decided prior to data collection to reduce the possible effects of decision-making bias on the outcomes of the study, but were not formally preregistered. Participants were excluded if they failed to give any response on more than 25% of trials in the cognitive tasks, or responded with only ‘k’ or ‘d’. Participants were also excluded if they rated every item in the BRUMS 0 or 4, or if they completed the BRUMS in less than one second per item. Of the nine participants who were removed, none were excluded based on their responses in the BRUMS. A summary of the responses of the excluded participants can be seen at https://osf.io/6arv9/.

Following these withdrawals and exclusions, the final sample consisted of 45 participants aged 19-63 years, with a mean age of 35 ±14.

Training protocol

Once participants had given informed consent, they were sent a link to the training program. In the training program, participants were given full instructions and the names of each cognitive task and practised each task for five minutes with self-paced breaks between tasks. Participants practised the AX-CPT first, followed by the n-back task, the visual search task, and the mental rotation task.

Mental fatigue protocol

Once participants had finished the training and this had been verified by the experimenter, they were sent a link to the testing program. Participants were instructed to do the testing program as close to 48 hours following the training session as possible and to ensure that they would be in a quiet environment where they would not be interrupted. They were also advised that they may be mentally fatigued following the testing session and that they should allow time for rest afterwards.

At the beginning of the testing program, participants completed a digitized version of the BRUMS questionnaire. Participants then completed each task three times for 10 minutes for a total of 120 minutes time on task (Figure 4.5). The AX-CPT was chosen as the “critical task” in which to measure task performance as in Marcora et al. (2009). Consequently, the AX-CPT was first and last. The remaining tasks were presented in a pseudorandom order. The order of the tasks was chosen so that participants did not repeat tasks back-to-back; to maximize the time between tasks being repeated so that the procedure felt less repetitive; so that the time between tasks being repeated was similar between the different tasks; and so that if any order effect was present it would be the same for all participants. A self-paced break was placed between each task. In this break, participants were shown brief instructions telling them which task would begin next and reminding them how to complete the task. They were also reminded to respond as quickly and accurately as possible.

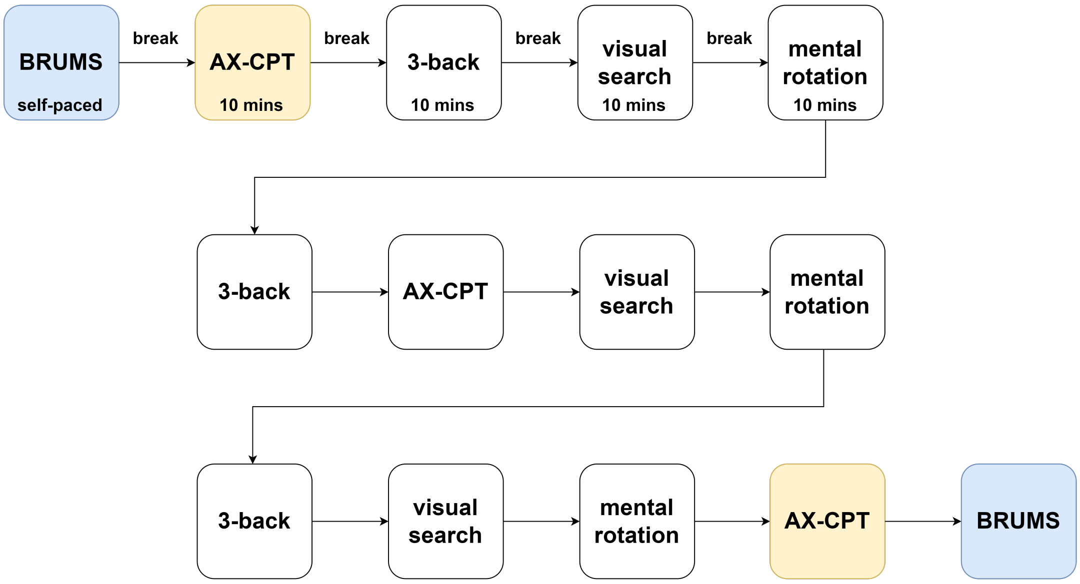


Figure 4.5: The Mental Fatigue Protocol. Participants completed a BRUMS questionnaire followed by three repeats of four different cognitive tasks: the AX-CPT, a 3-back task, a visual search task, and a mental rotation task. Each cognitive task was completed for 10 minutes at a time with optional self-paced breaks between tasks. After all the cognitive tasks had been completed, the BRUMS was administered again. The blue and yellow boxes highlight stages where data was collected to test hypotheses a) and b) respectively.

Statistical analysis

Data cleaning, visualization, and analysis was performed in RStudio (RStudio 2022.02.0+443 “Prairie Trillium” Release) using the here (Müller & Bryan, 2020), dplyr (Wickham et al., 2017), stats (Team, 2022), data.table (Dowle & Srinivasan, 2019), psych (Revelle, 2018), gtools (Warnes et al., 2018), ggplot2 (Wickham, 2016), car (Fox & Weisberg, 2011), tidyr (Wickham & Henry, 2018), gridExtra (Auguie & Antonov, 2017), and grid (Team, 2022) packages. All scripts and data, including data formatted for use with other statistical software, are available at https://osf.io/6hjc3/.

Two Wilcoxon Signed Rank Tests were used to analyse the data for the primary hypotheses. Both tests had time point (pre/post) as the independent variable. To assess subjective feelings of fatigue, BRUMS fatigue subscale score at the beginning and end of the testing program (highlighted in blue, Figure 4.5) was used as the dependent variable. To assess task performance in the AX-CPT (as discussed in subsection 4.1.1), reaction time and accuracy were integrated in order to control for participants changing their strategy as they become fatigued and prioritizing one or the other of the two performance metrics (van der Linden, 2011). To do this, the balanced integration score (BIS; Liesefeld and Janczyk, 2019) was used. The BIS combines reaction time and accuracy into a single metric which is standardized across all conditions (in this case, time points) and participants. A BIS score of zero represents an average level of performance across all participants and conditions, with above average and below average performance indicated by positive and negative numbers respectively. The BIS was chosen as it has been shown to be the least sensitive to speed-accuracy trade-offs in comparison to other integrated measures of reaction time and accuracy (Liesefeld & Janczyk, 2019). The BIS score was calculated using the reaction time and response data collected during the first and last repeat of the AX-CPT task (highlighted in yellow, Figure 4.5).

For all boxplots, the upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Where there are no outliers, the upper and lower whiskers extend to the full range of the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line or dot showing the median. All density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. Where there are multiple lines or dots, these display individual responses within the relevant category.

4.1.3 Results

Subjective ratings

A Wilcoxon Signed Rank Test with time point (pre/post) as the independent variable and BRUMS fatigue subscale score as the dependent variable revealed a significant increase in subjective feelings of fatigue, $z = -5.72$, $p < .001$, 95% CI [4.5, 7], $r = .85$. Participants reported feeling significantly more fatigued after completing the cognitive task battery than they were before they started the battery (Figure 4.6). Hypothesis (a) that completing two hours of a cognitive task battery will cause an increase in subjective feelings of fatigue was therefore accepted. Out of 45 participants, 43 reported an increase in subjective fatigue, with two participants reporting no change.

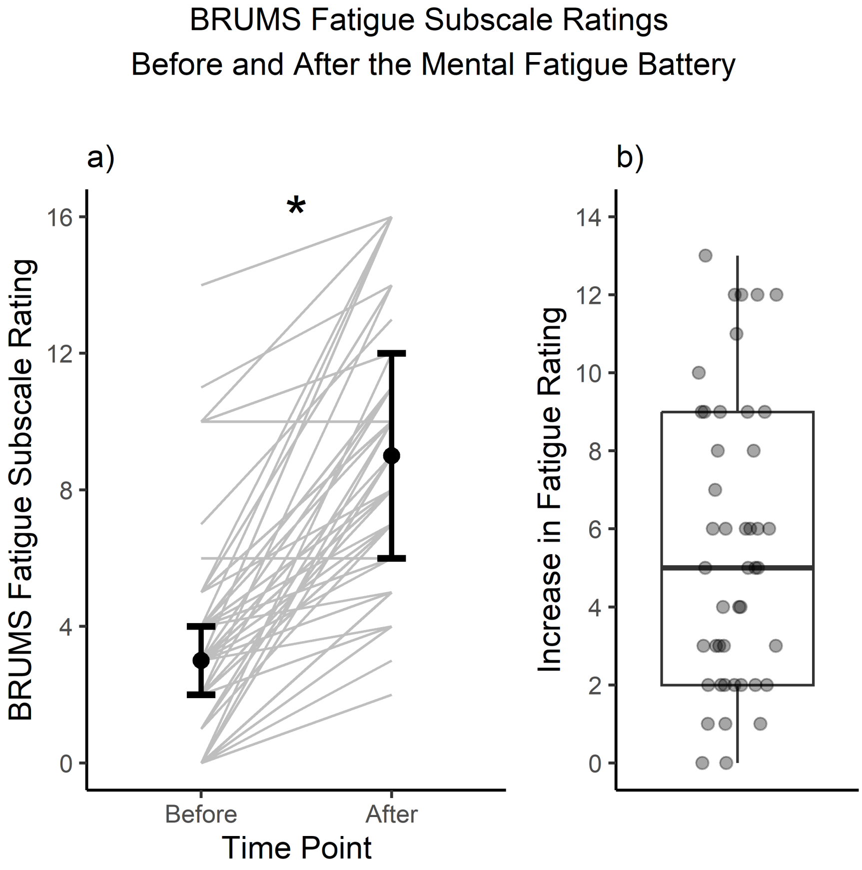


Figure 4.6: BRUMS Fatigue Subscale Ratings Before and After the Mental Fatigue Battery (n = 45). Grey lines and dots show individual observations. For a), top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle dot showing the median. For b), the upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range. The values in b) are calculated as post-pre, meaning that higher values indicate participants who reported greater increases in feelings of fatigue from the beginning to the end of the mental fatigue battery. * indicates significance at the *p* < .05 level.

AX-CPT performance

A Wilcoxon Signed Rank Test with time point (pre/post) as the independent variable and AX-CPT BIS as the dependent variable revealed a significant decrement in task performance, z = -2.64, p = .008, 95% CI [.09, .75], r = .39. Participants' performance in the AX-CPT was significantly worse at the end of the cognitive task battery in comparison to their performance at the beginning (Figure 4.7). Hypothesis (b) that completing two hours of a cognitive task battery will cause a decrement in cognitive task performance was therefore accepted.

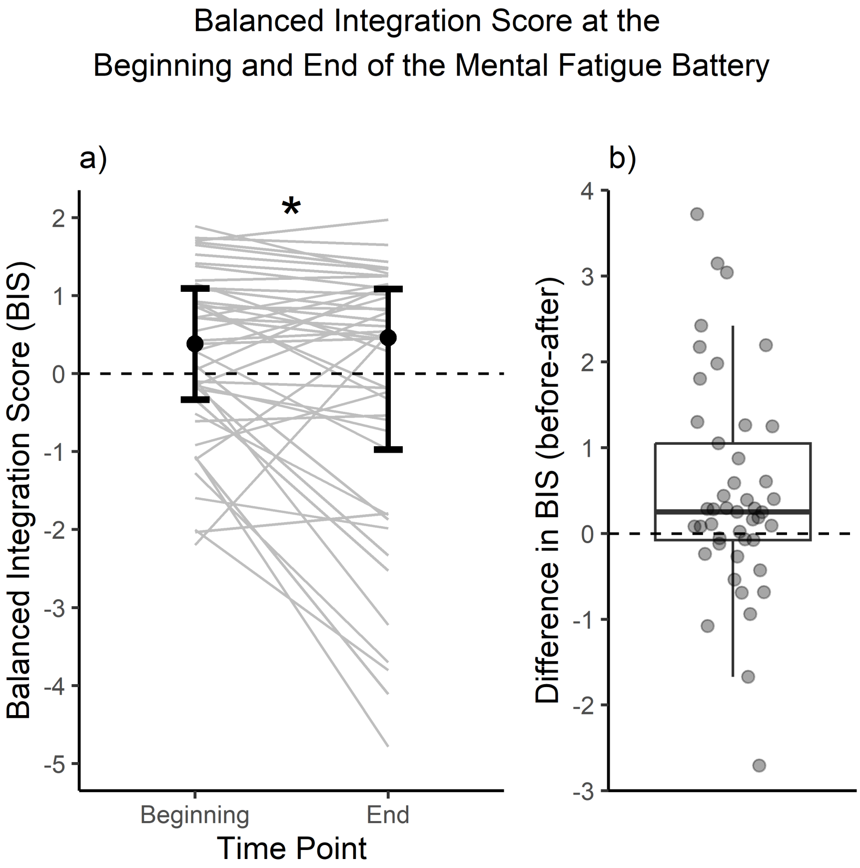


Figure 4.7: Balanced Integration Score at the Beginning and End of the Mental Fatigue Battery (n = 45). Grey lines and dots show individual observations. For a), top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle dot showing the median. The values in b) are calculated as pre-post, meaning that values above the zero line are participants who performed worse at the end of the mental fatigue battery. For b), the upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. * indicates significance at the *p* < .05 level.

A decrease in vigour has previously been identified as an important marker of mental fatigue (Pageaux et al., 2015), so this was tested statistically. A Wilcoxon Signed Rank test revealed a significant decrease in subjective feelings of vigour, *z* = -5.39, *p* < .001, 95% CI [-5.5, -3.5], *r* = .80 (Figure 4.8). A Spearman's rank correlation exploring the changes in vigour and fatigue also revealed a significant negative correlation, ρ (45) = -.52, p <.001. Overall, participants experienced decreases in vigour from before to after the cognitive task battery. Participants who experienced greater increases in fatigue also experienced greater decreases in vigour.

Further investigation of the remaining BRUMS subscales showed that participants also reported other mood changes. A series of Wilcoxon Signed Rank tests revealed statistically significant increases in anger, z = -3.15, p = .002, 95% CI [0.99, 4], r = .47, and confusion, z = -2.16, p = .031, 95% CI [0.00005, 2], r = .32. There were, however, no changes found in depression, z = -1.73, p = .084, 95% CI [-2.6, 3], r = .26, or tension, z = -0.19, p = .851, 95% CI [-1.5, 1], r = .03.

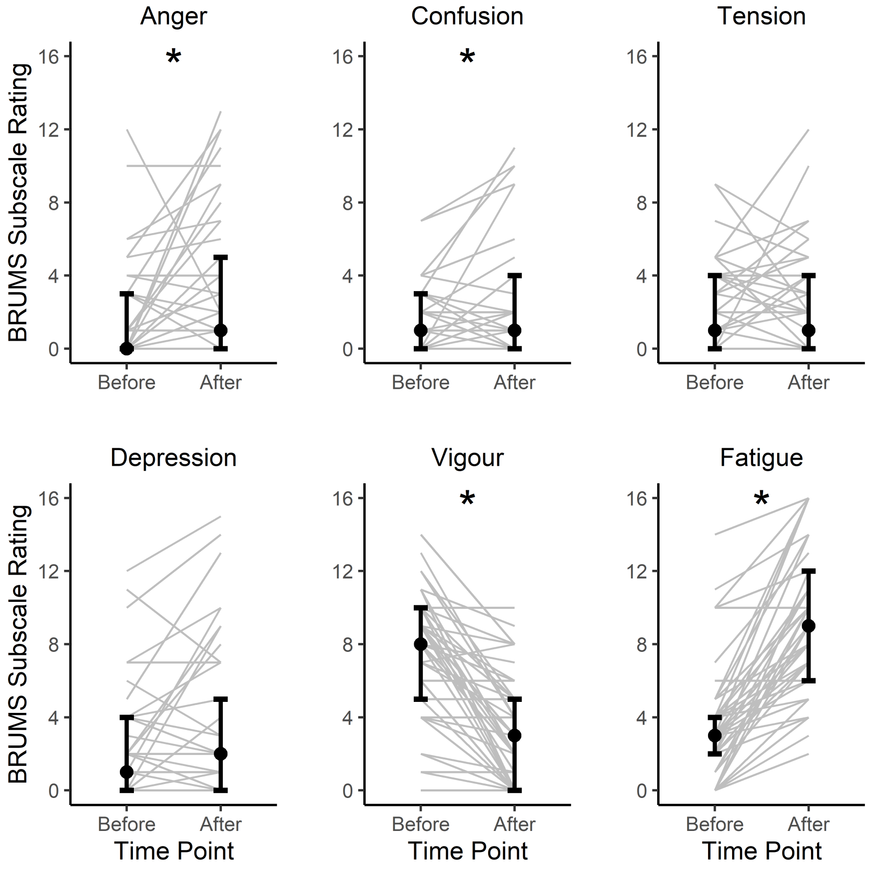


Figure 4.8: Participants' Responses in all BRUMS Subscales Before and After the Mental Fatigue Battery: anger, confusion, tension, depression, vigour, fatigue (n = 45). Grey lines show individual observations. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle dot showing the median. * indicates significance at the p < .05 level.

It is possible that the duration of self-paced breaks may affect mental fatigue development, with longer breaks possibly alleviating mental fatigue and allowing participants to recover sufficiently to improve or retain their behavioural performance. To examine the possible relationship between break duration and subjective fatigue, a Spearman's rank correlation was performed between mean break duration and BRUMS rating at the end of the cognitive task battery. No significant relationship was found, ρ (45) = .08, *p* = .607. A Spearman's rank correlation between mean break duration and AX-CPT BIS at the end of the cognitive task battery also found no significant relationship, ρ (45) = -.06, *p* = .689. Participants' changes in subjective feelings of fatigue and their performance in the cognitive task battery were not related to the length of breaks that they took throughout (Figure 4.9, Figure 4.10,).

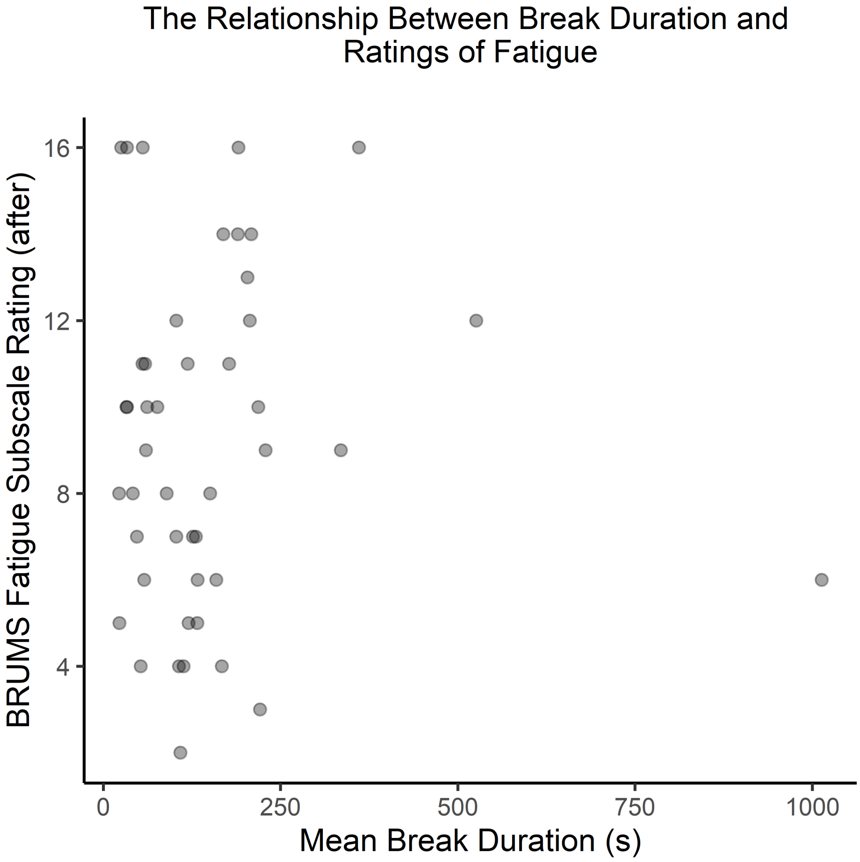


Figure 4.9: The Relationship Between Mean Break Duration and BRUMS Fatigue Subscale Ratings After the Mental Fatigue Battery (n = 45). Grey points show individual observations.

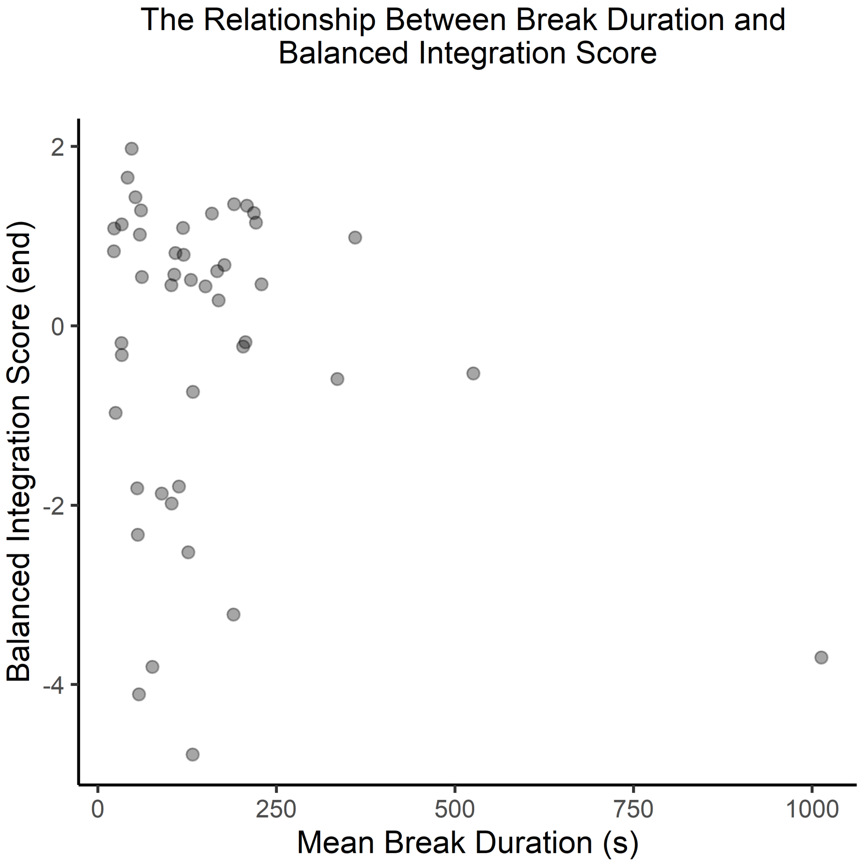


Figure 4.10: The Relationship Between Mean Break Duration and AX-CPT Balanced Integration Score After the Mental Fatigue Battery (n = 45). Grey points show individual observations.

To examine whether there was a relationship between the change in performance in the cognitive task and the change in perceived fatigue, a Spearman's rank correlation was performed. No significant relationship was found, ρ (45) = .04, *p* = .774. Participants' changes in subjective feelings of fatigue were not related to their changes in performance in the AX-CPT task (Figure 4.11).

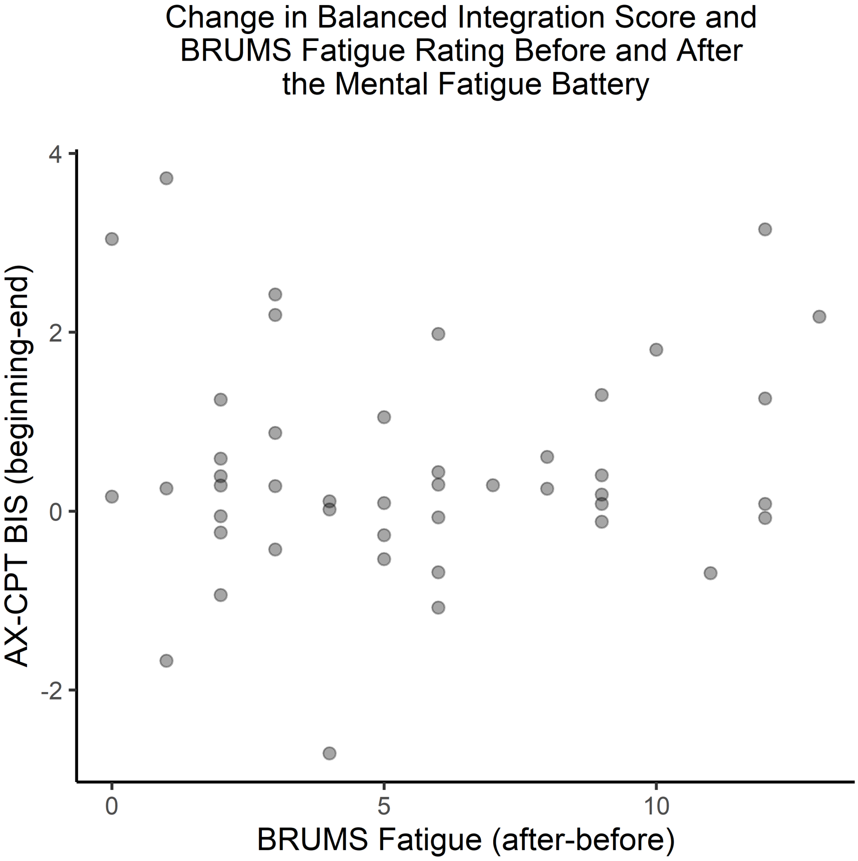


Figure 4.11: Change in AX-CPT Balanced Integration Score and BRUMS Fatigue Subscale Ratings (n = 45). Grey points show individual observations.

4.1.4 Discussion

The aim of this study was to develop and validate a novel method to induce mental fatigue. The task was successful at inducing both an increase in subjective feelings of fatigue and a decrement in cognitive task performance, supporting both the hypotheses. The task therefore seems suitable for inducing mental fatigue as defined by Marcora et al. (2009) – participants experienced subjective feelings of fatigue (including but not limited to tiredness and a lack of energy), and their cognitive task performance decreased over time indicating that task demands were high.

The subjective increase in mental fatigue observed using the BRUMS fatigue subscale is slightly larger than that reported by Marcora et al. (2009), who found that when participants completed a continuous 90 minute AX-CPT task, they experienced an increase from a mean of approximately 4 ± 4 to 7 ± 5, in comparison with 4 ± 3 to 9 ± 4 in this study. This indicates that this novel task can induce greater fatigue in participants than previous approaches, possibly due to the longer task duration. Given the heterogeneity of approaches in the current literature, in particular with different approaches to measuring subjective fatigue (e.g. by using different types of visual analogue scale; O'Keeffe et al., 2020; M. R. Smith et al., 2016), and the fact that there is no standardized way of reporting subjective fatigue outcomes, it is difficult to directly compare the size of this effect with that found in the literature more broadly. The decrement in cognitive task performance that was observed during this task was significant, but the effect was relatively small. Again, it is difficult to compare this result to that found in the broader literature, as here, an integrated measure of reaction time and accuracy (the BIS) was used, where previous literature has not integrated these two outcomes. For example, comparing changes in task accuracy in this study with changes in the accuracy in Marcora et al. (2009) – reductions of 3.5% and 5.9% - is possible but not meaningful due to different population types and sizes, the different experimental approaches, and the possibility of unaccounted changes in reaction time. Future researchers should use integrated measures such as the BIS to examine cognitive task performance to account for speed-accuracy trade-offs.

By examining individual participants' performance in the cognitive task battery, this study has identified that some participants' performance in the AX-CPT improved during the manipulation, with 14 out of our 45 participants performing better in the AX-CPT in the final ten minutes of the cognitive battery than in the initial ten minutes. Whilst all these participants nonetheless experienced an increase in subjective fatigue, this highlights the need for researchers to carefully consider other factors when assessing mental fatigue such as behavioural task performance (Van Cutsem et al., 2017). There are many possible reasons why these participants' performance might have improved. For example, as this study was conducted remotely, it is possible that participants were not fully engaged at the beginning of the task. Also, nine participants completed the testing session more than two days after the training session, and consequently may have needed time to remember how to perform the task, resulting in worse initial performance. This could have led to an apparent improvement in performance over time instead of a decrease in performance. However, if this effect was present in this data, it did not impact the overall outcome: the significant detrimental effect of the mental fatigue manipulation on task performance was evident at the group level despite the possibly confounding improvements in performance found at the individual level which was to find a decrement in task performance from the beginning to the end of the task battery. Similarly, a learning effect may have taken place, where participants improved due to practice over the two-hour time period of the battery, or this sub-group of participants may have independently monitored their elapsed time very closely allowing them to know the end-point of the task and invest more effort in the final ten minutes (Katzir et al., 2020), where other participants did not monitor their time closely enough to provide them with this information. Under the definition of fatigue used in this study, participants who experienced a subjective increase in feelings of fatigue with no concomitant performance decrement would still qualify as being mentally fatigued, as the level of cognitive demand placed on participants could be assumed. This interpretation, however, should be used with caution in a scenario where an experimenter is interested in examining the effects, correlates, or markers of mental fatigue, as subjective reports are subject to experimenter demands (Thompson et al., 2019).

To further characterise the mental fatigue that was induced by the cognitive task battery, additional analyses were conducted which focused in more detail on the subjective reports from participants, and how they related to other variables such as behavioural performance and participant characteristics. These analyses revealed additional information about the mental fatigue that was induced by the cognitive task battery. The decrease in vigour found in the current study is in line with some prior research (Pageaux et al., 2015). Whilst some researchers have highlighted a decrease in vigour as an important marker of mental fatigue, a decrease is not always found, and some have argued that it is important for vigour to be maintained so that effects can be isolated to fatigue alone (O'Keeffe et al., 2020). Nonetheless, given that it has been identified as important, the finding that the cognitive task battery used in this study resulted in a statistically significant decrease in vigour across the whole group of participants supports the contention that the task battery is appropriate for inducing mental fatigue. Closer inspection of the individual data shown in Figure 4.8 shows that this group-level trend was evident in the majority of participants, with six showing no change and one showing an increase of 1 in vigour. This indicates that the vigour outcome is relatively consistent across participants.

Participants' changing mood states were not limited to fatigue and vigour. In accordance with prior research into mental fatigue (Boksem & Tops, 2008), a great variety of emotional responses were reported across the BRUMS subscales for anger, confusion, tension, and depression. This supports the notion of mental fatigue as being related to mood change (O'Keeffe et al., 2020). From these findings, it appears that mental fatigue is a multifaceted experience which is not limited simply to changes in fatigue and vigour or changes in task performance. Participants' differing mood states could differentially affect their performance in subsequent or concurrent tasks, give misleading neural correlates of mental fatigue, or cause them to conflate fatigue with other feelings. As these different subjective responses are not habitually monitored by researchers, it is impossible to know whether this variety of emotions in the mental fatigue response is present in the extant literature, and whether it may be resulting in heterogenous outcomes. It is important that the way fatigue is measured and operationalized is able to detect changes in these possible confounding variables so that researchers can control, account for, or otherwise take into consideration their possible impacts.

One potentially confounding aspect of the current protocol is that participants' breaks were optional, self-paced, and - due to the online nature of the study - unsupervised. Participants' break duration, activity during breaks, and break frequency would have differed and this could have affected participants' mental fatigue development. Some participants showed relatively long mean break durations compared to others, with the most extreme example showing an average break duration of approximately 1000 seconds or 15 minutes. As seen in Figure 4.9 and Figure 4.10, however, there was no significant relationship between the break durations taken by participants and the subjective and objective mental fatigue outcomes. Whilst break duration did not affect the outcomes in this study, future investigation of the relationship between break duration and mental fatigue may be worthy. Specifically, there could be numerous reasons for longer break durations that are related to mental fatigue: participants may take longer breaks to alleviate greater fatigue; they may take longer breaks to keep fatigue low; they may take shorter breaks to reduce the overall duration of a task with the perception that that will reduce the onerousness of the task; or they may take longer breaks due to disengagement and thus not become very fatigued due to being disengaged from the task(s). All of these reasons could contribute to great variations in the mental fatigue induced in research, and in the effects of mental fatigue on subsequent tasks.

This study directly tested the relationship between subjective and objective behavioural measures of fatigue. There was no association between the change in mental fatigue from before to after the cognitive task battery and the change in behavioural performance from the beginning to the end of the battery. This supports the notion that it is important for researchers to consider both types of measures when examining the outcomes of mental fatigue manipulations, as behavioural performance and subjective perception are dissociable.

Experimenters aiming to induce fatigue in participants should try to mitigate the challenges that arose in this study with participant withdrawals and exclusions by supervising participants (as opposed to their completing the task remotely), motivating them to perform well (e.g. by providing a monetary reward), and excluding participants who do not appear to engage with the task (as done here, or for example by using attention checks). Disengagement may be an indicator of mental fatigue especially when the disengagement is towards the end of the fatigue-inducing task. In the current study, however, it is difficult to know the reason for disengagement as participants completed the study remotely and without supervision. Future research should investigate possible reasons for disengagement at different stages of mentally fatiguing tasks and aim to establish possible indicators.

Limitations

As part of this work, no replication of the findings was conducted. Researchers who are interested in using this task in their own work may wish to reproduce this study in order to better understand the replicability of the effects. This is especially relevant for researchers who might use different populations or for researchers using smaller sample sizes, given the varied behavioural responses across the broad range of participants. Researchers who are interested in the transfer of behavioural effects of mental fatigue may also wish to expand future replications to examine the effects of this task battery on a wider range of cognitive tasks (i.e. not only in the AX-CPT).

The current task design does not account for participants' perceptions of boredom or of mental effort. According to theories of underload (Van Cutsem et al., 2022), boredom should not be a risk in the current study as the cognitive challenge was high. Future research should seek to evaluate participants' levels of boredom as related to the implementation of the task battery, in order to identify and possibly adjust for any confounding affects. Related to boredom, mental effort is also an important aspect of mentally fatiguing tasks which was not directly measured in this study. Future research should measure mental effort rather than using assumed or inferred methods. A simple test such as the NASA-TLX (National Aeronautics and Space Administration, 2022) could measure mental effort as well as other potentially relevant outcomes such as perceptions of physical effort and task performance, which are not captured in the BRUMS. This would allow researchers to account for additional confounds that could be present if, for example, participants perceive physical fatigue as a consequence of the mental fatigue manipulation.

Finally, the online remote nature of this study meant that it was practically impossible to control or account for extraneous factors such as participants' sleep quality, caffeine or alcohol consumption, or physical illness. It is possible that this has added noise to the data, which future researchers may wish to avoid by conducting research in person, especially if they are using smaller sample sizes which may result in less statistical sensitivity to smaller effects in the presence of noise. This study was conducted remotely online due to ongoing COVID-19 lockdowns in the UK. This may present an additional limitation to the research findings, as participants may have been experiencing additional cognitive load due to this environmental stressor.

Future directions

Research into the neural and physiological correlates or hallmarks of mental fatigue is ongoing. Future research may wish to investigate, compare, and contrast the effects of this novel two-hour cognitive task battery on outcomes already associated with mental fatigue such as heart rate and cortical activity. As discussed, tasks which last for an extended duration and use only one or a few different aspects of working memory have low ecological validity. Quantifying the differences between long-duration simple tasks and more complex or varied tasks such as this two-hour battery through such neural and physiological measures could provide an insight into how these differences emerge at a biological level.

The over-reliance on subjective measures in extant research was addressed in this study with a novel approach to carefully examining and characterising a range of subjective measures, and the relationship between the subjective and behavioural responses. This found that mental fatigue is a complex phenomenon with a range of different subjective and behavioural responses from participants, with possible implications for subsequent tasks if e.g. a participant reports greater anger. Future researchers should similarly carefully monitor the effects of mental fatigue-inducing interventions in case of such confounding effects.

4.2 Conclusions

In conclusion, this novel task battery is suitable for inducing subjective increases in feelings of mental fatigue and a concurrent decrement in cognitive task performance. This method addresses issues of heterogeneity and lack of ecological validity in the current literature, as well as demonstrating the possible variety of participants' responses to mental fatigue-inducing tasks. By moving towards a unified way of inducing fatigue, the scientific literature on mental fatigue would move towards a greater consensus, allowing for comparison between studies and easier collaboration across different disciplines. This novel method provides an approach which could be used to test the effects, theoretical nature, and physiological markers of mental fatigue.

Chapter 5: The Effects of Mental Fatigue on Manual Dexterity

Following the development of a novel method to induce mental fatigue in Chapter 4, this chapter reports study 5 which examined the effects of mental fatigue induced by the novel two-hour cognitive task battery on dexterity. The measures of dexterity used in this study went beyond the measures examined in studies 1 and 2 by examining performance at a broad level, as well as perception, automatic feedforward control, and conscious reactive responses to visual and cutaneous feedback.

5.1 Study 5

5.1.1 Introduction

Mental fatigue has been extensively investigated in relation to its effects on physical tasks, with a number of reviews and meta-analyses having been produced examining the effects of mental fatigue on physical performance outcomes (Giboin & Wolff, 2019; Holgado et al., 2020; McMorris et al., 2018; Silva-Júnior et al., 2016; Van Cutsem et al., 2017). Reviews by Silva-Júnior et al. (2016) and Van Cutsem et al. (2017) found that there is general support across the literature for the effects of mental fatigue on exercise performance, with Van Cutsem et al. (2017) finding that mental fatigue appears to particularly affect endurance performance. Meta-analyses have, however, resulted in more contradictory and complex findings. McMorris et al. (2018) found that, whilst the pooled evidence showed a significant negative effect of mental fatigue on physical performance, this effect was small, and it appeared possible that it could be due to random error. In agreement with the meta-analysis by McMorris et al. (2018), a subsequent analysis by Giboin and Wolff (2019) found consistent evidence for the negative effects of mental fatigue on subsequent physical performance. Holgado et al. (2019) also found a small negative impact of mental fatigue on exercise performance, but, in contrast with McMorris et al. (2018), found that there was evidence of publication bias in the literature. On correcting for this bias, the estimated effect of mental fatigue was found to be smaller and non-significant. Whilst there was variation in which studies were sampled in these different reviews and meta-analyses, which in itself would lead to different outcomes, it appears that there is no consistent strong reliable supportive evidence for an effect of mental fatigue on physical tasks.

Despite the disagreement in the literature as to whether mental fatigue affects endurance performance (Clark, Vanhatalo, et al., 2018; Holgado et al., 2023; Marcora et al., 2009; Pageaux et al., 2015; Van Cutsem et al., 2017), there is evidence that mental fatigue can affect finer skill-based performance, having been found to reduce accuracy in table tennis (Le Mansec et al., 2017) and football (M. R. Smith et al., 2016). A small body of research has also investigated the effects of mental fatigue on hand grip. The findings in this area are, however, also contradictory. This is seemingly due to methodological differences and a lack of rigour (Bray et al., 2008; Guillery et al., 2017; Holgado et al., 2019; Muraven et al., 1998; Murtagh & Todd, 2004; Pattyn et al., 2018; Pereira et al., 2018; Shortz & Mehta, 2017; Voelcker-Rehage et al., 2006; Xu et al., 2014). Additionally, this research has limited meaning for activities of daily living which rely on dexterity, as such activities typically require lower force levels than those used in hand grip endurance research.

There is a recent growing interest in the effects of mental fatigue on motor tasks using the hands, with mixed findings. Duncan et al. (2015) examined the effects of mental fatigue on two different types of task. The first required participants to anticipate when a sequence of lights placed in a straight line would reach the participants' end of a 2.24m runway, with participants standing at the end and pressing a button in anticipation. The second required participants to pick up, turn over, and place back down 60 discs which are placed inside a frame as fast as possible. Duncan et al. (2015) found that, immediately following a 40-minute mentally fatiguing concentration grid task, participants were significantly less accurate at predicting the timing of the light sequence and were significantly slower at flipping the discs than following a documentary-watching control task. This indicates that participants' predictions of movement and broader dexterity performance were both negatively affected by mental fatigue. Whilst this gives an interesting novel insight into the effects of mental fatigue on participants feedforward predictions and general ability at a dextrous task, Duncan et al. (2015) did not perform manipulation checks for mental fatigue in this study. Thus we do not know whether the concentration grid task was successful in inducing mental fatigue as intended. Nonetheless, assuming that the mental fatigue manipulation was successful, these results indicate that mental fatigue may affect object lifting as feedforward processes are an important component of object interaction. Additionally, the slower completion time in the dexterity task indicates that participants may be generally poorer at dextrous tasks when mentally fatigued.

Valenza et al. (2020) also examined the effects of mental fatigue on motor tasks using the hands. In their repeated-measures experiment, Valenza et al.'s (2020) participants watched videos for 35 minutes or completed a 35-minute mental fatigue battery comprising five different cognitive tasks: three maths tasks for 7-11 year olds (21 mins total), a Stroop task (7 mins), and a problem-solving game (7 mins). Participants then completed a simple reaction time test, and two dexterity tasks. Participants had 30 seconds in each task and were tasked with either placing as many pins in holes as possible (simple), or unscrewing and screwing as many hex nuts as possible (complex). Valenza et al. (2020) found that the mental fatigue manipulation was successful, as it elicited a greater increase in mental fatigue and a greater increase in reaction time (e.g. participants became slower) when compared to the control task. Following the mental fatigue manipulation, participants were poorer at both the simple and complex dexterity tasks, with mental fatigue having large effects (explaining 36% and 49% of variance respectively). These findings support and complement those of Duncan et al. (2015), with both studies finding participants to be slower in dexterity tasks when mentally fatigued. The additional use of both subjective and objective manipulation checks by Valenza et al. (2020) demonstrate that participants were fatigued as intended, with the repeated-measures design reducing the likelihood of confounds from individual differences. Thus, the differences in participants' performance can be reasonably attributed to the effects of mental fatigue in the mental fatigue condition.

Most recently, Budini et al. (2022) examined the effects of mental fatigue on multiple motor tasks. In their study, 29 participants were assigned to 100 minutes of either a mentally fatiguing 'switch task' (Lorist et al., 2000) or a film-watching control task. Both before and after the tasks, participants completed a mood questionnaire, a postural tremor assessment, and three different motor tasks. The first task assessed hand movements with participants moving a wand along a bent wire whilst avoiding contact with the wire. The second task assessed finger dexterity with participants having 30 seconds to place as many pins in sequential holes as possible with their dominant hand (the Purdue Pegboard Test), and with tweezers held in their dominant hand. The final task was a pinch force steadiness task where participants had to squeeze a modified tweezer using their thumb and index finger at 3N and 5N for 25 seconds, with participants using visual feedback about how hard they were squeezing to guide their movements. Muscular EMG was recorded from the first interosseous muscle throughout the dexterity tasks, with VAS mental fatigue, oxygen saturation, heart rate, and blood pressure monitored throughout the intervention and control tasks. Manipulation checks showed that participants in the mental fatigue condition reported a greater increase in subjective fatigue, had greater capillary oxygen saturation, and had greater variations in heart rate and blood pressure than participants in the control condition. Hand movements, as assessed by the wand and wire task, were not affected by mental fatigue, with mentally fatigued participants being neither slower nor more error-prone. Purdue Pegboard Test performance with both the hand and tweezers was also no different between fatigued and control participants. There was no difference in EMG recordings between groups, and there were no differences in postural tremor or tremor during the force steadiness task. Overall these findings indicate that, though mental fatigue was induced successfully, it has no effects on a variety of different motor outcomes. The finding that the Purdue Pegboard Test was unaffected by mental fatigue contradicts the results of Duncan et al. (2015) and Valenza et al. (2020), who found effects of mental fatigue on similar dextrous tasks. The tremor, wand and wire task performance, and force steadiness performance findings are entirely novel.

Together these three studies indicate that participants may perform worse in tasks which require dexterity at the broad level, but it is unclear what underlies this as there is no evidence for underlying neural or physiological differences during dextrous tasks. Whilst Budini et al. (2022) extends the findings of prior research considerably, the tasks selected do not have high relevance for activities of daily living. Furthermore, Budini et al. (2022) did not measure performance in the force steadiness task, only tremor. Whilst this can give an insight into low-level muscular or neural alterations from mental fatigue, it does not give an insight into the dynamic interplay of feedback and feedforward sensorimotor processes that underlie dexterity. Finally, Valenza et al. (2020) and Duncan et al. (2015) both had relatively small sample sizes, whilst Budini et al. (2022) used a between-groups design, which may have reduced their power to detect small effects.

Study 5 aimed to extend the findings of Duncan et al. (2015), Valenza et al. (2020), Budini et al. (2022) by examining dexterity in three different tasks. The Purdue Pegboard Test was used to test broad behavioural performance (similar to Duncan et al. (2015) and Valenza et al. (2020)). The object lifting task was used to assess automatic feedforward processes in grip and load force control during a relatively naturalistic behaviour, as well as assessing prediction and feedback through asking participants to report their perception of object weight. Finally, the force matching task aimed to assess how participants used multisensory and unisensory feedback, as well as memory, to consciously control their level of grip force.

5.1.2 Methods

Materials

Cognitive task battery The cognitive task battery and training procedures described in Chapter 4 were used in this study as a method of inducing mental fatigue.

Control task We chose to use a documentary-watching control task, similar to prior research. Such prior research has commonly used the documentaries “World Class Trains—The Venice Simplon Orient Express” (Pegasus-Eagle Rock Entertainment, 2004) and “The History of Ferrari—The Definitive Story” (Boulevard Entertainment, 2006). The justification for choosing such documentaries is that they have been identified as emotionally neutral and they have not been found to affect participants’ heart rate. These documentaries are now 20 years old, of poor video quality, and of an unsuitable duration for matching with the duration of the two-hour cognitive task battery. We were also concerned that the subject matter would not be interesting for a range of participants and could result in them becoming bored. At the time of the study design, Netflix had made a number of nature documentaries available on their YouTube channel. Using freely accessible documentaries would allow other researchers to replicate our control task with no cost. We therefore chose to use the documentaries “Our Planet: One Planet” (Chapman, 2019) and “David Attenborough: A Life on Our Planet” (Fothergill et al., 2020). Approximately six minutes of footage was removed from “Our Planet” and 10 seconds of footage was removed from “A Life on Our Planet”. These pieces of footage depicted a hyena chase and a distressing clip of multiple walruses being injured and were removed to reduce the risk of causing emotional distress to participants. Additionally, the credits were shortened so that participants did not become bored, and so that the combined duration of the two videos would be just under 120 minutes. The exact running duration of the two combined and edited documentaries was 1:59:38.

Brunel Mood Scale (BRUMS) Questionnaire The Brunel Mood Scale (Terry et al., 1999, 2003), as described in Chapter 4, was used to assess participants’ subjective feelings of fatigue. In contrast with Chapter 4, however, a paper rather than computerized version of the BRUMS was used in both the fatigue and control conditions.

NASA Task Load Index (NASA-TLX) Due to the time constraints discussed in Chapter 2, the TLX was administered in a short format using only the Rating Sheet with brief instructions, and no familiarisation step. This adaptation of the ‘paper and pencil’ version of the NASA-TLX was used to assess participants’ perceptions of the mental demand of the fatigue and control tasks. The TLX Rating Sheet comprises six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level. Each subscale is shown as a horizontal line with 21 vertical tick marks which divide the 100-point scale into 20 increments of 5. At the far left and right of each subscale are the words “low” and “high”, with the exception of the performance subscale which has the word “good” on the left and “poor” on the right. Participants rating towards the right on all scales are therefore indicating a higher overall workload than participants rating towards the left on all scales.

Pinch strength gauge A Jamar Digital Pinch Gauge was used to measure participants’ maximal voluntary contraction using a pinch grip in kg.

Dexterity tasks Three tasks were chosen to provide an index of dexterity. As discussed in Chapter 2, these were chosen because they are fast to administer, do not require extensive instruction or familiarisation, and produce complementary and rich outcomes. Videos of all the tasks are available at https://www.youtube.com/watch?v=7iOrGsnnJBc.

Purdue Pegboard Test The Purdue Pegboard Test (Tiffin & Asher, 1948) was developed as a test of manual dexterity. The test was selected because it is simple to administer, widely-used, well-established, and because its outcome scores are easily interpretable. The Lafayette Instrument Company Purdue Pegboard Test was used in this study. As seen in Figure 5.1, the pegboard is a large rectangular plastic board with four indented cups spaced horizontally across the top of the board, and two parallel rows of 25 evenly-spaced holes running adjacent to the middle of the board, spaced approximately 2.5cm apart. The far left and right cups each hold 25 metal 'pegs' which are approximately 2.5cm long, whilst the middle two cups hold one of either 40 metal 'washers' or 25 metal 'collars' Figure 5.1. Either end of the metal pegs can be placed in the holes which run down the centre of the board, allowing the peg to stand upright. The washers and collars contain holes through their centre, allowing them to be dropped over the pegs. Picking up individual items from the cups, fitting the pegs in the holes, and placing the washers and collars over the pegs require precision. Accurate gross arm movements are required to collect the pegs, washers, and collars from their respective cups and transport them to the rows of holes.

(a) Purdue Pegboard Test

(b) Close-up of pegboard cups

Figure 5.1: The Lafayette Purdue Pegboard Test.

Object lifting For the object lifting task, five objects differing only in diameter and weight were used (Figure 5.2). Each object was a 3D printed black plastic cylinder which was 8cm in height. There were five different widths (5cm, 6.6cm, 7.5cm, 8.3cm, 10cm) with five corresponding weights (118g, 205g, 265g, 325g, 471g). To achieve the desired weight, each object was filled with small lead balls along with foam to prevent rattling sounds. The objects also had foam pads attached to the bottom so that they did not make a noise when placed on a surface. Each object had a mount on top onto which a force transducer (Nano17, ATI Industrial Automation, Apex, NC) was attached prior to each lift (Figure 5.2). The force transducer slid on and off the mount to act as a handle for participants to grasp when lifting the objects. Forces were sampled at a rate of 500Hz.

(a) The objects used in the experiment. L-R (width/weight): 5cm/118g; 6.6cm/205g; 7.5cm/265g (anchoring object); 8.3cm/325g ; 10cm/471g

(b) The anchoring object with force transducer attached as a handle.

Figure 5.2: The a) Objects and b) Force Transducer Used in the Experiment.

Four of the objects were experimental objects with the middle-diameter middle-weight object (7.5cm wide, 265g heavy) designated as an anchoring object. This distinction is explained further in procedures, below. The diameters of the experimental objects were chosen to maintain a consistent size increase of approximately 1.7cm diameter across the set of experimental objects. The weights of the objects were constrained by the available space inside each object for the lead filling, and were selected so that all the objects had a weight equivalent to a density of .75g$\frac{g}{cm^3}$ (where the density of water is 1$\frac{g}{cm^3}$). The differences in diameters and weights were chosen to be sufficiently distinct from one another. Finally, the object weights were chosen to be relatively low so as not to burden participants given the repetitive nature of the paradigm.

Force matching The force matching task used an ELAF Connectivity T1 amplified output single direction load cell collecting data at 1125Hz. This was plugged into a laptop which controlled each trial and continuously collected data a custom LabVIEW script. The laptop was plugged into a separate monitor on which participants were able to see the programme as shown in Figure 5.5. A paper version of a 5-point visual analogue scale with 5 boxes anchored with “1 - minimum effort” and “5 - maximum effort” was used to take participants’ ratings of effort.

Participants

Sample size was predetermined using a smallest effect size of interest approach. In real terms, the smallest effect size of interest was taken as a reduction in the assembly score of 3. Normative data from Tiffin and Asher (1948) shows that 853 US college-aged males and females had a mean assembly score of 38.3 ± 5.575. We therefore wanted to be able to detect a difference between two groups with means of 38.3 and 35.3 respectively. Assuming that the standard deviation in the mental fatigue condition is greater by 34%, as found in Valenza et al. (2020), a standard deviation of 6.915 was taken. Using the two means 38.3 and 35.3, the standard deviation of 6.915, and the formulas for calculating f in Cohen (1988; formula 8.2.1 and 8.2.2), an effect size of f = .21 was received. With alpha = .05, beta = .8, and a correlation among repeated measures of .7, a minimum recommended sample size of n = 29 was calculated. To allow for drop-outs, the aim was to recruit 36 participants.

32 adults age 18-65 were recruited via word of mouth, adverts on social media,

and posters across the University of Exeter campuses. All participants were free of cognitive and movement impairments, free of injury, and had normal or corrected-to-normal vision and hearing. Of the 32 participants who were recruited, one was excluded due to a low response rate during the cognitive task battery, and one dropped out. The final sample comprised 30 adults aged 38 ±14 years, of whom 18 were female, 12 were male, 26 were right-handed, and 4 were left-handed. Participants were paid £50 for their time.

Procedures

Overall All procedures were approved by the University of Exeter Sport and Health Sciences Ethics Committee (Reference 22-03-23-A-05). Once participants had given informed consent, they were sent links for a familiarisation video and for the training programme described in Chapter 4. The familiarisation video lasting approx. 15 minutes showed the three dexterity tasks with a voice-over explaining the task procedures to participants. The training programme was as described in Chapter 4, giving participants detailed instructions on each of the subtasks in the cognitive task battery and five minutes of practice for each. Participants were asked to confirm when they had completed both of these tasks, and this was checked by examining their training programme data.

Participants then visited the lab twice for approximately 3.5 hours for each visit. Prior to both lab visits, participants were asked to make sure they were well-rested, hydrated, and had eaten normally. Both lab visits were held at the same time of day to control for any possible effects of circadian rhythm, and with a minimum of 48 hours between visits.

At the beginning of their first lab visit, participants were asked to report their age, sex, and dominant hand (defined as the hand they used to write with). Both visits then proceeded as follows: object lifting familiarisation and anchoring; three pinch grip MVCs; force matching task familiarisation; BRUMS questionnaire; the experimental manipulation (fatigue or control); BRUMS questionnaire; NASA-TLX ratings; Purdue Pegboard Test; object lifting task; force matching task; force matching visual analogue scale; BRUMS questionnaire (Figure 5.3). At the end of the second lab visit, participants also did an object dropping task, were debriefed and thanked for their time, and completed forms so that they could be paid for their time. Throughout all tasks, participants were seated comfortably at a desk.

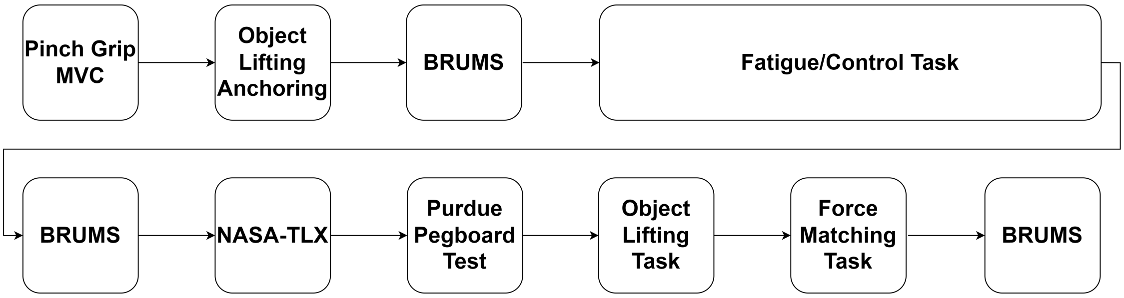


Figure 5.3: Schematic of Overall Study Procedures.

Object lifting procedure and anchoring For the familiarisation and anchoring procedure, participants were instructed that they would be rating objects on a scale of 0-100, with the anchoring object designated a weight of 50 on this scale. Participants were instructed that this scale did not have any units (i.e. grams) but that they were to decide the weight of later objects by using larger numbers for objects heavier than the anchoring object, and smaller numbers for objects lighter than the anchoring object.

Participants were seated opposite the experimenter. Participants rested their hands on the table in front of them with their eyes closed. An object was removed from a concealed box and quietly placed on the table in front of participants. A beep was played which signalled to the participants to open their eyes, reach forwards with their dominant hand, and grasp the object with their thumb and forefinger using the force transducer as a handle. Participants lifted the object upwards in a smooth motion and held it in place at the top of the lift, approximately 20 cm above the table (Figure 5.4). After three seconds another beep signalled to the participants to place the object back down. Participants gave a numerical rating of the perceived weight of the object, placed their lifting hand back on the table, and closed their eyes. The object was then returned to the concealed box and the procedure was then repeated.

For the familiarisation and anchoring procedure, participants lifted the anchoring object a minimum of three times in succession, and were offered the opportunity to repeat additional practice lifts until they felt confident that they would be able to use the weight of the anchoring object to guide their later weight reports. In the experimental trials, participants lifted the four objects four times each in a pseudorandom order, such that each object was preceded by each other object a roughly equal number of times (it is mathematically impossible for these to be exactly equal).

Figure 5.4: The Static Hold Phase of the Object Lifting Protocol.

Pinch grip MVCs The pinch gauge was placed on the desk in front of participants. They were instructed to rest their dominant forearm on the desk, to grasp the two metal pads on the gauge with only their thumb and forefinger, and to squeeze as hard as they could until they were told to stop. The digital display was facing away from participants so that they were not able to see their score. The display was monitored in real-time by the experimenter who verbally encouraged them to continue squeezing as hard as they could until the number shown on the gauge stopped increasing, at which point they were told they could stop. Their maximum value was then recorded. In some cases, participants used additional fingers to squeeze the pinch gauge, in which case the MVC was recorded as null. Participants were then given two minutes of rest, repeated another MVC, given another two minutes of rest, and completed the third and final MVC.

BRUMS questionnaire Participants were given a paper version of the BRUMS questionnaire with the instructions: *"Below is a list of words that describe feel-*

ings that people have. Please read each one carefully. Then circle the answer which best describes HOW YOU FEEL RIGHT NOW. Make sure you answer every question." Participants were told to read the instructions and complete the questionnaire, with the experimenter available to answer any questions.

Experimental manipulation Participants either watched the documentary or underwent the cognitive task battery as described in Chapter 4. The manipulations were conducted in a counterbalanced order so that half of participants completed the cognitive task battery in their first visit, and half completed the cognitive task battery in their second visit. This was to control for any practice effects in the dexterity tasks. During both manipulations, the experimenter sat behind and to the right of participants to monitor their behaviour and to be available in case participants had any questions.

NASA-TLX Participants were instructed to rate each of the Rating Scales by clearly marking the scale. The performance scale's "good/poor" rating was highlighted to participants as different from the other "low/high" ratings, to reduce the likelihood of error. Participants were given descriptions of the rating scale definitions on request.

Purdue Pegboard Test Participants completed each of the four subtests of the Purdue Pegboard Tests, repeating each three times. The first two tests were the right and left hand tests. In the right hand and left hand tests, participants were given 30 seconds to pick up and place as many pegs as possible in the holes running down the respective side of the board using only their right or left hand, beginning with the hole at the top of the board. In the third test, participants repeated the same procedure but using both hands simultaneously, picking up pegs with both hands at the same time and placing them in the holes as the same time.

The fourth test, the assembly test, lasted for 60 seconds. Participants started by picking up a peg with their dominant hand. As soon as this was placed, they picked up a washer with their non-dominant hand which they placed over the peg. Whilst they were placing the washer, they used their dominant hand to pick up a collar. Whilst the collar was being placed, the participant picked up a second washer. Finally, whilst the second washer was being placed, the participant picked up another peg ready for another assembly.

For all tests, participants were only allowed to pick one item from the cups at a time, were not allowed to use their other hand to manipulate the item, and had to pick up a new item if the one they were holding was dropped. After each subtest, the participants' score was recorded by the experimenter. The experimenter also recorded an 'error' metric, where each additional 1 equated to an item that had been dropped after being removed from the cup.

Force matching task Participants sat an arms' length from a computer screen, with their forearm resting on the desk in front of them and their elbow at a comfortable angle approximating 90 degrees. With the medial aspect of the hand resting on the desk, they held the force transducer in their dominant hand using their thumb and forefinger. The computer screen showed a graph with three coloured rectangles around the outside in an arch shape, a black horizontal target line across the middle, and a moving blue fill tank visualisation filling up the centre (Figure 5.5). The harder participants squeezed the transducer, the higher up the blue fill tank visualisation would move, giving participants real-time visual feedback as to their force levels. Each trial began with participants holding the transducer at rest whilst the coloured rectangles showed as red. After 10 seconds of rest, the rectangles turned green indicating that the participants should squeeze the transducer with enough force to match their force level to the target line. In 50% of trials, after 8 seconds of squeezing, the visual feedback would disappear but the coloured rectangles would remain green, indicating to participants to continue squeezing the transducer with the same amount of force they were using to match the black line. After 20 seconds of force matching had elapsed, the rectangles turned red, indicating to participants to relax. Another trial was then manually cued by the experimenter, for a total of 12 trials. Trials were conducted in a pseudorandom order with visual feedback removed in 50% of the trials. The pseudorandom order was selected so that participants had nearly equal numbers of vision -> no vision and no vision -> vision transitions, as well as similar numbers of vision -> vision and no vision -> no vision transitions. This was chosen to control for the possible effects of preceding trials on successive ones. As with the object lifting procedure, it is mathematically impossible to have fully equal numbers of each type of transition.

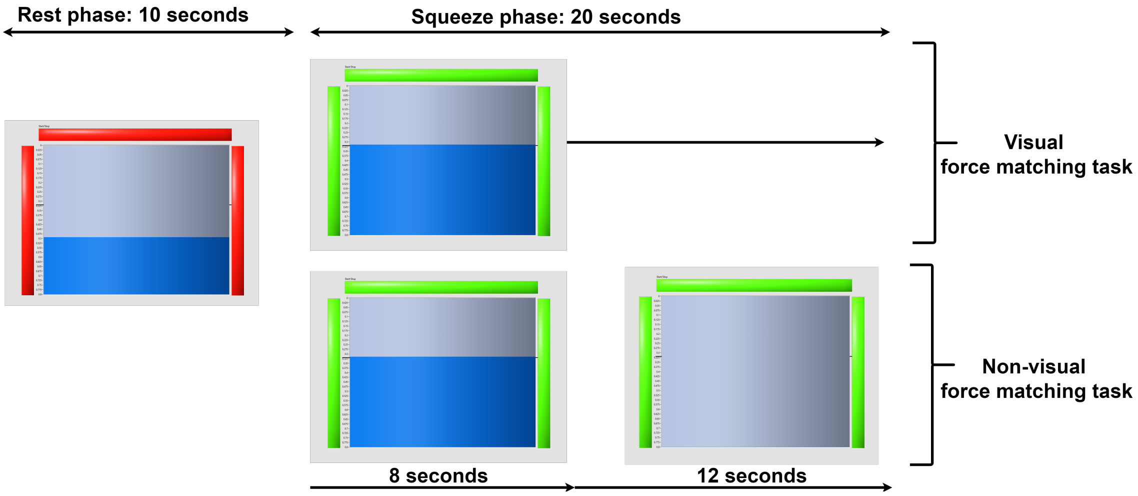


Figure 5.5: Schematic of Different Phases in the Force Matching Task.

Rating of effort VAS Participants were instructed to indicate with a cross in one of the five boxes on the visual analogue scale indicating how much effort they had to expend for the visual and non-visual feedback trials of the force matching task. Participants were not given any definitions but were told to be consistent in their interpretation of effort between their two visits.

Data processing and analyses

Data cleaning, calculations, visualisation, and analysis were conducted in RStudio (RStudio 2022.02.0+443 “Prairie Trillium” Release) using here (Müller and Bryan, 2020), dplyr (Wickham et al., 2017), stats (R Core Team, 2022), data.table (Dowle and Srinivasan, 2019), psych (Revelle, 2018), gtools (Warnes et al., 2018), ggplot2 (Wickham, 2016, p. 2), car (Fox and Weisberg, 2011), tidyr (Wickham and Henry, 2018), gridExtra (Auguie and Antonov, 2017), and grid (R Core Team, 2022). Force data processing for both the object lifting task and the force matching task was conducted using custom programmes in MATLAB 2014a and 2022b respectively. The custom programme used to process object lifting force data can be downloaded from https://osf.io/tzpdg/.

BRUMS ratings were coded manually into Microsoft Excel. Each subscale rating was calculated as described in Chapter 4 resulting in a rating of 0-16 for each subscale, visit, and time point. The change in ratings over time was also calculated using simple subtraction (post-pre), where a more positive number indicates a greater increase in that subscale’s rating, and more negative difference scores indicate greater reductions in that subscale's rating.

The numerical NASA-TLX ratings were entered manually into Microsoft Excel. The absolute values, on a scale of 0-100, were used for the statistical analyses.

Purdue Pegboard Test scores were coded into Microsoft Excel. The total score was then calculated by simple addition of the left hand, right hand, and both hands scores. The mean of each task type was calculated for each participant and condition. As the assembly subtest results in considerably higher numerical scores than the other subtests, the scores were converted into z-scores for use in the analysis investigating performance in all the subtests. For both the standardised and non-standardised scores, greater positive numbers indicate better performance.

Weight reports were coded into Microsoft Excel. The mean weight report for each object was calculated for each participant and condition. The mean was then transformed into a z score for each participant, with greater positive numbers indicating heavier perceived object weights.

Reaction time and accuracy data during the cognitive task battery were automatically recorded in PsychoPy (Peirce et al., 2019). These were used to calculate a Balanced Integration Score as described in Chapter 4 - a standardised integrated measure of reaction time and accuracy where 0 is the average performance, scores above 0 (i.e. positive scores) are better than average, and scores below 0 (i.e. negative scores) are worse than average.

Four variables relating to force using in the object lifting task were processed using a custom MATLAB script: peak grip force rate (pGFR; N/s); peak load force rate (pLFR; N/s); time at peak grip force (tPGF; ms); and time at peak load force (tPLF; ms). Peak grip force (PGF; N) was defined as force applied orthogonally to the force transducer during the object lift. Peak load force (PLF; N) was defined as the vector sum of the vertical and lateral forces applied to the force transducer during the object lift. To attain the rate for each of these measures, the force data was filtered through a 14-Hz 4th-order Butterworth filter and differentiated using a 5-point central difference equation, providing values for pGFR and pLFR, where more positive numbers indicate greater increases and more negative numbers indicate greater decreases in the forces being applied. The custom MATLAB programme automatically identified and recorded the PGF, PLF, pGFR, and pLFR, and timings of all of these during the object lifts. The force data was then visually inspected and the peaks identified by the programme were either confirmed or, in the case of erroneous selection by the programme, manually re-selected. For lifts where there were no clearly identifiable peaks corresponding to the object lift, the peaks were manually removed from the data set. The process of analysing this data is described in detail in https://osf.io/crjkv.

To remove possibly confounding outliers, data points lying outside of ±3 SD for each variable were removed from the data. For the purposes of investigating sensorimotor prediction, only the pGFR and pLFR for the first lift of each object were used, as after the first lift pGFR and pLFR normalise to object weight regardless of participants' predictive behaviours. The time difference between tPGF and tPLF was calculated by simple subtraction (tPLF-tPGF; ms), with the mean of these difference scores then calculated for each participant, object, and condition. Positive mean difference scores indicate that PGF preceded PLF, with negative mean difference scores indicating that PLF preceded PGF.

Throughout each trial in the force matching task, raw voltage data was collected. Using the raw voltage data from the force transducer, a custom MATLAB programme calculated mean and RMSE force production for 18 x 1 second time bins, excluding the first and final second of each trial. The custom MATLAB programme identified and excluded participants whose data were incomplete or contained erroneous values.

Statistical reporting All parametric assumptions were tested prior to each statistical analyses using visual inspections of the data, descriptive statistics, Shapiro-Wilk tests, and Levene tests. Where assumptions were violated, non-parametric analyses have been used, and the details of the violations are reported alongside the statistical outcomes. All ANOVAs were calculated using Type III sums of squares. Where the assumption of sphericity was violated as identified by Mauchly's Test, a Greenhouse-Geisser correction was applied and this is reported alongside the results of the relevant tests.

For all boxplots, the upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Where there are no outliers, the upper and lower whiskers extend to the full range of the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line or dot showing the median. All density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. Where there are multiple lines or dots, these display individual responses within the relevant category. Non-significant results are highlighted *ns*, with significant results' associated *p* value displayed on the figure.

5.1.3 Results

Manipulation checks

A factorial repeated measures ANOVA with BRUMS fatigue subscale rating as the outcome variable and condition (control/fatigue) and time point (pre intervention/post intervention) as the predictors revealed significant main effects of condition, *F* (1, 29) = 12.75, *p* < .001, η^2_p = .31, and time point, *F* (1, 29) = 38.08, *p* < .001, η^2_p = .57. A significant interaction between condition and time point was also found, *F* (1, 29) = 15.03, *p* < .001, η^2_p = .34. The significant interaction between condition and time point was followed up using a paired Wilcoxon Signed Rank test with difference in rating over time (calculated as post-pre) as the dependent variable and condition (control/fatigue) as the dependent variable. This found significant differences in change in fatigue over time between the two conditions, *z* = -3.37, *p* = <.001, 95% CI [-4.5, -2], *r* =.62. Participants' subjective fatigue at the beginning of each visit was similar, but they reported feeling significantly greater increases in fatigue from completing the cognitive task battery than from completing the control task (Figure 5.6). The fatigue manipulation was successful in inducing greater increases in subjective feelings of mental fatigue than the control task.

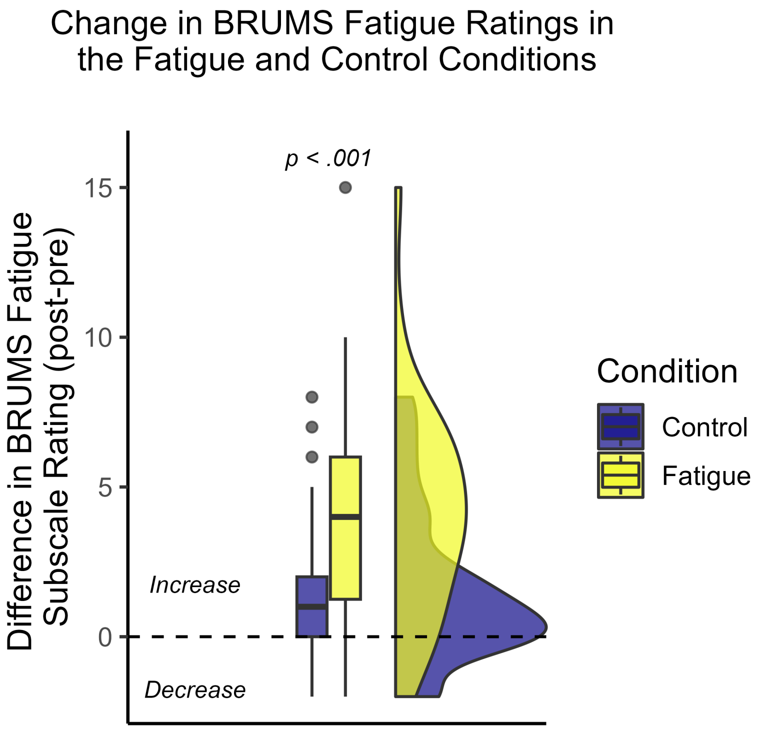


Figure 5.6: Change in BRUMS Fatigue Subscale Ratings in the Fatigue and Control Conditions (n = 30). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas.

The distribution of the NASA TLX mental demand ratings was not normal as identified by a significant Shapiro-Wilk test ($p < .001$). A paired Wilcoxon Signed Rank test with TLX mental demand rating as the dependent variable and condition (control/fatigue) as the dependent variable revealed a significant effect of condition, $z = -4.71$, $p < .001$, 95% CI [-55, -32.5], $r = .86$. Participants reported that the cognitive task battery was significantly more mentally demanding than the control task (Figure 5.7). The fatigue manipulation was successful in being more mentally demanding than the control task.

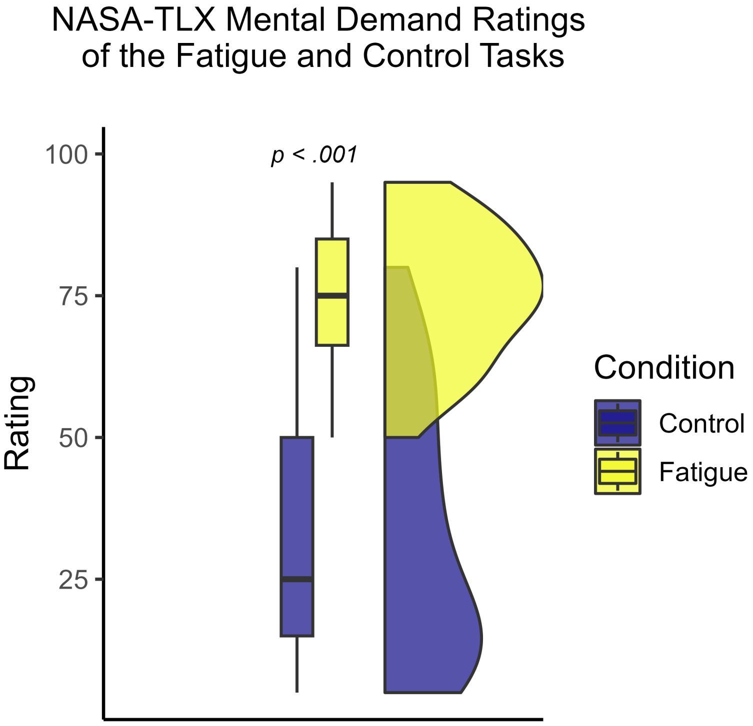


Figure 5.7: NASA-TLX Mental Demand Ratings of the Fatigue and Control Tasks (n = 30). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas.

The distribution of the BIS values was not normal as identified by a significant Shapiro-Wilk test ($p < .001$). A paired Wilcoxon Signed Rank test with BIS as the dependent variable and condition (control/fatigue) as the dependent variable found no significant effect of condition, $z = -0.98$, $p = .325$, 95% CI [-.24, .45], $r = .18$. There was no overall decrease in participants' performance in the cognitive task battery from the beginning to the end of the battery. The fatigue manipulation did not consistently induce a behavioural performance decrement in the cognitive task battery, with only 17 out of 30 participants showing a reduced performance at the end of the battery compared to their performance at the beginning (Figure 5.8).

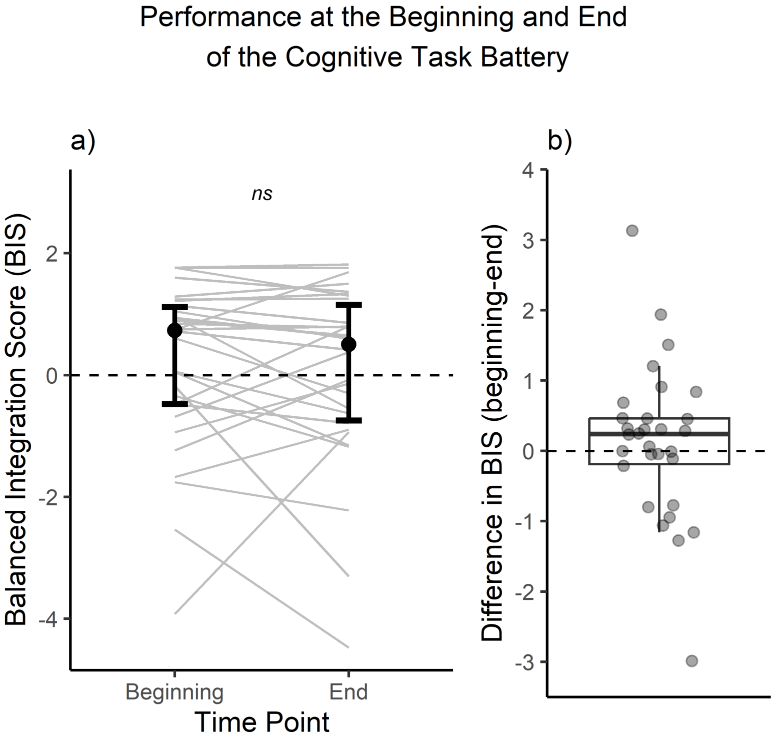


Figure 5.8: Performance at the Beginning and End of the Cognitive Task Battery (n = 30). Grey lines and dots show individual observations. For a), top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle dot showing the median. For b), the upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range. The values in b) are calculated as post-pre, meaning that higher values indicate participants who reported greater increases in feelings of fatigue from the beginning to the end of the mental fatigue battery. *ns* denotes non-significance ($p \geq .05$).

Purdue Pegboard Test

A paired t-test with Purdue Pegboard Test assembly score as the dependent variable and condition (control/fatigue) as the dependent variable found no significant effect of condition, *t*(29) = 1.37, *p* = .183, 95% CI [-.51, 2.55], *d* = .25. There was no significant difference between assembly task performance in the fatigue and control conditions (Figure 5.9). Participants' performance in the Purdue Pegboard assembly subtest was not affected by mental fatigue.

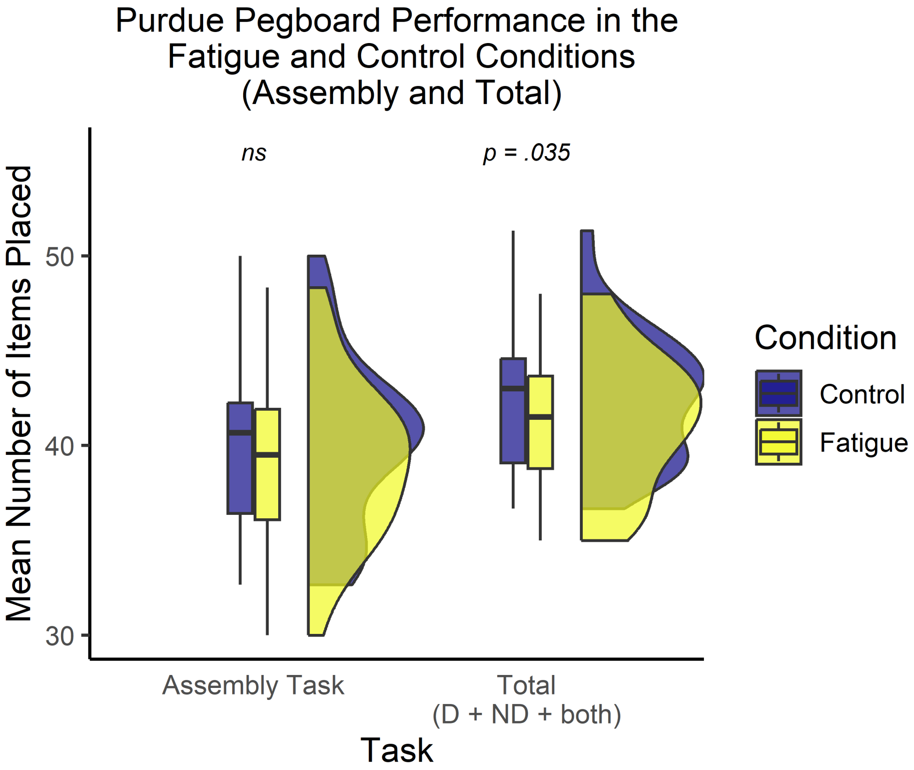


Figure 5.9: Purdue Pegboard Assembly and Total Test Performance in the Fatigue and Control Conditions (n = 30). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. *ns* denotes non-significance ($p \geq .05$). "D" = dominant, "ND" = non-dominant.

A paired t-test with Purdue Pegboard Test mean total score as the dependent variable and condition (control/fatigue) as the dependent variable revealed a significant effect of condition, *t* = 2.22, *p* = .034, 95% CI [.09, 2.23], *d* = .4. Participants' performance - when examined as a composite score from the dominant, non-dominant, and both hands subtests - was significantly worse in the fatigue condition (Figure 5.9). Participants' overall performance was worse when they were mentally fatigued.

To examine the Purdue Pegboard total test performance in more detail, three paired t-tests with Purdue Pegboard dominant, non-dominant, and both hands scores as the three dependent variables and condition (control/fatigue) as the dependent variable found a significant effect of condition on performance with the dominant hand, *t*(29) = 2.22, *p* = .034, 95% CI [.04, 1.09], *d* = .41. There was, however, no significant effect of condition on performance in the non-dominant hand, *t*(29) = 1.75, *p* = .126, 95% CI [-.09, .72], *d* = .29 or in the both hands task *t*(29) = 1.42, *p* = .167, 95% CI [-.11, .62], *d* = .26. Participants' Purdue Pegboard performance was only significantly affected by mental fatigue in the dominant hand subtest (Figure 5.10).

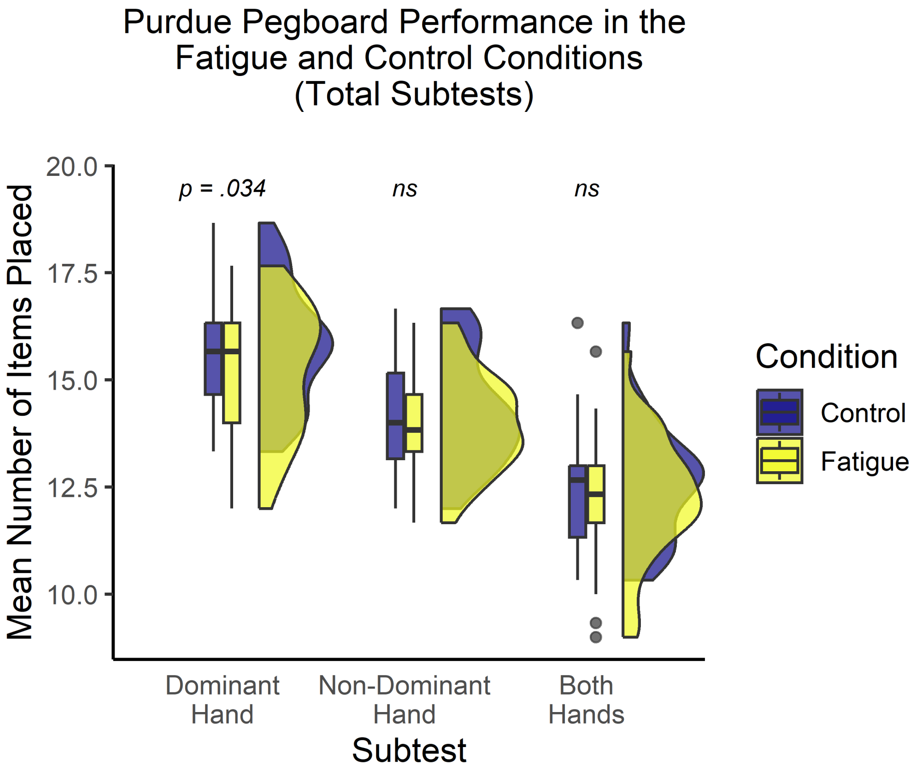


Figure 5.10: Purdue Pegboard Test Dominant, Non-Dominant, and Both Hands Performance in the Fatigue and Control Conditions (n = 30). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. *ns* denotes non-significance ($p \geq .05$).

A Greenhouse-Geisser corrected factorial repeated measures ANOVA with z-standardised mean score across all tasks (excluding 'total', as it is a composite of other subtests) as the outcome variable and condition (control/fatigue) and trial (1-3) as the predictors found no significant effect of condition, F (1, 27) = 3.24, p = .083, η_{p}^2 = .11. There was, however, a significant main effect of trial, F (.95, 52.72) = 68.05, p <.001, η_{p}^2 = .72. The interaction between condition and trial was also significant, F (1.58, 42.71) = 3.7, p = .042, η_{p}^2 = .12. To follow up the condition and trial interaction, a difference score was calculated between the standardised mean score in the fatigue and control conditions (con-fat), and these were statistically compared between trials 1, 2, and 3. None of these were significant (all p > .05). Together, these results indicate that participants' performance on the Purdue Pegboard Test improved with repetition, and that the extent of this improvement may have been affected by mental fatigue (Figure 5.11).

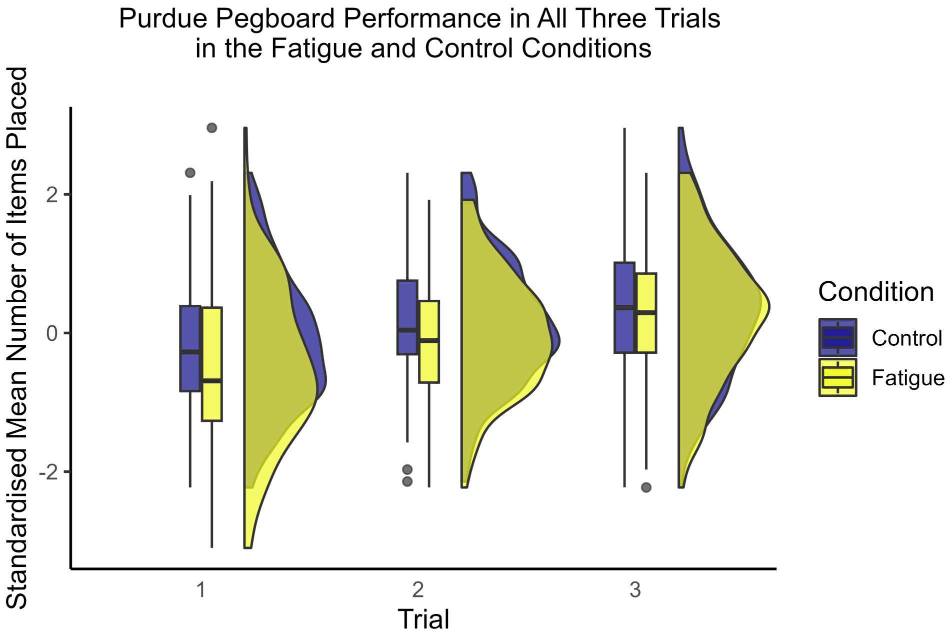


Figure 5.11: Purdue Pegboard Test Performance Throughout All Trials in the Fatigue and Control Conditions (n = 27). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. The "total" test results are excluded from this figure and its associated analysis as it is a composite of the dominant, non-dominant, and both hands subtests.

Object lifting task

A Greenhouse-Geisser corrected factorial repeated measures ANOVA with z-standardised mean ratings of object weight as the outcome variable and condition (control/fatigue) and object size (5/6.6/8.3/10) as the predictors found no significant effect of condition, F (1, 29) = 0.14, p = .714, η_p^2 = .01. There was, however, a significant main effect of object size, F (2.32, 67.26) = 780.07, p <.001, η_p^2 = .96. The interaction between condition and object size was not significant, F (1.96, 56.86) = 1, p = .373, η_p^2 = .03. The significant main effect of object size indicates that participants were able to correctly identify differences in object weight associated with size. The absence of other significant effects indicates that there was no difference in participants' ability to do this between the control and fatigue conditions (Figure 5.12).

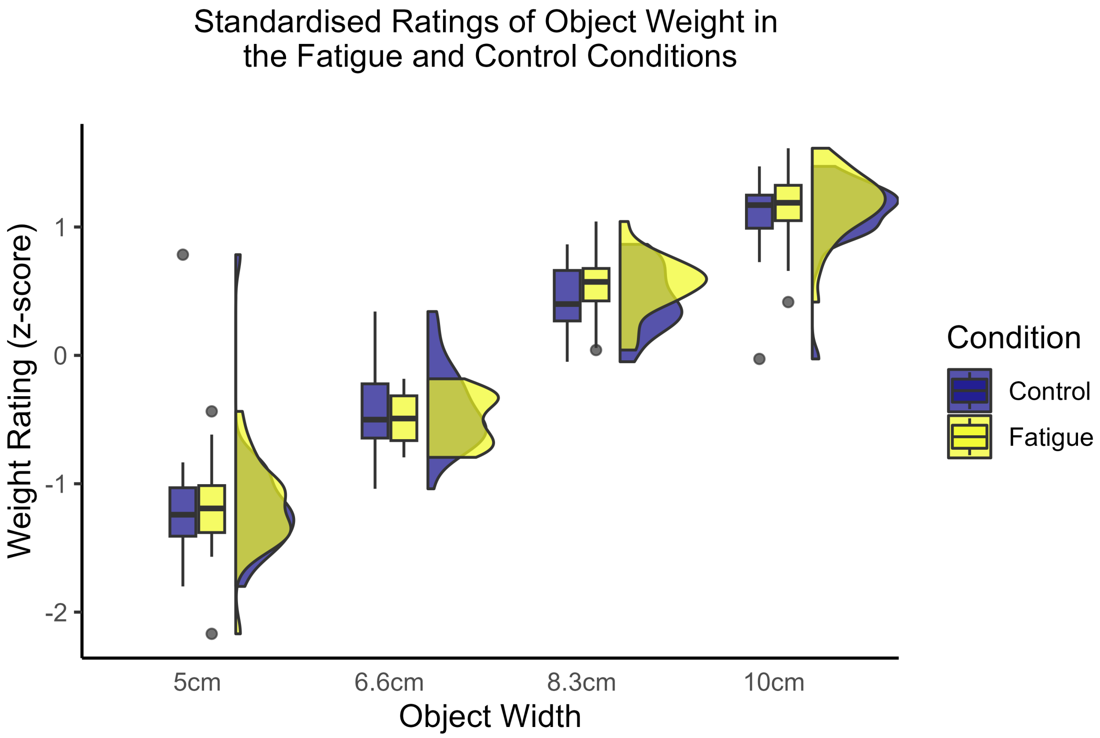


Figure 5.12: Ratings of Object Weight in the Fatigue and Control Conditions (n = 30). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas.

Ten participants' data were excluded from the pGFR analysis due to there being missing values for the first object lift. A Greenhouse-Geisser corrected factorial repeated measures ANOVA with pGFR as the outcome variable, and condition (control/fatigue) and object size (5/6.6/8.3/10) as the predictors found no significant effect of condition, *F* (1, 20) = .05, *p* = .826 η_p^2 = .002. There was, however, a significant main effect of object size, *F* (2.01, 40.14) = 23.36, *p* <.001, η_p^2 = .54. The interaction between condition and object size was not significant, *F* (1.95, 39.05) = .45, *p* = .638, η_p^2 = .02. The significant main effect of object size indicates that participants correctly scaled their grip force, using greater forces to grasp larger and heavier objects. The absence of other significant effects indicates that there was no difference in participants' ability to do this between the control and fatigue conditions (Figure 5.13).

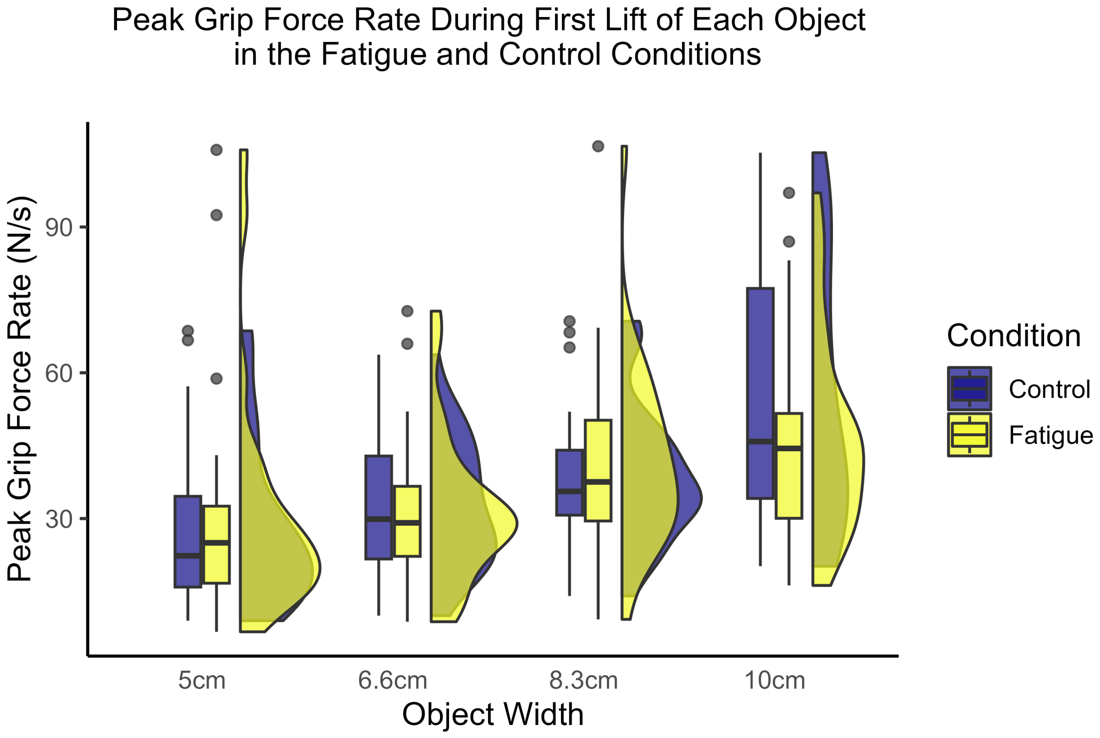


Figure 5.13: Peak Grip Force Rate used to Grasp each Object in the Fatigue and Control Conditions (n = 20). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas.

Eleven participants' data were excluded from the pLFR analysis due to there being missing values for the first object lift. A factorial repeated measures ANOVA with pLFR as the outcome variable, and condition (control/fatigue) and object size (5/6.6/8.3/10) as the predictors found no significant effect of condition, *F* (1, 19) = 0, *p* = .989, η_p^2 = <.001. There was, however, a significant main effect of object weight, *F* (3, 57) = 32.44, *p* <.001, η_p^2 = .63. The interaction between condition and object weight was not significant, *F* (3, 57) = .5, *p* = .583, η_p^2 = .026. The significant main effect of object size indicates that participants correctly scaled their load force, using greater forces to lift larger and heavier objects. The absence of other significant effects indicates that there was no difference in participants' ability to do this between the control and fatigue conditions (Figure 5.14).

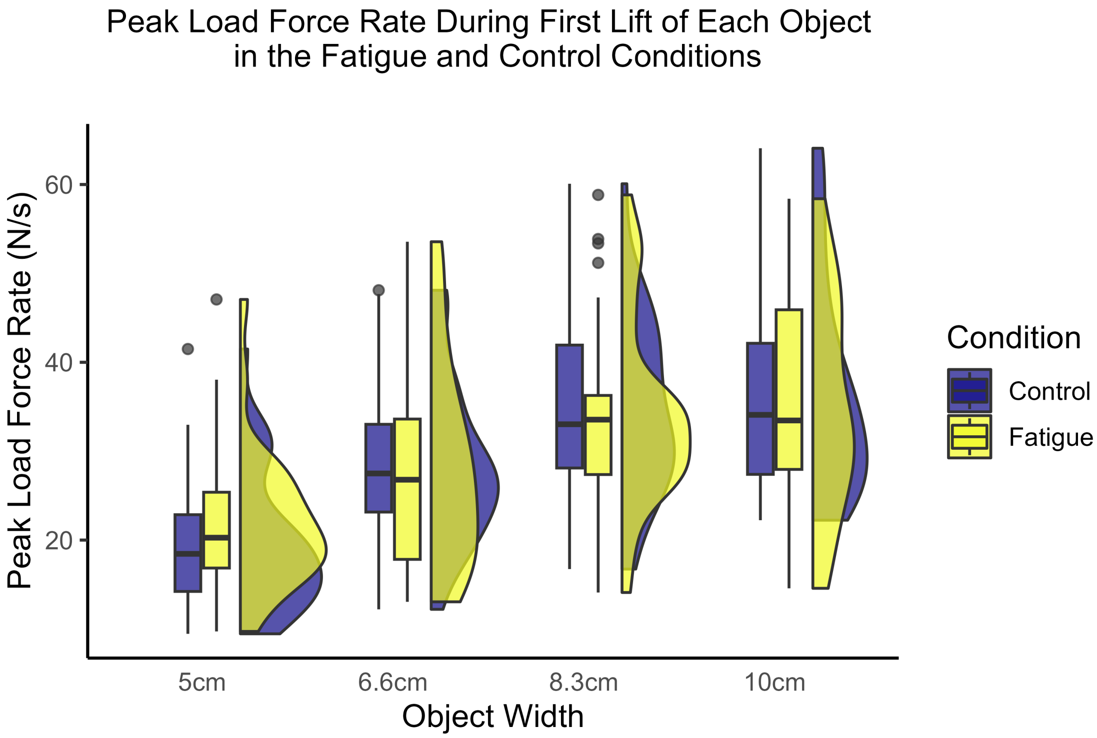


Figure 5.14: Peak Load Force Rate used to Lift each Object in the Fatigue and Control Conditions (n = 29). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas.

As a positive control, a correlation between tPGF and tPLF was conducted to examine the temporal coupling of participants' PGF and PLF. The distributions of tPGF and tPLF were not normal as identified by significant Shapiro-Wilk tests (both p < .001). A Spearman's rank correlation between tPGF and tPLF found a significant strong positive correlation, ρ (28) = .98, p < .001. The timing of participants' PGF and PLF was overall highly correlated, in line with prior research, indicating that their behaviour was broadly normal (Figure 5.15).

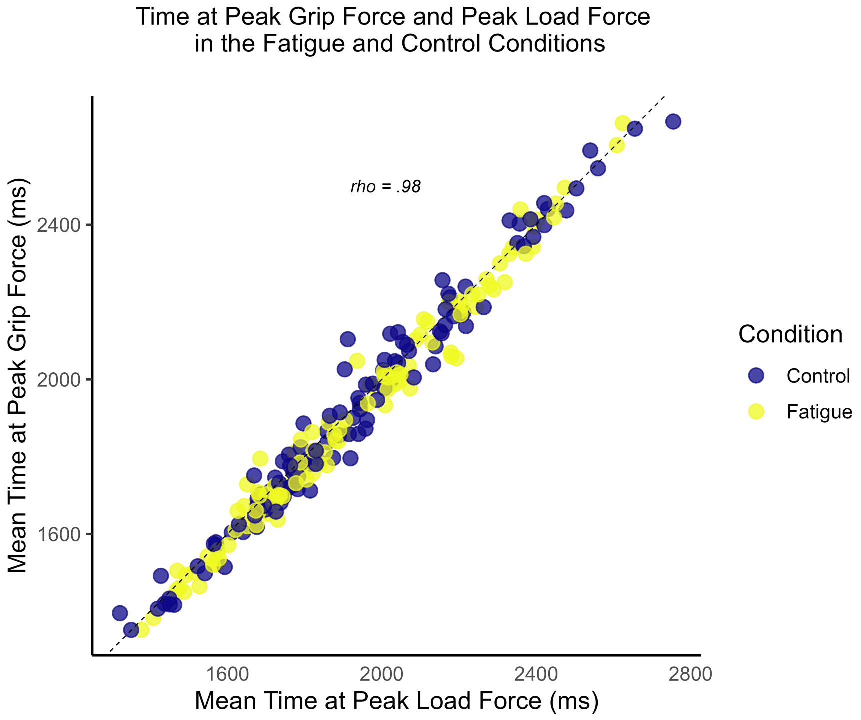


Figure 5.15: Correlation between Time of Peak Grip Force and Time of Peak Load Force During Object Lifting in the Fatigue and Control Conditions (n = 30). Each dot shows the mean values applied by each participant for each of the four objects in both conditions. Dotted line indicates ρ = 1 i.e. a perfect correlation.

The distribution of the mean differences between tPGF and tPLF was not normal as identified by a significant Shapiro-Wilk test ($p < .001$). A paired Wilcoxon Signed Rank test with mean difference between tPGF and tPLF (ms) as the dependent variable, and condition (control/fatigue) as the independent variable revealed a significant effect of condition, $z = -2.20$, $p = .003$, 95% CI [.08, 17.17], $r = .41$. The time difference between PGF and PLF was significantly greater in the mental fatigue condition (Mdn 20.25 ±42.08 IQR) compared to the control condition (-13.5 ±52.75), indicating that participants' coordination was affected by mental fatigue (Figure 5.16).

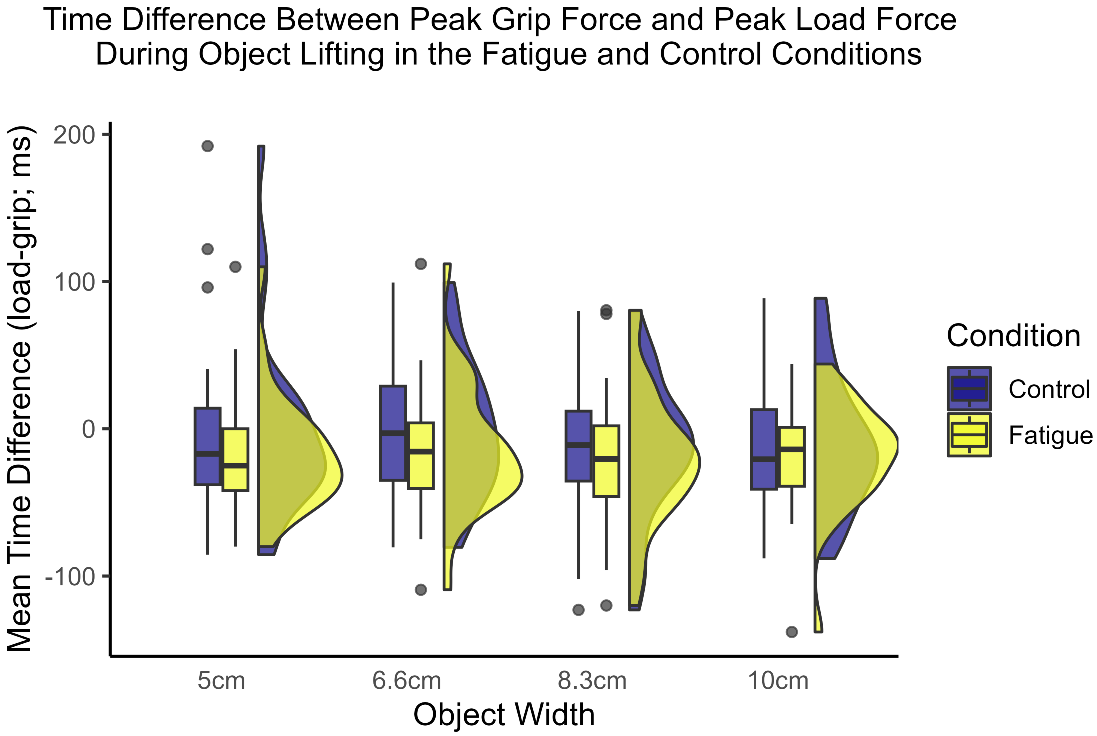


Figure 5.16: Time Difference Between Peak Grip Force and Peak Load Force During Object Lifting in the Fatigue and Control Conditions (n = 29). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. Above zero, grip force precedes load force. Below zero, load force precedes grip force.

The distribution of the ratio between GF and LF was not normal as identified by a significant Shapiro-Wilk test ($p < .001$). A paired Wilcoxon Signed Rank test with ratio as the dependent variable and condition (control/fatigue) as the independent variable found no significant effect of condition, $z = -.72$, $p = .469$, 95% CI [-.1, .05], $r = .13$. The relationship between the forces that participants applied to grasp and lift objects was not affected by mental fatigue (Figure 5.17).

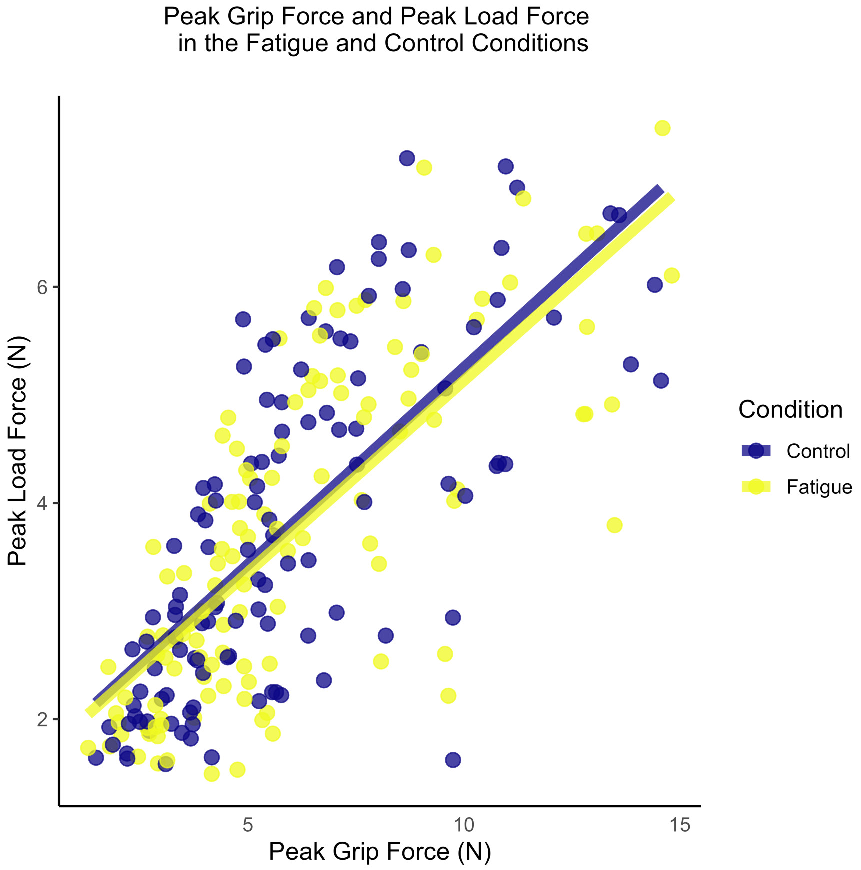


Figure 5.17: Peak Grip Force and Peak Load Force During Object Lifting in the Fatigue and Control Conditions (n = 29). Each dot shows the mean values applied by each participant for each of the four objects in both conditions. Coloured lines show the line of best fit for each condition.

Force matching task

The results of a Greenhouse-Geisser corrected factorial repeated measures ANOVA with mean force as the outcome variable, and condition (control/fatigue), feedback (vision/no vision), and time (8s-19s) as the predictors can be seen in Table 5.1. Significant main effects of feedback and time were found which were superseded by a significant interaction between feedback and time, indicating that force production changed over time differently depending on the availability of visual feedback (Figure 5.18, Figure 5.19). There were no other significant effects including no significant main effects or interactions with condition, indicating that mental fatigue did not affect performance in the force matching task.

	Effect	*df*	*F*	η_p^2	*p*
1	Condition	1, 25	0.96	.037	.336
2	Feedback	1, 25	4.53	.153	**.043**
3	Time	1.72, 43.02	9.84	.282	<**.001**
4	Condition x Feedback	1, 25	0.36	.014	.555
5	Condition x Time	2.87, 71.81	0.65	.025	.580
6	Feedback x Time	1.70, 42.41	9.43	.274	<**.001**
7	Condition x Feedback x Time	2.81, 70.30	0.52	.020	.659

Table 5.1: Results of a Greenhouse-Geisser corrected factorial repeated measures ANOVA Investigating the Effects of Condition and Feedback on Mean Force Production Throughout the Force Matching Task. Bold ***p*** values are significant at the $p < .05$ level.

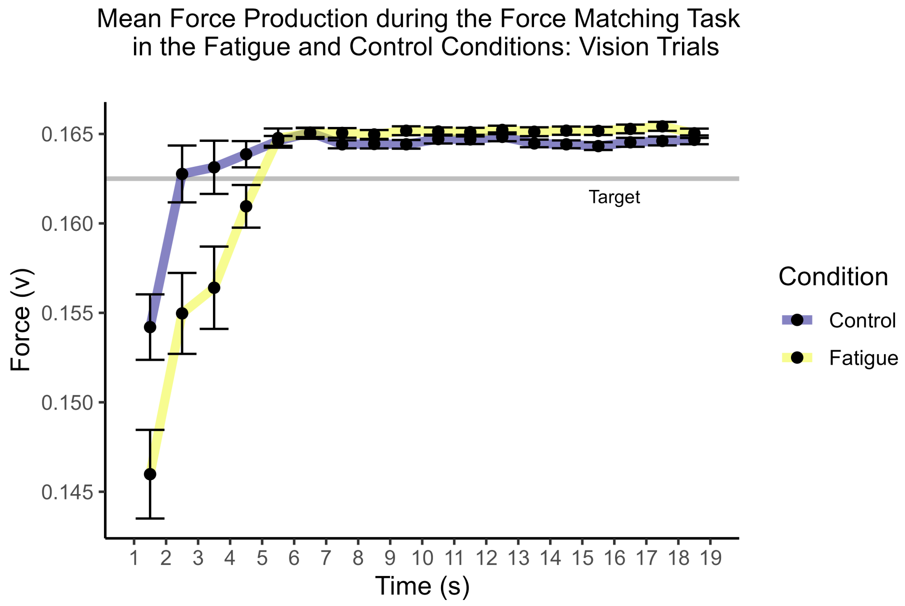


Figure 5.18: Mean Force Production During the Force Matching Task with Visual Feedback (n = 26). Top and bottom horizontal lines indicate the standard error, with the lines and black dots showing the mean.

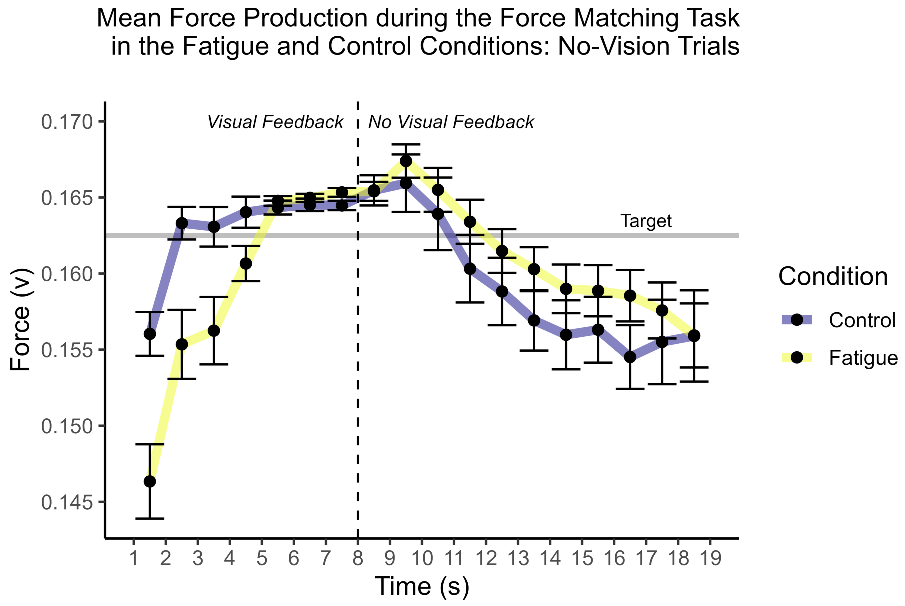


Figure 5.19: Mean Force Production During the Force Matching Task with Visual Feedback Disappearing at 8 Seconds (n = 26). Top and bottom horizontal lines indicate the standard error, with the lines and black dots showing the mean.

The results of a Greenhouse-Geisser corrected factorial repeated measures ANOVA with root mean square error of force as the outcome variable, and condition (control/fatigue), feedback (vision/no vision), and time (8s-19s) as the predictors can be seen in Table 5.2. Significant main effects of feedback and time were found, which were superseded by a significant interaction between feedback and time, indicating that visual feedback affected the accuracy of force production over time (Figure 5.20, Figure 5.21). There were no other significant effects including no significant main effects or interactions with condition, indicating that mental fatigue did not affect performance in the force matching task.

	Effect	*df*	*F*	η^2_{p}	*p*
1	Condition	1, 25	1.81	.068	.191
2	Feedback	1, 25	57.85	.698	$<$**.001**
3	Time	1.49, 37.13	15.52	.383	$<$**.001**
4	Condition x Feedback	1, 25	2.64	.095	.117
5	Condition x Time	3.07, 76.81	0.24	.009	.875
6	Feedback x Time	1.59, 39.69	16.05	.391	$<$**.001**
7	Condition x Feedback x Time	2.97, 74.17	0.20	.008	.893

Table 5.2: Results of an ANOVA Investigating the Effects of Condition and Feedback on Root Mean Square Error of Force Production Throughout the Force Matching Task. Bold ***p*** values are significant at the $p < .05$ level.

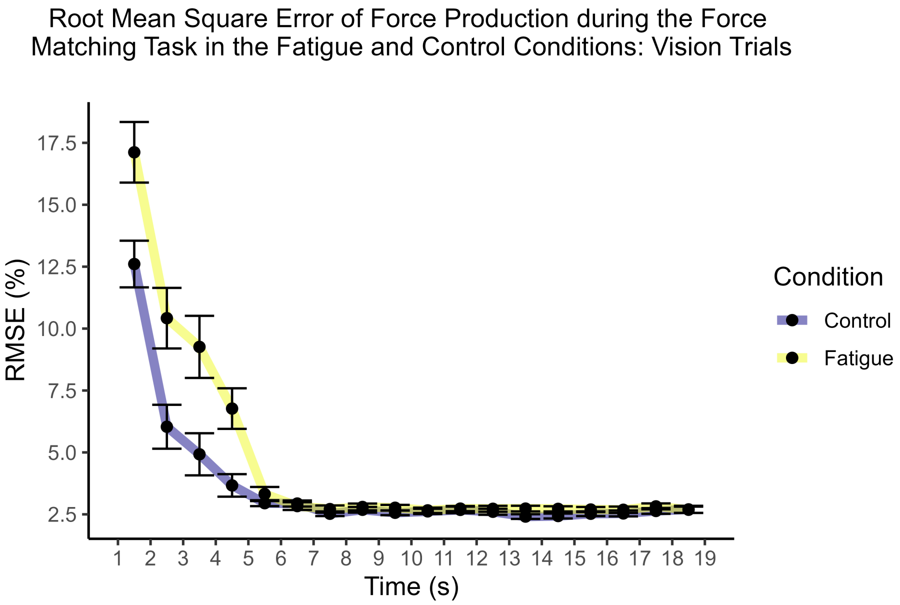


Figure 5.20: Root Mean Square Error of Force Production During the Force Matching Task with Visual Feedback (n = 26). Top and bottom horizontal lines indicate the standard error, with the lines and black dots showing the mean.

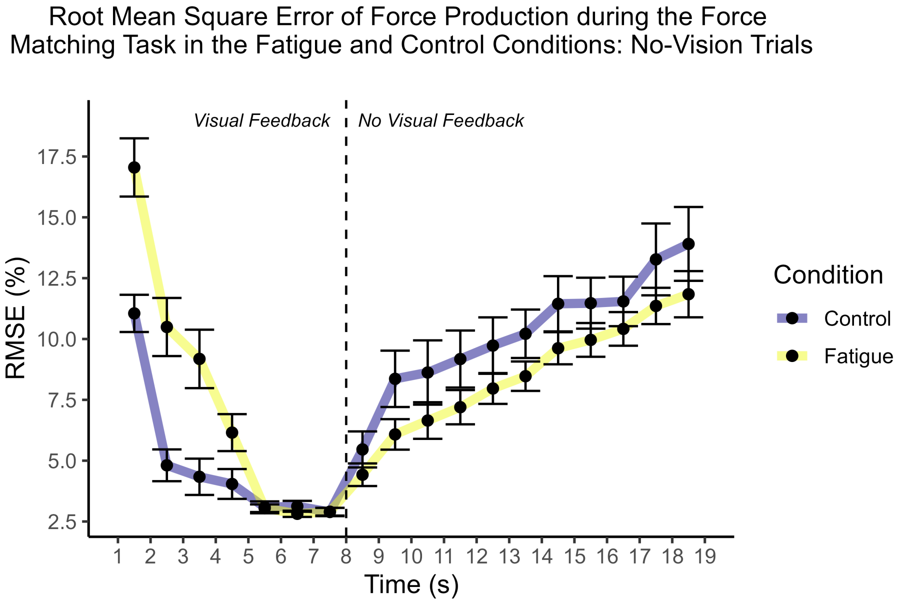


Figure 5.21: Root Mean Square Error of Force Production During the Force Matching Task with Visual Feedback Disappearing at 8 Seconds (n = 26). Top and bottom horizontal lines indicate the standard error, with the lines and black dots showing the mean.

A factorial repeated measures ANOVA with VAS ratings of task difficulty as the outcome variable and condition (control/fatigue) and feedback (vision/no vision) as the predictors found no significant effect of condition, F (1, 28) = 0.16, p = .690, η^2_p = .01. There was, however, a significant main effect of feedback, F (1, 28) = 33.81, p <.001, η^2_p = .55. The interaction between condition and feedback was not significant, F (1, 28) = 1.21, p = .281, η^2_p = .04. Participants rated the no visual feedback trials of the force matching task as significantly more difficult than the trials where visual feedback was available throughout, with mean ratings of 3.7 ±.83 SD for the no vision trials and 2.76 ±.95 for the vision trials. Mental fatigue, however, did not affect participants' perception of task difficulty.

Subjective reports

The prior research reported in Chapter 4 suggested that mental fatigue was a multifaceted experience. To investigate further the subjective experience of mental fatigue in this study, five additional paired Wilcoxon Signed Rank tests were performed. These examined the change in ratings of anger, confusion, depression, tension, and vigour from before to after the control and fatigue tasks. The results of these tests are reported in Table 5.3. Other than the already-identified difference in the fatigue elicited by the mental fatigue task, the control task was revealed to elicit significantly greater increases in subjective reports of depression than the mental fatigue task. Vigour also did not decrease significantly more during the mental fatigue task than during the control task.

Subscale	Control	Fatigue	*z*	*p*	95% CI	*r*
Anger	0 (1)	0 (.75)	-.26	.795	-1, 2.5	.05
Confusion	0 (.75)	0 (.75)	-.51	.607	-1.5, 2.5	.09
Depression	1 (3)	0 (0)	-3.05	**.002**	1.5, 5	.56
Fatigue*	1 (2)	4 (4.75)	-3.37	**<.001**	-4.5, -2	.62
Tension	0 (1)	0 (1)	-1.87	.061	-5.04, 2.5	.34
Vigour	-2 (4)	-2.5 (4.5)	-.096	.336	-1, 2.5	.18

Table 5.3: Results of six paired Wilcoxon Signed Rank tests with change in BRUMS subscale score (calculated as post-pre) as the dependent variable and condition as the independent variable (n = 30). X (y) denotes Mdn (IQR). *as reported previously in subsubsection 5.1.3. Bold ***p*** values are significant at the p < .05 level.

To further investigate participants' perceptions of the control and fatigue tasks, five additional paired Wilcoxon Signed Rank tests were performed. These examined the difference in ratings of effort, frustration, mental demand, performance, physical demand, and temporal demand for the control and fatigue tasks. The results of these tests are reported in Table 5.4. Along with rating the mental fatigue task significantly more mentally demanding than the control task, participants reported that the mental fatigue task was significantly more effortful, physically demanding, and temporally demanding. Participants also reported a perception that they performed significantly worse in the mental fatigue task. Frustration was not significantly different between the two tasks.

Subscale	Control	Fatigue	*z*	*p*	95% CI	*r*
Effort	10 (13.75)	75 (18.75)	-4.67	**< .001**	-65, -42.5	.85
Frustration	22.5 (33.75)	27.5 (45)	-1.79	.073	-27.5, 2.5	.33
Mental Demand*	25 (35)	75 (18.75)	-4.71	**<.001**	-55, -32.5	.86
Performance	90 (18.75)	55 (23.75)	-3.38	**<.001**	15, 35	.62
Physical Demand**	5 (10)	20 (17.5)	-4.15	**<.001**	-17.5, -10	.76
Temporal Demand	7.5 (10)	45 (23.75)	-4.26	**<.001**	-45, -22.5	.78

Table 5.4: Results of six paired Wilcoxon Signed Rank tests with TLX subscale score as the dependent variable and condition as the independent variable (n = 30). X (y) denotes Mdn (IQR). *as reported previously in subsubsection 5.1.3. ** n = 29. Bold ***p*** values are significant at the $p < .05$ level.

5.1.4 Discussion

This study examined the effects of mental fatigue on three different tests of dexterity. The manipulation checks indicate that the cognitive task battery was partially successful at inducing mental fatigue, with participants reporting greater increases in subjective fatigue from completing the cognitive task battery compared to watching the documentary. The significantly higher rating of mental demand for the cognitive task battery indicates that the difference in subjective ratings of mental fatigue is likely due to the differences in demand between the two tasks. There were, however, some inconsistencies in behavioural performance patterns in the cognitive task battery. Not all participants showed the expected decrement in performance over time. As discussed in Chapter 4, it is important to test an objective indicator of mental fatigue such as a decrement in behavioural task performance over time when ascertaining whether a mental fatigue manipulation has been successful. The majority of participants did show this decrement. Additionally, some authors have argued that a subjective indicator in itself is sufficient evidence of mental fatigue. Finally, the pattern of responses found in this study is similar to those found in the main study reported in Chapter 4, with the same possible reasons underlying the variation in responses such as learning effects and individual differences in ability.

The results as a whole indicate that despite experiencing high levels of mental fatigue and reporting high demands of the mental fatigue task, participants' broad dextrous abilities were maintained, with the effects of mental fatigue being very subtle. This is in line with the findings of Budini et al. (2022), who found no effects of mental fatigue on force steadiness, dexterity, or tremor. The current findings and those by Budini et al. (2022) contrast with Valenza et al. (2020) and Duncan et al. (2015), who found that mental fatigue did affect dexterity in three different tasks comparable to the Purdue Pegboard Test.

The current research, however, considerably extends the research of Duncan et al. (2015), Valenza et al. (2020), and Budini et al. (2022). Whilst Budini et al. (2022) and Valenza et al. (2020) report extensive physiological measures, their dexterity outcomes give a limited insight into the processes underlying dextrous behaviour. The tasks used by Duncan et al. (2015) give an insight into both broader behavioural performance and predictive or feedforward processes. Valenza et al. (2020) chose to use relatively naturalistic tasks - placing pins and unscrewing/screwing nuts and bolts - but did not collect additional data such as force data from the fingertips which may be more sensitive to subtle changes in dexterity. Budini et al. (2022) used a single Purdue Pegboard Test, which gives good insight into behavioural performance in a naturalistic and simplistic task, but does not give an insight into more complex or bimanual tasks. Budini et al. (2022) went further than Duncan et al. (2015) and Valenza et al. (2020) by assess fingertip forces as well as physiological data such as muscular EMG and heart rate. Their tasks, however, were short, and they did not assess fingertip forces during a more naturalistic task such as the object lifting task used in the current study. Consequently, the battery of dexterity assessments in the current study reveal some additional information about the relationship between mental fatigue and dexterity.

Whilst mental fatigue was successfully induced, the effects on behavioural performance in the Purdue Pegboard Test were not consistent across all subtasks. The analyses of assembly and total scores in the Purdue Pegboard Test did not provide a consistent picture as to the possible effects of mental fatigue on performance in a dextrous task. Whilst there was no significant effect of mental fatigue on assembly score, a significant difference was found between the total score in the fatigue and control conditions. Whilst both tasks place similar demands on participants, there are some differences in task demands between the two. For example, in the assembly task, participants must remember and execute a sequence of events involving multiple different types of item assembled in a specific order, with both hands concurrently performing different movements with different items. In the subtests which make up the total score, participants simply use one or both hands to pick up pegs and place them sequentially in holes, and where they are using both hands, are performing the same action with each hand at the same time. It is possible that the additional demands of the assembly task constrain performance in the control condition, creating a floor effect. Furthermore, the effect of mental fatigue on total performance may be driven by an effect of mental fatigue on one specific subtest e.g. the non-dominant hand test. To investigate this possibility, further analyses examined performance in the different Purdue Pegboard subtests in more detail.

The further analyses of performance in the Purdue Pegboard subtests found that mental fatigue appeared to selectively affect performance in the dominant hand only. This would indicate that performance in the dominant hand is particularly susceptible to mental fatigue. There are, however, other possibilities. Firstly, every other task in the Purdue Pegboard Test required participants to either solely use their non-dominant hand or to conduct bimanual tasks with both their non-dominant and dominant hand. It could be that using the non-dominant hand in a task - regardless of whether it is unimanual or bimanual - limits participants' performance in that task regardless of whether they are mentally fatigued or not i.e. creates a floor effect. A second possibility was also revealed by the analysis of performance throughout all the trials. This analysis found that participants' performance was worse when they were doing the first instance of the task, regardless of whether they had performed that task in a prior visit. The analysis also found an interaction which implies that this effect is more pronounced when participants are mentally fatigued. As the dominant hand task was performed first in both trials the significant effect of mental fatigue on the dominant hand task could be driven by this broader interaction: when participants are switching tasks, they are worse at doing the new task when they are mentally fatigued. The dominant hand subtest was entirely different to the tasks immediately preceding it, where the non-dominant, both hands, and assembly tasks were all preceded by other subtests. This outcome should be interpreted with caution as, firstly, it was exploratory and so is subject to bias, and secondly, the interaction was not supported by follow-up tests, possibly due to a lack of power. It has, however, already been established that mental fatigue affects cognitive control, which could affect participants' performance when they switch tasks (Lorist et al., 2005). Overall, the results from the Purdue Pegboard Test analyses indicate that behavioural performance in dexterity tasks is not inherently disrupted by mental fatigue, but that mental fatigue may affect feedforward cognitive processes that support the execution of dexterity tasks - such as goal setting, planning, and updating - which consequently has an initial small to moderate effect on performance in those tasks. This finding is in agreement with the suggestion by Valenza et al. (2020) that cognitive processes may mediate of any effects of mental fatigue on dexterity.

Despite extensive prior research into fingertip forces and perception during object lifting (Buckingham, 2014; Buckingham et al., 2018; Hermsdörfer et al., 2011), this is the first study to examine whether mental fatigue affects these processes. Participants' perception was not affected by mental fatigue, and their ability to scale the force used to grasp and lift the objects was also unaffected. In contrast, the statistical analyses of perceptual reports, grip, and load forces were in line with what would be expected from normal, healthy participants. Participants were able to accurately perceive when objects were heavier or lighter than others, and used visual information about object size to scale their forces appropriately based on the predicted weights of the objects. Participants also closely timed their grasp and lift behaviours, as is typically found in normal healthy adults (Flanagan & Tresilian, 1994). Together, these results indicate that mental fatigue does not affect prediction or planning during the simple task of object lifting. There was, however, a significant difference in the timing of grip and load forces applied by participants when they were mentally fatigued compared to when they were not mentally fatigued. Despite participants' timing of grip and load forces being highly correlated, in line with findings in prior research (Flanagan & Tresilian, 1994), mentally fatigued participants had greater time lags between their peak grip and load forces. This might indicate that participants' coordination was affected by mental fatigue. This is in line with the findings from the Purdue Pegboard Test that mental fatigue may affect the cognitive processes underlying dexterity.

The force matching task findings corroborate those by Budini et al. (2022), who also found no significant effects of mental fatigue. The current study examined the magnitude and accuracy of forces produced by participants during force production, and found that there were no differences that could be attributed to mental fatigue. The current research also extends their findings, firstly as the forces required were greater in this study (approximately 20N compared to 2 and 5 in Budini et al., 2022), and secondly as participants were required to maintain the same level of force production with no visual feedback in half of trials. As with prior research using the same paradigm (Neely et al., 2016, 2017), participants' force production reduced over time and consequently became less accurate during the time periods with no visual feedback. In line with this, participants found the trials with no visual feedback more challenging than the trials where visual feedback was continuously available. These findings were no different when participants were mentally fatigued than when they were not mentally fatigued. Participants ability to control and correct their forces in a dynamic manner with visual and haptic feedback therefore appears not to be susceptible to mental fatigue. Participants successfully integrated visual and, to a lesser extent, haptic information about the force they were using to squeeze the transducer and used this to correct any perceived errors, even though feedforward coordination appears to have been affected by mental fatigue in the other dexterity tasks. The reported task difficulty aligns with the outcomes of the force matching task - participants' performance was worse where the task was reported as more difficult, and unaffected where there were no perceived differences in difficulty. This aligns with the notion of mental fatigue as affecting tasks via perception of that task's difficulty (Marcora et al., 2009).

Limitations

As discussed in subsection 5.1.4, not all participants showed the expected decrement in performance in the cognitive task battery. As discussed in Chapter 4, researchers would ideally have concurrent objective and subjective evidence of participants' fatigue as opposed to only subjective evidence, as using one or the other risks oversimplifying fatigue and risking error through bias. Other researchers have, however, proposed that if participants show increased perceptions of fatigue whilst sustaining task performance, that this is still sufficient evidence of mental fatigue (e.g. Pageaux, 2014; Van Cutsem et al., 2017). In the current study, rather than exclude participants who did not show a decrease in performance in the cognitive task battery, these participants were retained in the analyses on the basis that they all nonetheless showed subjective increases in mental fatigue. Similarly, two participants who reported a decrease in perceived fatigue during the mental fatigue task - as visible in Figure 5.6 (page 109) - nonetheless showed a decrease in performance in the cognitive task battery.

There was one unexpected finding from the analyses of the BRUMS questionnaire responses: depression increased significantly more in the control task than in the fatigue task. This analysis is slightly limited as there is a floor effect in reports of depression in the fatigue task - with the median and IQR both being 0 - inflating the likelihood that a significant difference would be found. Nonetheless, this finding perhaps indicates that the choice of control task was not appropriate for ensuring participants maintained a neutral mood. This is possibly as the documentaries chosen also included information about the impacts of climate change on the natural world, which could have negatively affected participants' mood. Whilst there is no reason to believe that this would have affected the outcomes in the current study, future research may choose to avoid this by more carefully screening the content of documentaries used as control tasks. Whilst not unexpected - as the same has been found in prior research (Marcora et al., 2009) - the decrease in vigour found in the control task is similarly not optimal, though there is no reason to think that it would have affected the outcomes of the current study.

The NASA-TLX results also provided some important insights into participants' subjective experiences. Whilst participants' reporting of increased effort and mental, physical, and temporal demand supports the challenging nature of the mental fatigue task, there are some other findings which future researchers should consider carefully. Firstly, there was no significant difference in ratings of frustration, where one might expect that a task which is perceived as effortful, demanding, and difficult to perform well in would be perceived as more frustrating than watching a documentary. This may be related to the issues discussed in the previous paragraph, where participants may have found the discussions of climate change in the documentaries frustrating. It could also be that participants reported the cognitive task battery as relatively not frustrating due to experimenter demands. Similar to this, despite being significantly lower than the mental demands of the cognitive task battery, the mental demands of the control task were somewhat higher than might be expected. Informal reports from participants suggested that focusing on documentaries for two hours in a laboratory without being able to engage in other tasks - such as snacking, drinking a hot drink, or using a smartphone to communicate with friends or check social media - was quite demanding of their attention. Speculatively, the lack of agency and potential for negative mind-wandering or rumination during the control task could also have contributed to the BRUMS and NASA-TLX reports of frustration and other aversive mood states. In the future, researchers may wish to consider this potential limitation when designing control tasks. Other documentaries could be selected, a choice of activities or documentaries could be provided so that participants are able to engage in a task they consider sufficiently interesting, or participants could be allowed occasional breaks to use social media. This would more closely replicate the experience of resting neutrally in a home environment than the protocol in the current experiment.

There is some disagreement amongst the present findings and those of Duncan et al. (2015), Valenza et al. (2020), and Budini et al. (2022). The present study completed thorough manipulation checks and used a novel method to induce mental fatigue which has been validated, whereas other researchers did not. Future researchers may wish to perform a pseudoreplication of this and other research into mental fatigue and dexterity with some key improvements: using this validated novel method to induce mental fatigue; using thorough manipulation checks to investigate mental fatigue; and increasing sample size and using a repeated-measures design to increase statistical power.

Given the findings in the current study that cognitive and/or feedforward processes appear to be the most affected by fatigue, and the theory that the effects of mental fatigue on other tasks is primarily due to cognitive or perceptual processes, future research may wish to focus on tasks which can provide more insight into these aspects of dexterity.

5.2 Conclusions

This study suggests that mental fatigue does not broadly affect dexterity. There do, however, appear to be some effects of mental fatigue on the cognitive processes underlying dexterity, as small differences in coordination were found, and the ability to switch between dissimilar tasks appears to have been negatively impacted by mental fatigue. This finding is broadly in line with previous suggestions that mental fatigue's impact on subsequent tasks is mediated by cognitive or perceptual effects rather than being due to underlying neuromuscular alterations.

Chapter 6: The Effects of Neuromuscular Fatigue on Manual Dexterity

Whilst there is some research into the effects of neuromuscular fatigue on skill-based performance in sport, which gives an insight into how neuromuscular fatigue may affect dexterity, prior research is mainly focused on aspects of sports performance such as the ability to produce maximal power and endurance, or accuracy in gross movements such as hitting a ball. This research gives limited insight into what implications neuromuscular fatigue may have for the movements typically performed in activities of daily living. As outlined in Chapter 1, neuromuscular fatigue affects brain and muscle function in ways that could affect dexterity. Study 6, therefore, aimed to further this research area by examining the effects of neuromuscular fatigue on the same measures of dexterity as used in study 5. In doing so, study 6 gave a rich insight into how the sensorimotor system functions under neuromuscular fatigue, as well as allowing qualitative comparison between the effects of mental and neuromuscular fatigue on dexterity.

6.1 Study 6

6.1.1 Introduction

As outlined in Chapter 1, there are numerous mechanisms of fatigue that could affect the feedforward and feedback processes used to enact dextrous movements. In brief, neuromuscular fatigue results in central, peripheral, and perceptual changes. Central fatigue results in altered neural drive, affecting voluntary force production (Gandevia, 2001), and has been associated with changing levels of a wide range of neurotransmitters such as serotonin, noradrenaline, adenosine, dopamine, and glutamate (Meeusen et al., 2006; Meeusen & Roelands, 2018; Meeusen et al., 2020; Tornero-Aguilera et al., 2022) some of which also play a role in motor function. Peripheral fatigue is associated with metabolic perturbations in the muscle which can result in reduced maximal (J. L. Smith et al., 2007) and submaximal (Singh et al., 2013) force production, and altered motor unit recruitment, which can reduce the accuracy of movements (Boyas & Guével, 2011; Gates & Dingwell, 2008; Hoffman et al., 1992; Jaric et al., 1999). The altered neural drive in central fatigue is also linked with perception of effort, which has a complex relationship with perception of object weight (Burgess & Jones, 1997).

To date, there is no research which comprehensively examines the effects of neuromuscular fatigue on dexterity. Duncan et al. (2015), examined the effects of both mental and physical fatigue on two different motor tasks, as outlined in Chapter 5. In their repeated-measures study, participants completed these tasks at six different time points: immediately prior to a mental fatigue intervention, immediately following a mental fatigue intervention/control task, and immediately following each of four wingate tests - where participants cycled at maximal effort for 30s followed by four minutes of rest. Their results found an interaction between mental fatigue and repeated exercise tests, where mental fatigue resulted in poorer performance on both dexterity tasks, but this effect diminished with repeated exercise. No main effect of exercise i.e. neuromuscular fatigue was reported, with participants who had physically exercised but not been subjected to a mental fatigue intervention having no apparent change in performance on the motor tasks throughout the experiment. Manipulation checks showed that participants in both conditions experienced increases in RPE, heart rate, and blood lactate with each exercise repetition, indicating progressive alterations in the physiological response to exercise consistent with fatigue. Participants also showed a decrease in mean power output, with a reduced ability to generate power also consistent with ongoing fatigue development. Altogether, this indicates that neuromuscular fatigue may not affect dexterity.

Duncan et al. (2015) chose to use repeated wingate tests to induce neuromuscular fatigue as intermittent anaerobic exercise mixed with perceptual and skill-based tasks closely replicates the features of sports such as football and basketball. Short-term maximal exercise, however, primarily accelerates peripheral fatigue development, with relatively little central fatigue development (Thomas et al., 2015, 2016). Peripheral fatigue can recover within three to five minutes (Carroll et al., 2019), which means that participants in Duncan et al.'s (2015) study may have recovered from peripheral fatigue throughout the four-minute rest period. As the wingate test is a cycling-based exercise, one would also expect peripheral fatigue development to occur almost if not exclusively in the lower body musculature which is involved in cycling movements, as opposed to in the upper body musculature which is used in dextrous tasks. Therefore the peripheral fatigue induced by Duncan et al.'s (2015) study might be expected to influence lower-body movements but is less likely to affect dexterity.

As peripheral fatigue can recover quickly, and as central fatigue has been found to affect neural drive and perception - which could affect feedforward and feedback processes in dextrous hand movements - study 6 aimed to maximise central rather than peripheral fatigue development. At work rates above critical power, physiological responses to exercise within the muscle cannot be stabilised and so peripheral fatigue develops rapidly (Poole et al., 2016). Below critical power - in the heavy domain - peripheral fatigue develops more slowly, with central mechanisms thought to be the main contributors to a loss of force output (Burnley & Jones, 2018; Burnley et al., 2012). The physiological changes that occur in the heavy domain are well-documented. Black et al. (2017) found that constant exercise at a heavy work rate resulted in metabolic perturbations in the muscle and also affected voluntary muscle activation as measured by electromyography. Clark, Vanhatalo, Thompson, Wylie, et al. (2019) found changes in oxygen and carbon dioxide kinetics, carbohydrate and fat oxidation, and heart rate throughout a two-hour heavy intensity cycling intervention, with such cardiorespiratory changes indicative of an attempt to maintain homeostasis in the presence of progressive muscle metabolic perturbations. Blood lactate concentration becomes elevated with exercise in the heavy-intensity domain (Clark, Goulding, et al., 2018), again indicating metabolic perturbations, whilst increases in frontal cortex blood flow and oxygenation from the beginning to the end of the cycling bout were also found, indicating changes in front lobe activation in response to the heavy-intensity exercise. Overall, these findings show that exercise in the heavy intensity domain can induce neuromuscular fatigue, with muscle metabolic perturbations and central nervous system alterations both being apparent.

Study 6 therefore used a similar intervention to that of Clark, Vanhatalo, Thompson, Wylie, et al. (2019) to induce neuromuscular fatigue, with the three dexterity tests in study 5 used to assess the possible effects of neuromuscular fatigue on behavioural performance, feedforward and feedback processing, and perception.

6.1.2 Methods

Materials

The control task, subjective measures, and hand function tasks were the same as in Chapter 5. Briefly, the control task comprised two nature documentaries. The BRUMS and a brief version of the NASA-TLX were used to take subjective measures of fatigue and other feelings. Participants' hand strength was measured using a digital pinch strength gauge. The tasks used to assess participants' dexterity were the Purdue Pegboard Test, an object lifting task, and a force matching task.

For all exercise, the same electrically braked-cycle ergometer was used with its associated software (Lode Excalibur Sport, Lode BV, Groningen, The Netherlands), with heart rate collected using a Polar T31 Heart rate strap and monitor (Polar Electro, Finland). During the ramp test, pulmonary gas exchange was measured breath by breath using an oronasal mask (Hans Rudolf 7450 Series V2 Mask, Kansas, USA) and metabolic cart (Cortex Metalyser 3B and Metasoft v2.1, Cortex, Leipzig, Germany). The 6-20 Borg Scale was used to take participants' RPE during exercise (Borg, 1970, 1982).

Participants

Sample size was determined by practical constraints, with data collection ceasing when the study end date had been reached. 11 healthy recreationally active adults aged 18-40 were recruited via word of mouth, adverts on social media, and posters across the University of Exeter campuses. All participants were free of cognitive and movement impairments, free of injury, and had normal or corrected-to-normal vision and hearing. One participant was not able to attend the final study visit. The final sample size therefore comprised 10 right-handed adults aged 27 ±4 years, of whom 9 were female and 1 was male. Participants were paid £75 for their time.

Procedures

All procedures were approved by the University of Exeter Sport and Health Sciences Ethics Committee (Ref: 528118). Prior to all procedures, participants gave informed consent via an online form.

Throughout the duration of the study, participants were instructed to follow their habitual diet and exercise routine. For 24 hours prior to each visit, participants were asked to refrain from strenuous exercise or alcohol. On the day of each visit, participants were asked to refrain from consuming caffeine. Participants were asked to arrive for each visit rested and hydrated. At the beginning of each visit, the experimenter confirmed with the participant that they had followed these instructions. Participants completed all visits at the same self-selected time of day to control for any possible effects of circadian rhythm, and there was a minimum of 48 hours between each visit. Participants visited the lab a total of four times, with the final two visits counterbalanced to control for order effects.

In Visit 1, participants completed a health questionnaire to determine whether it was safe for them to perform maximal exercise. They were given an overview of the experimental procedures for each visit, and had the opportunity to ask any questions. Their age and gender were self-reported, their height and weight were measured, and the heart rate monitor strap was fitted. Participants freely adjusted the bike with the help of the experimenter until it was comfortable, and these settings were recorded and replicated for all exercise. The face mask was then fitted and connected to the metabolic cart. The ramp test then began. Participants cycling at a self-selected cadence for three minutes at 20W to warm up. Following this, resistance was increased at 30W/min for males and 25W/min for females. The ramp test finished when participants' cadence fell >10rpm despite strong verbal encouragement. There was then an optional unloaded cool down which was not time-constrained.

The heavy-intensity work rate was then estimated used the gas exchange threshold (GET) and respiratory compensation point (RCP) to demarcate the heavy-intensity domain from the moderate- and severe-intensity domains respectively (Bergstrom et al., 2013). Breath-by-breath data from the ramp test was taken in 10-second averages and used to estimate participants' GET and RCP. The power at GET and RCP were estimated using the methods described in Beaver et al. (1985) and D. A. Schneider et al. (1993). To account for the lag in the pulmonary gas exchange data, 2/3rds of the ramp rate was then subtracted from both the GET and RCP values. 25% of the difference in watts between the adjusted GET and adjusted RCP was calculated, and this was added to the adjusted GET to compute participants' target power for the heavy-intensity cycling intervention.

This target was chosen so as to ensure that participants were cycling below critical power, but at a high enough intensity within the heavy domain that fatigue would develop. Participants' individual GET, RCP, target powers, and average attained power are displayed in Table 6.1.

Participant	Adjusted GET (W)	Adjusted RCP (W)	Target (W)	Mean Power Output (W)
1	100	187	121	121
2	175	237	190	**154**
3	83	125	93	**88**
4	53	117	69	69
5	135	286	173	173
6	146	208	161	161
7	67	125	81	**79**
8	104	204	129	**114**
9	75	137	90	**85**
10	75	117	85	85

Table 6.1: Participants' GET, RCP, Target Power derived from the ramp test, and Mean Power achieved in the two-hour fatiguing intervention. **Bold** mean power output values highlight participants who were unable to maintain the target power for the full duration of the intervention.

The purpose of Visit 2 was to check that participants were able to cycle at the target power calculated for them, and to familiarise them with the sensation of exercising at their target power prior to the two-hour fatiguing intervention. Participants cycled unloaded for three minutes, with resistance then immediately increased on the ergometer to participants' target power. Participants cycled at this target power for 10 minutes. Participants' heart rate was monitored throughout, and participants gave an RPE in the final minute of the practice using a printed Borg Scale placed in front of the ergometer. Finally, there was an optional unloaded cool-down.

Visits 3 and 4 followed the same overall procedure lasting approximately 3.5 hours. Participants reported their age, gender, and dominant hand (defined as the hand they use to write with). Both visits then proceeded as follows: object lifting familiarisation and anchoring; three pinch grip MVCs; force matching task familiarisation; BRUMS questionnaire; the experimental manipulation (fatigue or control); NASA-TLX ratings; three pinch grip MVCs; BRUMS questionnaire; Purdue Pegboard Test; object lifting task; force matching task; force matching visual analogue scale; BRUMS questionnaire (Figure 6.1). At the end of Visit 4, participants also did an object dropping task, were debriefed and thanked for their time, and completed forms so that they could be paid for their time. Throughout all tasks, participants were seated comfortably at a desk. The procedures for the individual tasks were as described in Chapter 5.

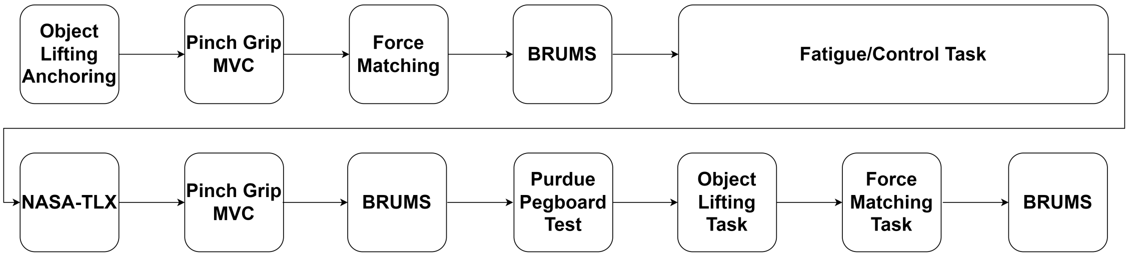


Figure 6.1: Schematic of Overall Study Procedures.

For the fatiguing intervention, participants cycled unloaded for three minutes, with resistance then immediately increased on the ergometer to participants' target power. Participants then cycled continuously for two hours. RPE was taken at 3, 6, 9, 12, and 15 minutes, and every 15 minutes thereafter. Heart rate was also monitored throughout. During exercise, participants were allowed to listen to music of their choice using headphones, and were allowed to drink plain water ad libitum. Participants were instructed to maintain their self-selected cadence from the ramp test and were able to see their cadence throughout the two hour bout. If participants' cadence fell >10rpm below their target cadence, they were strongly encouraged to increase their cadence back to the target. If they were unable to do so, the resistance was decreased by 10%. Half of participants failed to maintain their cadence at some point during the two-hour cycling intervention and so had their target reduced. The average power attained by these participants over the two-hour cycling bout is included with their target power in Table 6.1.

Data processing and analyses

Data was processed and analysed as described in study 5 methods.

6.1.3 Results

Manipulation checks

A series of manipulation checks were performed to determine whether participants perceived the experimental intervention to be physically demanding. The distribution of the NASA TLX physical demand ratings was not normal as identified by a significant Shapiro-Wilk test (p < .001). A paired Wilcoxon Signed Rank test with TLX physical demand rating as the dependent variable and condition (control/fatigue) as the dependent variable revealed a significant effect of condition, z = -2.81, p = .005, 95% CI [-80, -57.5], r = .89. Participants reported that the cycling intervention was significantly more physically demanding than the control task (Figure 6.2). The fatigue manipulation was successful in being more physically demanding than the control task.

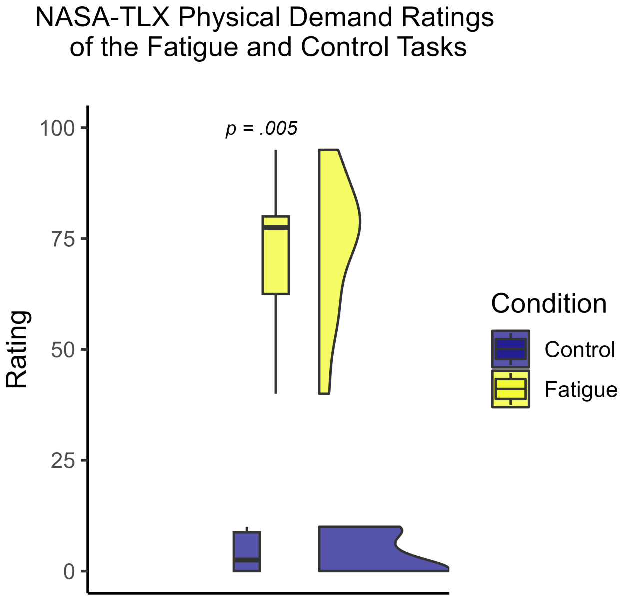


Figure 6.2: NASA-TLX Physical Demand Ratings of the Fatigue and Control Tasks (n = 10). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas.

To examine how participants' perceptions of the cycling task changed throughout the task, a correlation between time (mins) and rating of perceived exertion (RPE; Borg Scale, 6-20) was conducted. The distribution of RPE was not normal as identified by a significant Shapiro-Wilk test (p = .005), so a Spearman's rank correlation was used. This found a positive correlation, ρ (10) = .66, *p* < .001. Participants' RPE increased over time throughout the cycling intervention (Figure 6.3).

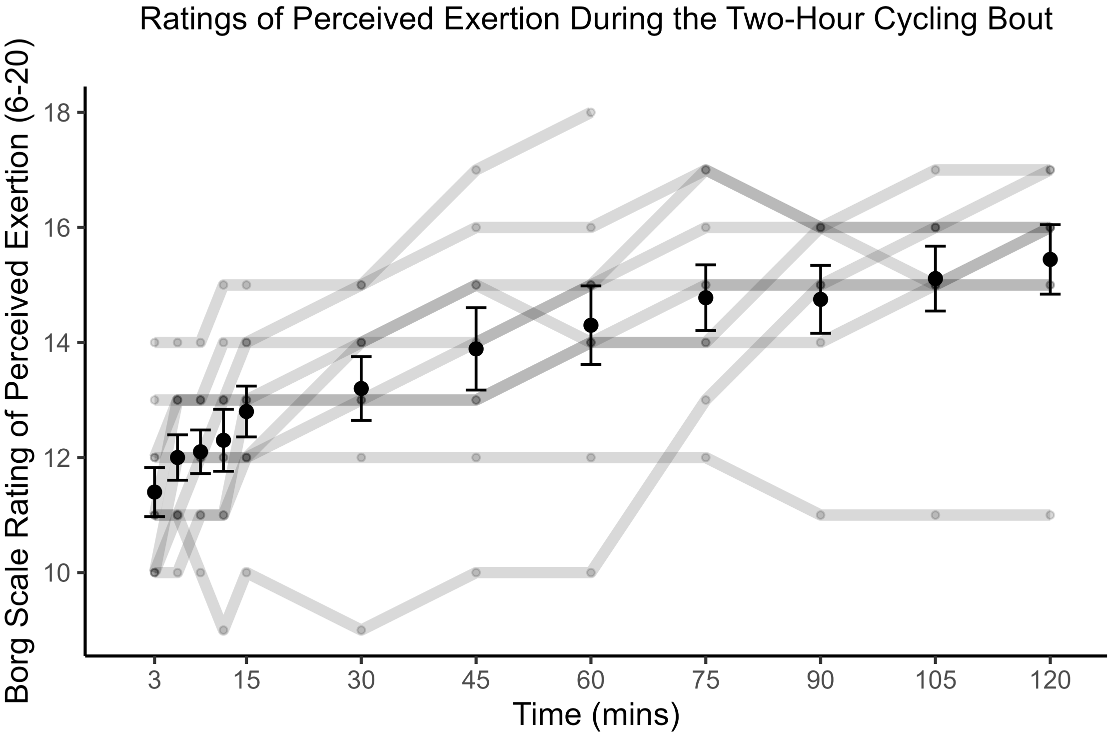


Figure 6.3: Participants' Rating of Perceived Exertion During the Two-Hour Cycling Bout. Grey lines show individual ratings. Top and bottom horizontal lines indicate the standard error, with the black dots showing the mean.

A factorial repeated measures ANOVA with pinch grip MVC as the outcome variable and condition (control/fatigue) and time point (pre/post) as the predictors found no significant effect of condition, *F* (1, 8) = 1.33, *p* = .283, η_p^2 = .14. There was, however, a significant main effect of time point, *F* (1, 8) = 7.17, *p* = .028, η_p^2 = .47. The interaction between condition and time point was not significant, *F* (1, 8) = .07, *p* = .805, η_p^2 = .01. Together, these results indicate that participants' pinch grip MVC decreased over two hours, regardless of whether they were cycling or not (Figure 6.4).

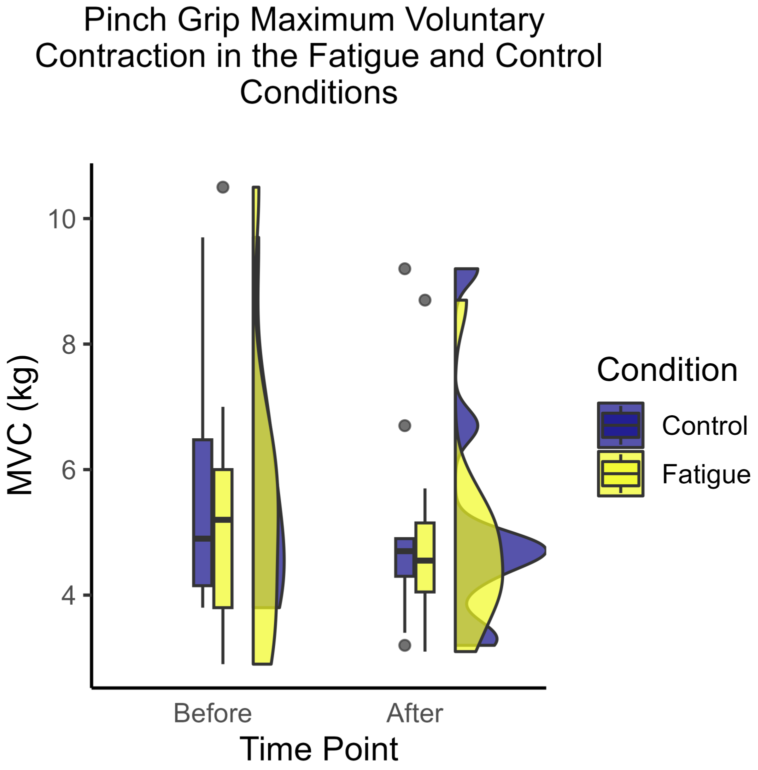


Figure 6.4: Maximum Voluntary Pinch Grip Contraction Before and After the Experimental and Control Interventions (n = 10). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas.

Purdue Pegboard Test

A paired t-test with Purdue Pegboard Test assembly score as the dependent variable and condition (control/fatigue) as the dependent variable found no significant effect of condition, $t(9) = .91$, $p = .389$, 95% CI [-1.8, 4.2], $d = .29$. There was no significant difference between assembly task performance in the fatigue and control conditions (Figure 6.5). Participants' performance in the Purdue Pegboard assembly subtest was not affected by neuromuscular fatigue.

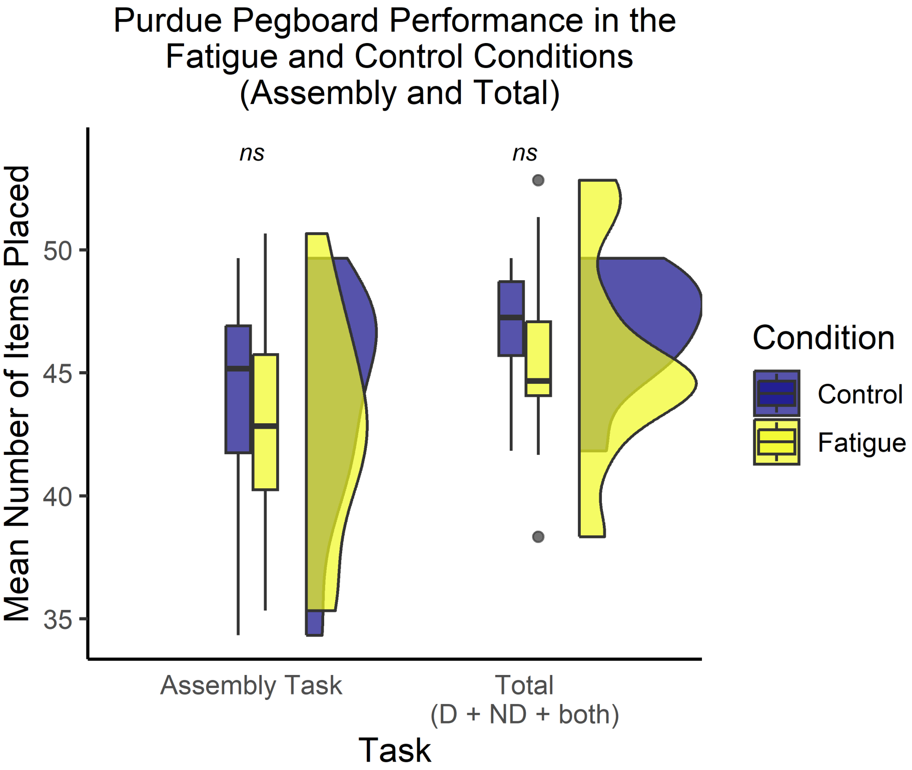


Figure 6.5: Purdue Pegboard Assembly and Total Test Performance in the Fatigue and Control Conditions (n = 10). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. *ns* denotes non-significance ($p \geq .05$). "D" = dominant, "ND" = non-dominant.

A paired t-test with Purdue Pegboard Test mean total score as the dependent variable and condition (control/fatigue) as the dependent variable found no effect of condition, $t(9) = 1.03$, $p = .330$, 95% CI [-1.58, 4.21], $d = .32$. There was no significant difference between performance on the dominant, non-dominant, and both hands subtests in the fatigue and control conditions (Figure 6.5). Participants' performance across the dominant hand, non-dominant hand, and both hands subtests was unaffected by physical fatigue.

Given the findings in Chapter 5, the Purdue Pegboard total test performance was examined in more detail. Three paired t-tests with Purdue Pegboard dominant, non-dominant, and both hands scores as the three dependent variables and condition (control/fatigue) as the dependent variable were performed. No significant effects of condition were found on performance with the dominant hand, $t(9) = 1.37$, $p = .204$, 95% CI [-.05, 2.03], $d = .43$, non-dominant hand, $t(9) = .77$, $p = .462$, 95% CI [-.91, 1.84], $d = .24$, or both hands $t(9) = .26$, $p = .804$, 95% CI [-.65, .82], $d = .08$. Participants' Purdue Pegboard Test performance was not significantly affected by neuromuscular fatigue in any of the subtests. Visual inspection of the results does, however, indicate that participants' performance may have been worse in the dominant and non-dominant subtests when they were fatigued (Figure 6.6).

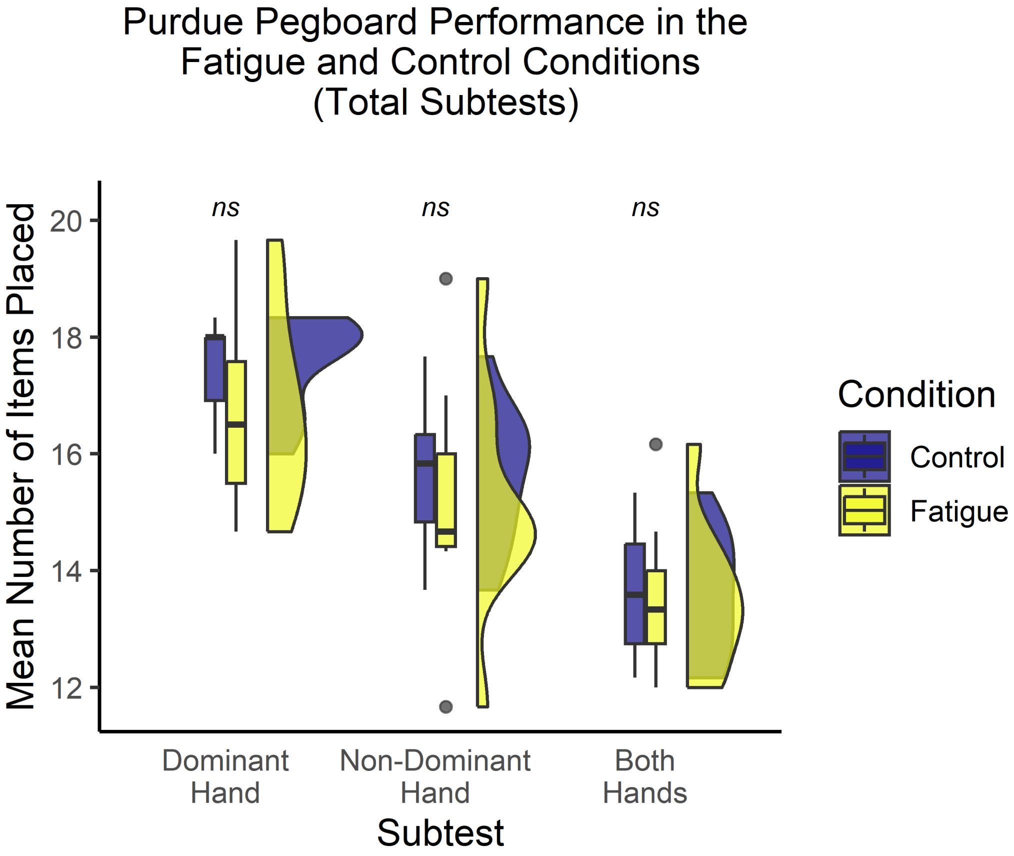


Figure 6.6: Purdue Pegboard Test Dominant, Non-Dominant, and Both Hands Performance in the Fatigue and Control Conditions (n = 10). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. *ns* denotes non-significance ($p \geq .05$).

A Greenhouse-Geisser corrected factorial repeated measures ANOVA with z-standardised mean score across all tasks (excluding ‘total’, as it is a composite of other subtests) as the outcome variable and condition (control/fatigue) and trial (1-3) as the predictors found no significant effect of condition, F (1, 9) = 1.33, p = .278, η_{p}^2 = .13. There was, however, a significant main effect of trial, F (1.75, 15.75) = 16.55, p <.001, η_{p}^2 = .65. The interaction between condition and trial was not significant, F (1.80, 16.16) = .59, p = .550, η_{p}^2 = .06. Together, these results indicate that participants’ performance on the Purdue Pegboard Test improved with repetition, regardless of whether they were fatigued or not (Figure 6.7).

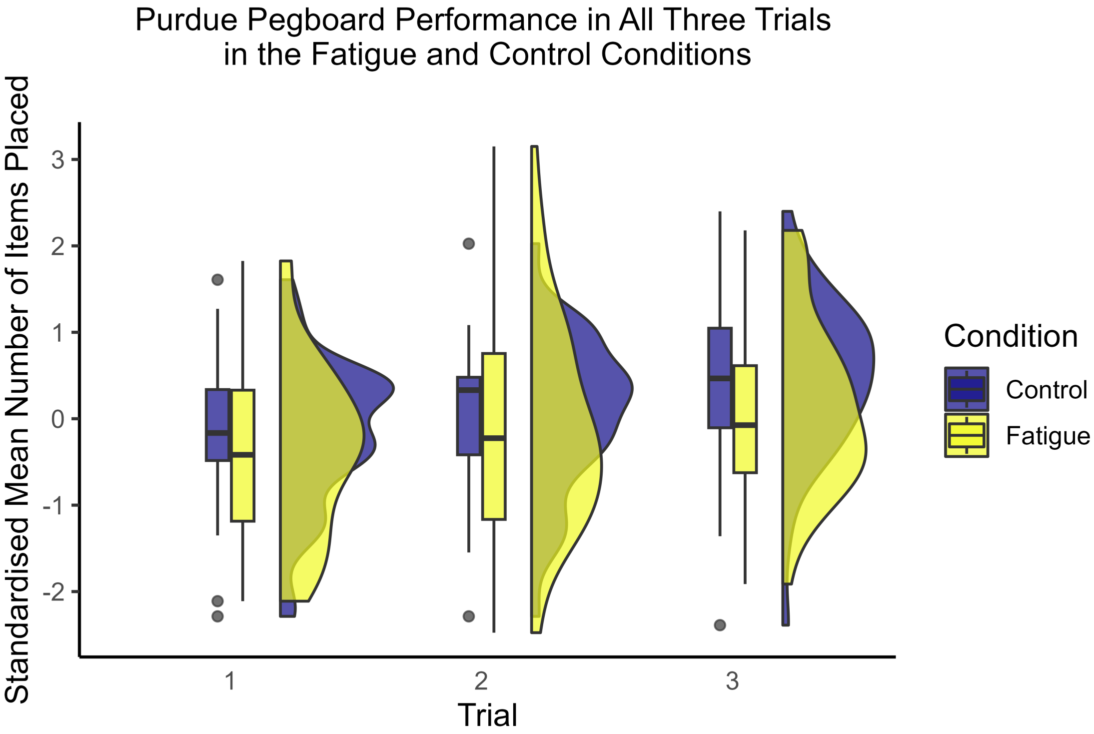


Figure 6.7: Purdue Pegboard Test Performance Throughout All Trials in the Fatigue and Control Conditions (n = 10). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. The “total” test results are excluded from this figure and its associated analysis as it is a composite of the dominant, non-dominant, and both hands subtests.

Object lifting task

A Greenhouse-Geisser corrected factorial repeated measures ANOVA with z-standardised mean ratings of object weight as the outcome variable and condition (control/fatigue) and object size (5/6.6/8.3/10) as the predictors found a significant effect of condition, *F* (1, 29) = 8.29, *p* = .018, η_p^2 = .48. Object size also significantly predicted weight ratings, *F* (1.24, 11.18) = 474.63, *p* <.001, η_p^2 = .98. There was no interaction between condition and object size, *F* (1.91, 17.22) = 1.12, *p* = .347, η_p^2 = .11. The significant main effect of object size indicates that participants were able to correctly identify differences in object weight associated with size. When participants were fatigued, they overall reported objects as being heavier than when they were not fatigued (Figure 6.8).

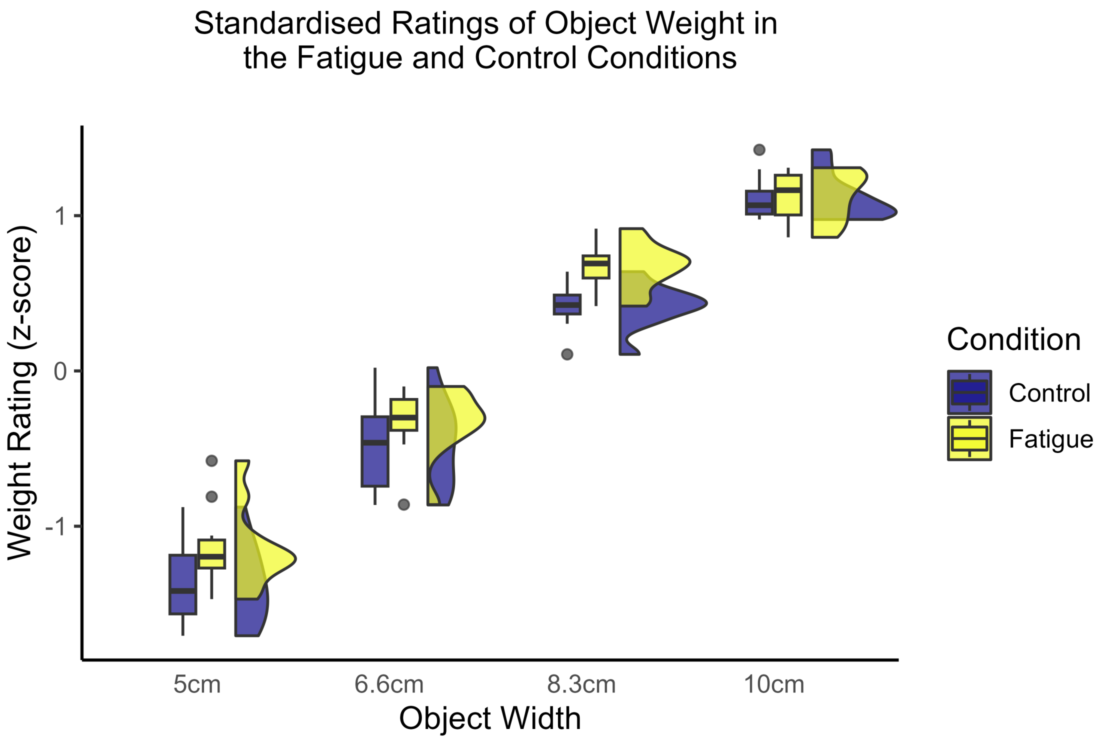


Figure 6.8: Ratings of Object Weight in the Fatigue and Control Conditions (n = 10). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas.

Four participants' data were excluded from the pGFR analysis due to there being missing values for the first object lift. A Greenhouse-Geisser corrected factorial repeated measures ANOVA with pGFR as the outcome variable, and condition (control/fatigue) and object size (5/6.6/8.3/10) as the predictors found no significant effect of condition, *F* (1, 5) = .68, *p* = .447 η_{p}^2 = .12.There was, however, a significant main effect of object size, *F* (2.48, 12.41) = 5.23, *p* = .018, η_{p}^2 = .51. The interaction between condition and object size was not significant, *F* (1.54, 7.69) = 1.22, *p* = .332, η_{p}^2 = .2. The significant main effect of object size indicates that participants correctly scaled their grip force, using greater forces to grasp larger and heavier objects. The absence of other significant effects indicates that there was no difference in participants' ability to do this between the control and fatigue conditions (Figure 6.9).

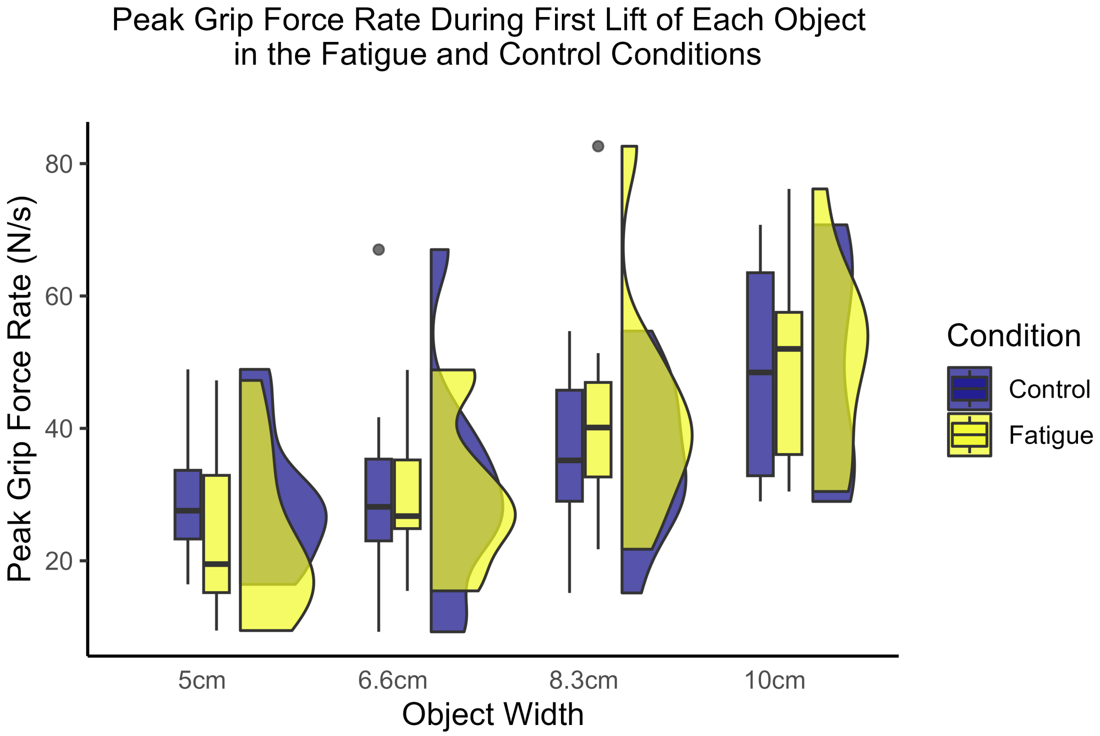


Figure 6.9: Peak Grip Force Rate used to Grasp each Object in the Fatigue and Control Conditions (n = 6). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas.

Two participants' data were excluded from the pLFR analysis due to there being missing values for the first object lift. A factorial repeated measures ANOVA with pLFR as the outcome variable, and condition (control/fatigue) and object size (5/6.6/8.3/10) as the predictors found no significant effect of condition, *F* (1, 7) = 0.03, *p* = .860, η_{p}^2 = 005. There was, however, a significant main effect of object weight, *F* (2.27, 15.86) = 9.57, *p* <.001, η_{p}^2 = .58. The interaction between condition and object weight was not significant, *F* (2.07, 14.52) = .55, *p* = .592, η_{p}^2 = .07. The significant main effect of object size indicates that participants correctly scaled their load force, using greater forces to lift larger and heavier objects. The absence of other significant effects indicates that there was no difference in participants' ability to do this between the control and fatigue conditions (Figure 5.14).

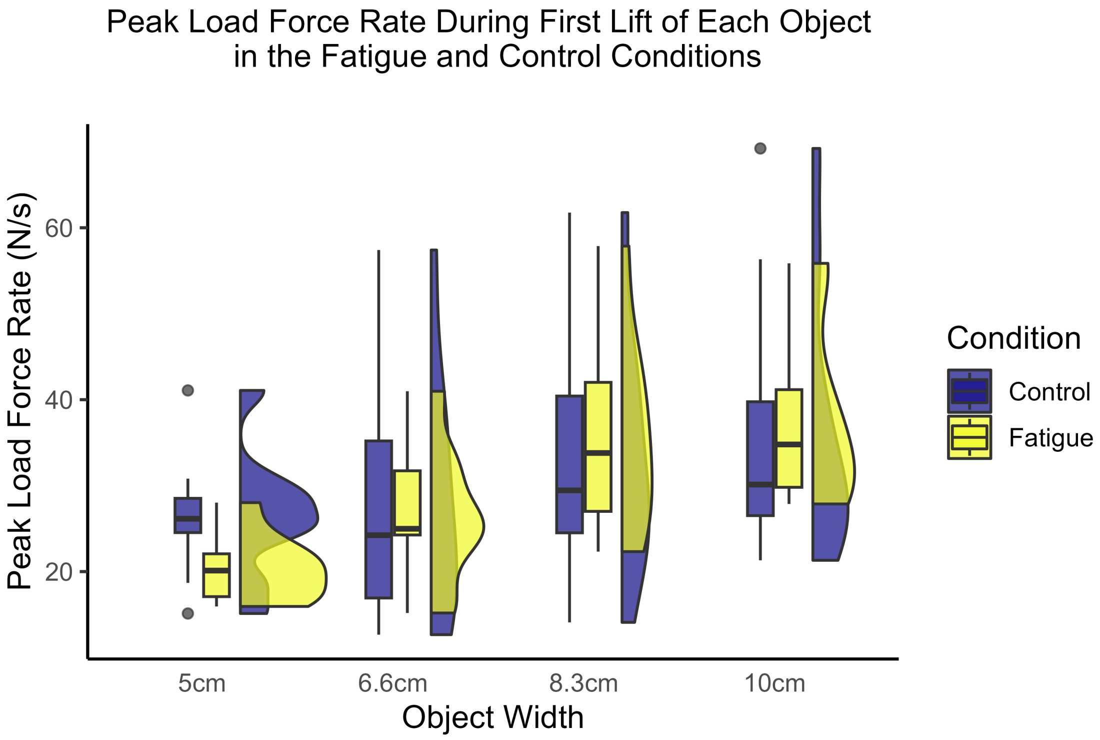


Figure 6.10: Peak Load Force Rate used to Lift each Object in the Fatigue and Control Conditions (n = 8). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas.

As a positive control, a correlation between tPGF and tPLF was conducted to examine the temporal coupling of participants' PGF and PLF. A Pearson's correlation between tPGF and tPLF found a significant strong positive correlation, t (78) = 64.21, p < .001, r = .99. The timing of participants' PGF and PLF was overall highly correlated, in line with prior research, indicating that their behaviour was broadly normal (Figure 6.11).

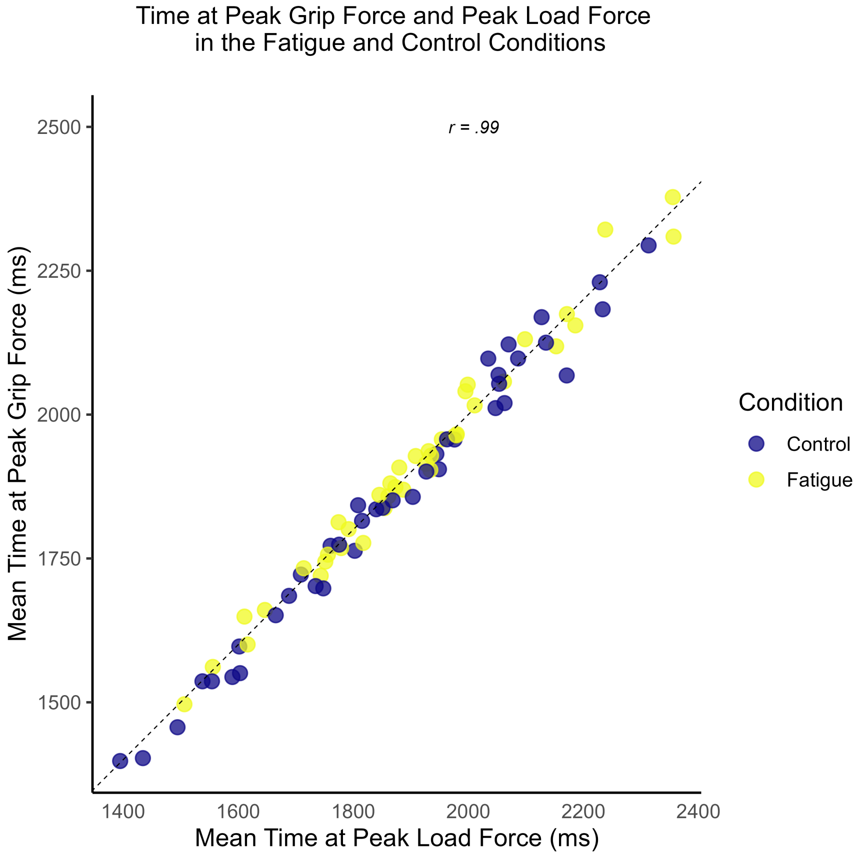


Figure 6.11: Correlation between Time of Peak Grip Force and Time of Peak Load Force During Object Lifting in the Fatigue and Control Conditions (n = 10). Each dot shows the mean values applied by each participant for each of the four objects in both conditions. Dotted line indicates $\rho = 1$ i.e. a perfect correlation.

A paired t-test with mean difference between tPGF and tPLF (ms) as the dependent variable, and condition (control/fatigue) as the independent variable revealed a significant effect of condition, *t*(39) = -2.35, *p* = .024, 95% CI [.29.87, -2.26], *D* = .37. The time difference between PGF and PLF was significantly greater in the fatigue condition (mean 2.6 ±31.48 SD) compared to the control condition (-13.46 ±31.48), indicating that participants' coordination was affected by neuromuscular fatigue (Figure 6.12).

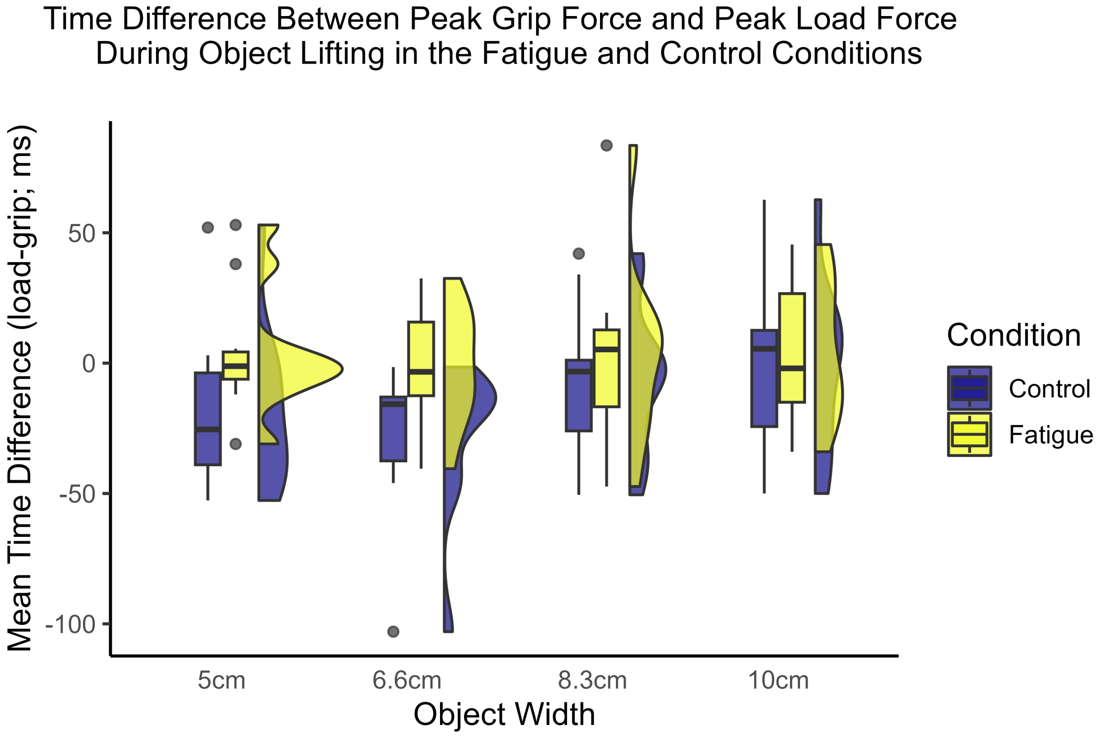


Figure 6.12: Time Difference Between Peak Grip Force and Peak Load Force During Object Lifting in the Fatigue and Control Conditions (n = 10). The upper and lower whiskers (vertical lines) of the box plot extend to 1.5 times the interquartile range, with points outside these whiskers being outliers that were not removed from the data. Top and bottom horizontal lines indicate the first and third quartiles (25th and 75th percentiles), with the middle line showing the median. Density plots show the distribution of the data, with wider areas indicating points along the y axis where scores fell with greater frequency than narrower areas. Above zero, grip force precedes load force. Below zero, load force precedes grip force.

The distribution of the ratio between GF and LF was not normal as identified by a significant Shapiro-Wilk test ($p < .001$). A paired Wilcoxon Signed Rank test with ratio as the dependent variable and condition (control/fatigue) as the independent variable found a significant effect of condition, z = -2.44, p = .015, 95% CI [.03, .19], r = .77. The relationship between the forces that participants applied to grasp and lift objects was different when participants were fatigued, with participants applying slightly greater load forces than grip forces (Figure 6.13).

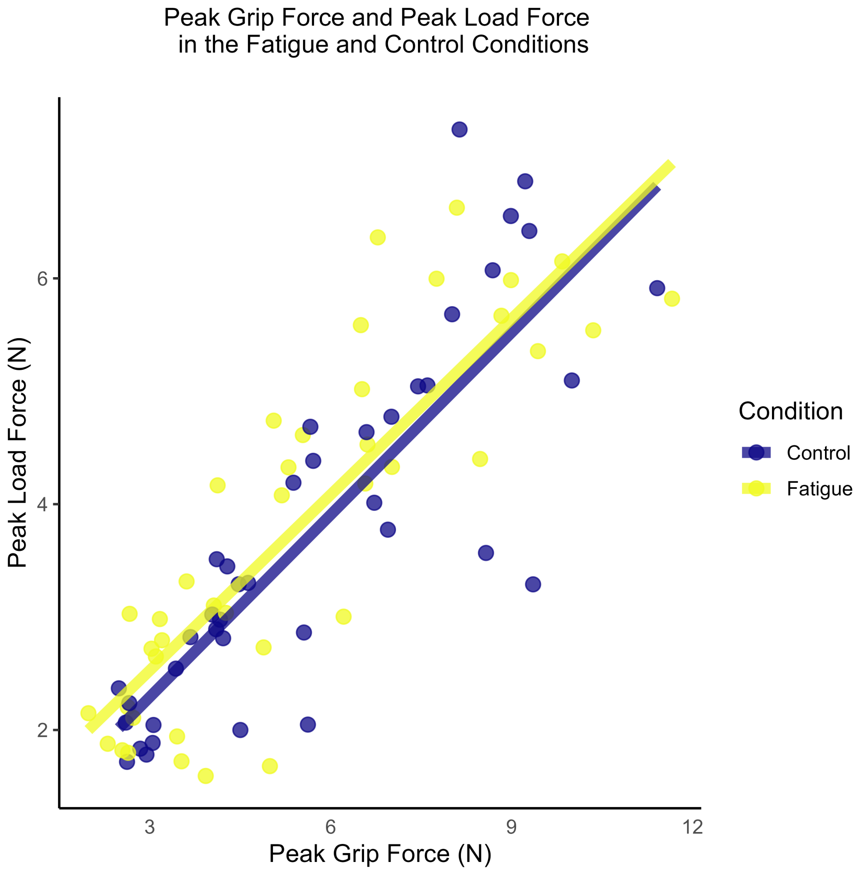


Figure 6.13: Peak Grip Force and Peak Load Force During Object Lifting in the Fatigue and Control Conditions (n = 10). Each dot shows the mean values applied by each participant for each of the four objects in both conditions. Coloured lines show the line of best fit for each condition.

Force matching task

The results of a Greenhouse-Geisser corrected factorial repeated measures ANOVA with mean force as the outcome variable, and condition (control/fatigue), feedback (vision/no vision), and time (8s-19s) as the predictors can be seen in Table 6.2. A significant main effect of time was found, as well as two significant two-way interactions between condition and time, and feedback and time. These were all superseded by a three-way interaction between condition, feedback, and time. This indicates that force production over time was affected differently by condition depending on the availability of visual feedback (Figure 6.14, Figure 6.15).

	Effect	*df*	*F*	η^2_{p}	*p*
1	Condition	1, 9	2.42	.212	.154
2	Feedback	1, 9	2.88	.243	.124
3	Time	11, 99	6.63	.424	$<$**.001**
4	Condition x Feedback	1, 9	3.08	.255	.113
5	Condition x Time	11, 99	2.62	.226	**.006**
6	Feedback x Time	11, 99	5.77	.391	$<$**.001**
7	Condition x Feedback x Time	11, 99	2.35	.207	**.013**

Table 6.2: Results of a Greenhouse-Geisser corrected factorial repeated measures ANOVA Investigating the Effects of Condition and Feedback on Mean Force Production Throughout the Force Matching Task. Bold ***p*** values are significant at the *p* < .05 level.

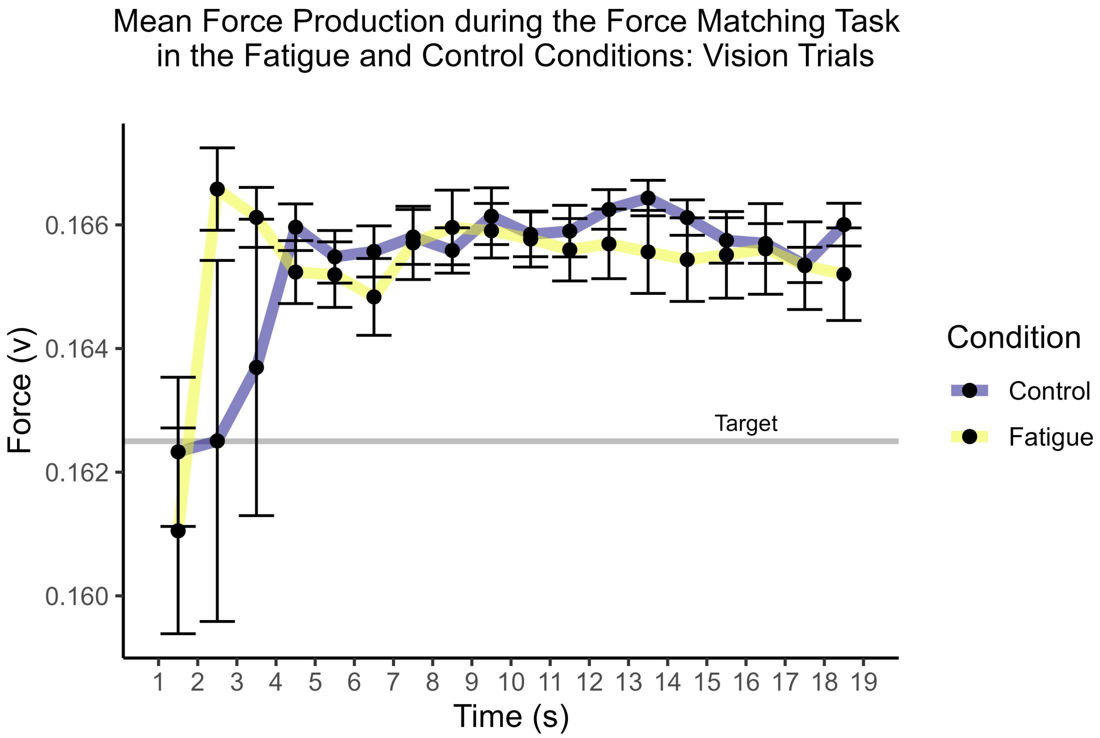
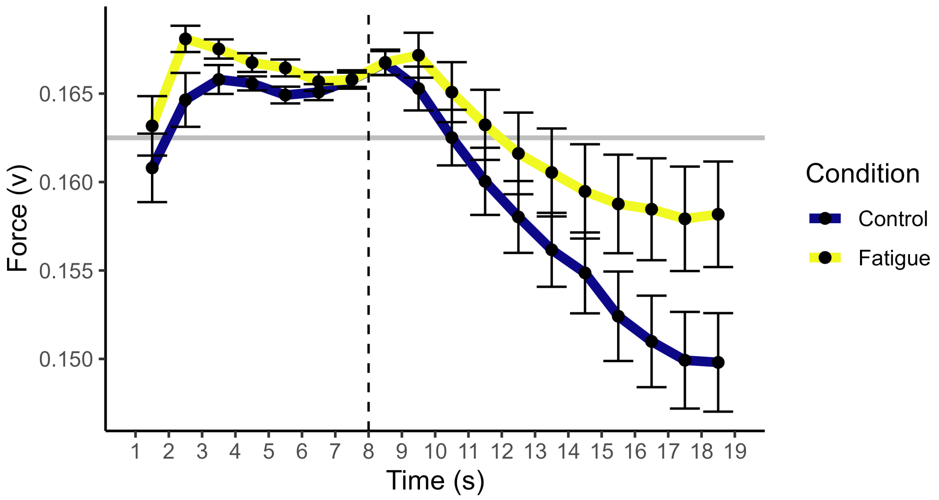
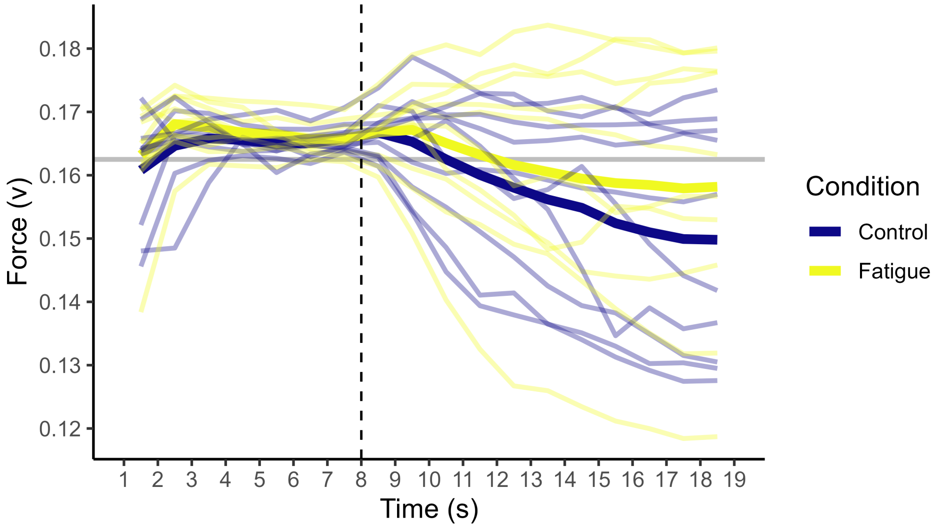


Figure 6.14: Mean Force Production During the Force Matching Task with Visual Feedback (n = 10). Top and bottom horizontal lines indicate the standard error, with the lines and black dots showing the mean.



a) Mean Force Production during the Force Matching Task in the Fatigue and Control Conditions: No-Vision Trials



b) Individuals' Mean Force Production during the Force Matching Task in the Fatigue and Control Conditions: No-Vision Trials

Figure 6.15: Mean Force Production During the Force Matching Task with Visual Feedback Disappearing at 8 Seconds (n = 10). In a) top and bottom black horizontal lines indicate the standard error, with the coloured lines and black dots showing the mean values. In b), each line is the mean force production of one individual in each condition, with the bolder darker lines indicating the overall mean for each condition.

The results of a Greenhouse-Geisser corrected factorial repeated measures ANOVA with root mean square error of force as the outcome variable, and condition (control/fatigue), feedback (vision/no vision), and time (8s-19s) as the predictors can be seen in Table 6.3. Significant main effects of feedback and time were found. These were superseded by a significant interaction between feedback and time, indicating that visual feedback affected the accuracy of force production over time (Figure 6.16, Figure 6.17). There were no other significant effects including no significant main effects or interactions with condition, indicating that mental fatigue did not affect performance in the force matching task.

	Effect	*df*	*F*	η_p^2	*p*
1	Condition	1, 9	0.43	.046	.528
2	Feedback	1, 9	19.73	.687	**.002**
3	Time	11, 99	12.31	.578	<**.001**
4	Condition x Feedback	1, 9	0.00	<.001	.946
5	Condition x Time	11, 99	0.37	.040	.965
6	Feedback x Time	11, 99	13.16	.594	<**.001**
7	Condition x Feedback x Time	11, 99	0.57	.059	.850

Table 6.3: Results of an ANOVA Investigating the Effects of Condition and Feedback on Root Mean Square Error of Force Production Throughout the Force Matching Task. Bold ***p*** values are significant at the *p* < .05 level.

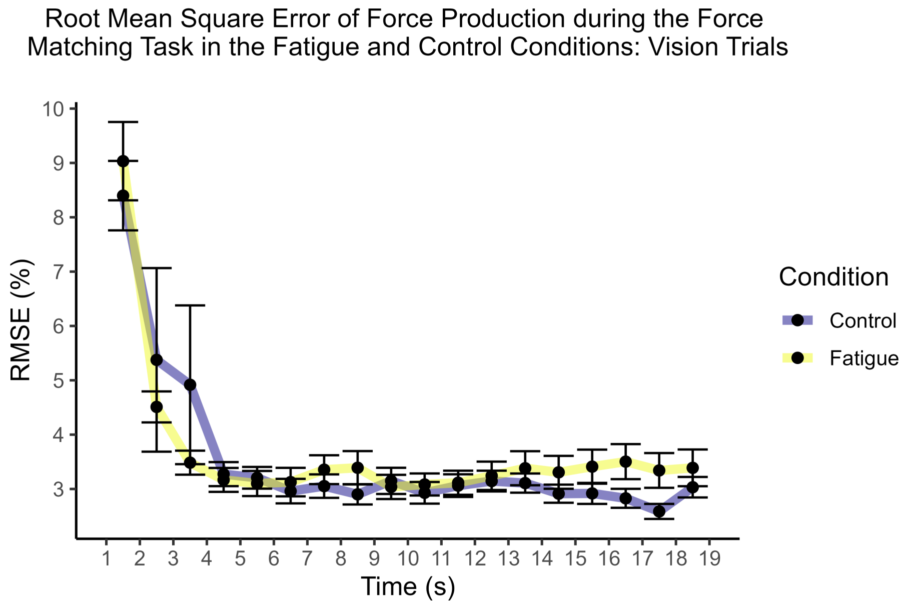


Figure 6.16: Root Mean Square Error of Force Production During the Force Matching Task with Visual Feedback (n = 10). Top and bottom horizontal lines indicate the standard error, with the lines and black dots showing the mean.

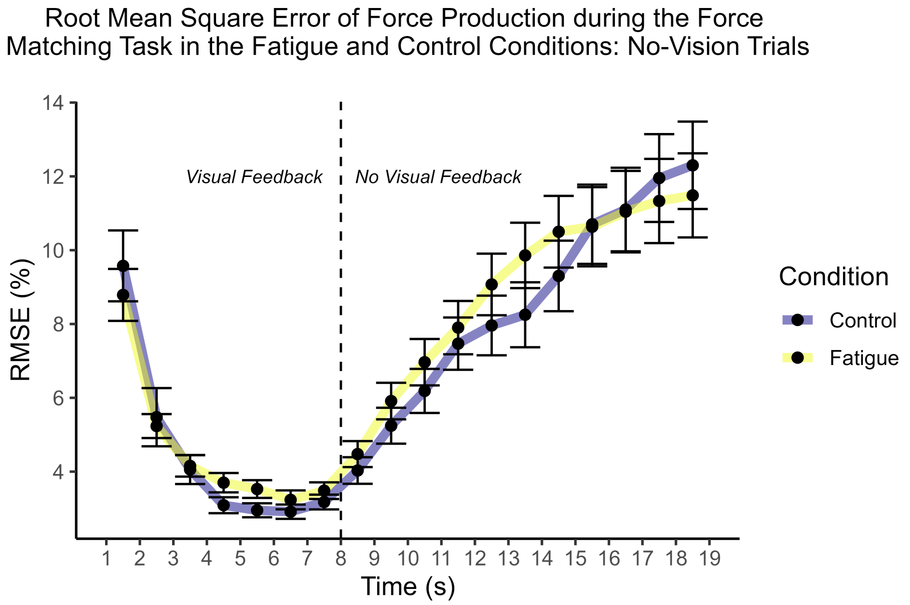


Figure 6.17: Root Mean Square Error of Force Production During the Force Matching Task with Visual Feedback Disappearing at 8 Seconds (n = 10). Top and bottom horizontal lines indicate the standard error, with the lines and black dots showing the mean.

A factorial repeated measures ANOVA with VAS ratings of task difficulty as the outcome variable and condition (control/fatigue) and feedback (vision/no vision) as the predictors found no significant effect of condition, F (1, 9) = 0.12, p = .735, η_p^2 = .01. There was, however, a significant main effect of feedback, F (1, 9) = 27.43, p <.001, η_p^2 = .75. The interaction between condition and feedback was not significant, F (1, 9) = 3.27, p = .104, η_p^2 = .27. Participants rated the no visual feedback trials of the force matching task as significantly more difficult than the trials where visual feedback was available throughout, with mean ratings of 3.25 ±.83 SD for the no vision trials and 2.45 ±.98 for the vision trials. Neuromuscular fatigue, however, did not affect participants' perception of task difficulty.

Subjective reports

To gain further insight into the subjective experience of physical fatigue in this study, and to allow comparison with participants' mental fatigue reports in Chapter 5, six additional paired Wilcoxon Signed Rank tests were performed. These examined the change in ratings of anger, confusion, depression, fatigue, tension, and vigour from before to after the control and fatigue tasks. The results of these tests are reported in Table 6.4. There were no significant differences in the changes in anger, confusion, depression, tension, or vigour between conditions. Fatigue, however, increased significantly more in the fatigue condition compared to in the control condition.

Subscale	Control	Fatigue	*z*	*p*	95% CI	*r*
Anger	0 (0)	0 (0)	-.32	.753	-4, 3.5	.1
Confusion	0 (0)	0 (0)	-.33	.739	-1, 1	.12
Depression	0 (.75)	0 (0)	-1.51	.131	-4, 2.5	.48
Fatigue	1.5 (1.75)	4.5 (3.75)	-2.15	**.015**	-6.5, -2	.68
Tension	0 (.75)	0 (1)	-.64	.523	-1.5, 2.5	.2
Vigour	-3.5 (2)	-2 (3.25)	-1.19	.233	-6.5, 2	.38

Table 6.4: Results of six paired Wilcoxon Signed Rank tests with change in BRUMS subscale score (calculated as post-pre) as the dependent variable and condition as the independent variable (n = 10). X (Y) denotes Mdn (IQR). Bold ***p*** values are significant at the *p* < .05 level.

To further investigate participants' perceptions of the control and fatigue tasks, five additional paired Wilcoxon Signed Rank tests were performed. These examined the difference in ratings of effort, frustration, mental demand, performance, and temporal demand for the control and fatigue tasks. The results of these tests are reported in Table 6.5. Along with rating the two-hour cycling bout as significantly more physically demanding than the control task, participants also reported that it was significantly more effortful, frustrating, mentally demanding, and temporally demanding. Participants reported that they felt they had performed similarly well at completing both the fatigue and control tasks.

Subscale	Control	Fatigue	*z*	*p*	95% CI	*r*
Effort	22.5 (25)	82.5 (13.75)	-2.7	**.007**	-75, -32.5	.85
Frustration	15 (7.5)	50 (27.5)	-2.14	**.032**	-47.5, -5	.68
Mental Demand	25 (15)	55 (18.75)	-2.35	**.019**	-45, -7.5	.74
Performance	85 (17.5)	77.5 (26.25)	.92	.36	-15, 50	.29
Physical Demand*	2.5 (8.75)	77.5 (17.5)	-2.81	**.005**	-80, -57.5	.89
Temporal Demand	5 (8.75)	25 (28.75)	-2.81	**.005**	-25, -12.5	.89

Table 6.5: Results of six paired Wilcoxon Signed Rank tests with TLX subscale score as the dependent variable and condition as the independent variable (n = 10). X (y) denotes Mdn (IQR). *as reported previously in subsubsection 6.1.3. Bold ***p*** values are significant at the *p* < .05 level.

6.1.4 Discussion

The manipulation checks indicate that participants experienced a physical demand from the two-hour cycling bout when compared to the documentary-watching control task. Participants reported an increase in perceived exertion throughout the cycling task, and experienced a decrease in maximum voluntary contraction. Together these results indicate that the cycling intervention was successful in inducing perceived fatigue, as well as successful in inducing some neuromuscular fatigue. The results of the manipulation checks were, however, somewhat mixed, as the control task appears to have also caused a reduction in pinch grip MVC despite not being rated as physically demanding. There was no interaction between condition and time point, indicating that the reduction in MVC was similar across the two tasks. Whilst a reduced MVC could be due to the progression of neuromuscular fatigue, it is unclear what the origin of a reduced MVC would be when a participant has not been physically challenged. Thus, while the cycling task reduced participants' MVC as would be expected if they were experiencing neuromuscular fatigue, this was not distinguishable from the decrease in MVC when participants had not undergone a fatiguing intervention and were not experiencing neuromuscular fatigue. Nonetheless, exercise in the heavy-intensity domain has previously been found to affect multiple parameters of fatigue (Black et al., 2017; Clark, Goulding, et al., 2018; Clark, Vanhatalo, Thompson, Wylie, et al., 2019; Clark, Vanhatalo, et al., 2018), it is highly unlikely that participants would not be fatigued following two hours of heavy-intensity cycling, and the ratings of perceived exertion and ratings of physical demand support this. To further investigate possible origins of participants' reduced MVC in the control condition, and to compare the results of this study to those in Chapter 5 the BRUMS subscale results were analysed further.

This study is the most comprehensive investigation to date into the possible effects of neuromuscular fatigue on dexterity, with three tasks giving an insight into different aspects of dexterity. In agreement with Duncan et al.'s (2015) findings that neuromuscular fatigue did not affect two different dexterity tasks, there were no significant effects of neuromuscular fatigue on performance in any of the Purdue Pegboard Test subtests. Participants were able to successfully execute the subtests to the same level when they were fatigued as when they were not fatigued. Practice effects were also preserved, as participants' performance increased across repeats of each subtest to the same extent regardless of whether they were fatigued or not. This indicates that the human sensorimotor system is able to compensate for any possible effects of neuromuscular fatigue at this broad behavioural level, maintaining performance even when there may be disruption e.g. to feedforward or feedback processes, or muscular control.

Neuromuscular fatigue appears to have affected participants' perceptions of object weight in the object lifting task. Participants' ability to correctly distinguish real differences in object weight relating to size throughout the task was intact. After the fatigue intervention, however, participants erroneously report that objects felt overall significantly heavier compared to in the control condition. This contrasts with the findings of Burgess and Jones (1997), who reported that fatigue resulted in increased perceptions of effort when lifting objects, but that this was dissociable from perceptions of object weight. In the present study, participants may have conflated effort and weight when lifting the objects, resulting in increased object weight reports. There are numerous methodological differences between this study and that of Burgess and Jones (1997) which could contribute to these different findings. Burgess and Jones (1997), used repeated arm contractions to induce localised fatigued in the lifting limb, used a pulley system to lift the objects, and also explicitly asked participants to rate both effort and weight. This is in contrast with the methods here which used cardiovascular cycling exercise to induce both central and peripheral fatigue, had participants lift objects in a naturalistic way, and only asked participants to rate object weight. Participants between the two studies likely experienced different sensations from the different methods of inducing fatigue, and also experienced different experimenter demands. These differences are likely responsible for the different outcomes between this study and that of Burgess and Jones (1997). The analyses of pGFR and pLFR in the first lift of the object show that fatigued participants did not initially predict that objects would be heavier, as there were no differences in pGFR and pLFR between conditions. There is therefore a dissociation between predictive grip behaviour and perception of object weight. This is a well-established dissociation (Flanagan & Beltzner, 2000; Grandy & Westwood, 2006).

When looking at peak force *magnitudes* as opposed to *rates*, some differences did emerge. Participants' behaviour was broadly normal in both conditions, with the timings of peak grip and load forces being highly correlated. There were nonetheless subtle but significant differences in participants' grip-load force coupling between conditions, with the timing of participants' grip forces being comparatively earlier than load forces when they were fatigued compared to when they were not fatigued. This could reflect a disruption in coordination between grip and load forces, possibly due to disruptions to feedforward planning, or could be due to participants taking a more cautious approach when fatigued, choosing to steadily grip objects more before lifting them.

The ratio between the magnitudes of grip and load forces was also different when participants were fatigued. Compared to when they were not fatigued, fatigued participants used significantly greater load forces to move objects upwards in comparison to the grip forces that they used to securely grasp the objects. As the force magnitude data includes data from all object lifts, this may reflect a change in feedforward behaviour from participants as a consequence of perceiving the objects to be heavier: on perceiving apparently heavier weights, participants increased the amount of force they applied to lift the objects upwards. This may also explain the differences in timings between conditions: if participants applied load force at a similar rate across conditions but chose to apply more load force when they were fatigued, then it would take longer for them to reach the peak magnitude of load force when they were fatigued, and if they did not also alter their grip force behaviour then the timing between load and grip force would be less closely coupled. Together, the findings from the object lifting task show a complex interplay between feedforward, predictive processes and feedback, perceptually-driven processes.

There were mixed effects of neuromuscular fatigue on the magnitude and accuracy of participants' force production in the force matching task. With regards to the magnitude of participants' force production, a significant three-way interaction was found between condition, availability of visual feedback, and time course. Underlying this significant three-way interaction are two different patterns of performance based on condition and visual feedback. When visual feedback was available throughout the entirety of the trial, participants' mean force production settled at around .166V and this was maintained until the end of the trial. This pattern was the same regardless of condition. When visual feedback disappeared partway through the trial, participants' mean force production significantly reduced over time - a common finding in prior literature (e.g. Neely et al., 2017). As time went on, however, participants' mean force production differed significantly depending on whether they were fatigued or not, with participants' mean force production remaining higher over time when fatigued than when they were not fatigued. This pattern of behaviour is similar to the behaviour shown by older adults in Neely et al. (2017). As the force matching task relies on integrating cutaneous feedback and memory during the non-visual portion of the trial, and as older adults' memory and cutaneous feedback is impaired, this indicates that participants' sensory perception and memory may be affected by neuromuscular fatigue. Considering accuracy, the results showed that participants were significantly less accurate when no visual feedback was available, and that their accuracy progressively declined throughout the time when there was no visual feedback. Accuracy was not significantly affected by condition, however, and there were no significant interactions with condition. In line with the poorer performance in the no visual feedback trials, participants reported these trials as significantly more effortful than the trials where there was visual feedback throughout. These ratings of effort did not differ when participants were fatigued compared to when they were not fatigued.

Subjective reports of participants' mood revealed significant differences only in the BRUMS fatigue subscale. Participants reported significantly greater increases in fatigue from the fatiguing intervention than from the control task. There was, however, still a small increase in subjective reports of fatigue from the control task. As discussed in Chapter 5, the control task appears to have elicited a variety of emotional responses in participants, and this small increase in subjective fatigue may represent a flaw of the control task. Similarly, there was no significant difference between the decrease in vigour from the fatigue and control tasks. In fact, the decrease in vigour from the control task was greater than the decrease in vigour from the two-hour cycling bout. This is perhaps surprising as the two-hour cycling bout was rated as significantly more physically demanding than the control task. This may again reflect the fact that the control task selected was not optimal for maintaining a neutral mood. The NASA-TLX findings showed that participants rated the fatigue intervention as significantly more effortful, frustrating, mentally demanding, physically demanding, and temporally demanding. Participants did not, however, rate their performance significantly differently between the two conditions. This is perhaps due to the unusual question being asked of participants with regards to this measure in the control task - "How well did you perform at watching the two-hour documentary" - which is difficult to evaluate in a lab-based experiments where, unless they choose to withdraw from the study, participants have little choice other than to sit and watch the documentary. Altogether, the NASA-TLX results indicate that the fatiguing intervention was demanding in many ways, as well as moderately frustrating. This is the first study to investigate the subjective experience of completing this type of heavy-intensity endurance exercise bout. This could be useful information for researchers who are interested in measuring performance outcomes in these kinds of tasks, as it gives an insight into how fatigue affects perception of success, and how this subjective perception may affect subsequent or concurrent tasks.

Limitations

The current study had numerous limitations with regards to the sample size and characteristics. The sample was relatively small, possibly resulting in low statistical power for some of the analyses. This means that where smaller effects may be present in the results, our sample may not have sufficient power to detect those effects. Finally, the focus of this research was in a younger group comprising mostly females. The current findings therefore have limited applications for the general population. Future researchers could improve on these limitations by increasing sample size, and could consider recruiting more males and older adults to improve the generalisability of findings and investigate whether sex and age affect the impacts of fatigue on dexterity.

In this study, there were no significant differences between participants' Purdue Pegboard Test performance when they were fatigued compared to when they were not fatigued. Visual inspection of the results, however, shows that participants generally scored lower in the Purdue Pegboard Test when they were fatigued compared to when they were not fatigued. This indicates that there may have been a Type II error relating to the statistical power being too low to detect a real effect. The results, however, are consistent with those of Budini et al. (2022), who also used a pegboard test to measure dexterity.

The lack of difference between the change in vigour from the control and fatigue tasks indicates that the documentary-watching control is unsuitable as a neutral control, as it creates a similar decrease in vigour as a fatiguing heavy-intensity cycling task. Future research could improve on the current study by using an alternative control task that is shown to maintain vigour.

6.2 Conclusions

This study suggests that neuromuscular fatigue does not affect successful execution of dextrous tasks. Participants were able to complete complex dextrous tasks as well as lift objects naturally without any major disruption to these processes. There were, however, subtle changes in perception, grip, and load force behaviours, that indicate there was some disturbance to some of the processes which underlie dextrous manipulation. This indicates that the sensorimotor system is capable of adapting to changes elicited by neuromuscular fatigue, allowing movements to remain safe and effective, with minimal perceived disruption.

Chapter 7: General Discussion

7.1 Thesis aims and key findings

Fatigue is a commonplace experience in everyday life, but its effects on dexterity remain largely unknown. The aim of this work was to discover how transient mental and neuromuscular fatigue affect dexterity in healthy adults. Chapter 3 comprises pilot work which explored and investigated the effects of existing mental fatigue paradigms on dexterity and related outcomes. In Chapter 4, a novel method for inducing mental fatigue was developed and participants' subjective and behavioural responses to the task were investigated in-depth to characterise the nature of the mental fatigue that had been induced and to validate the protocol. Chapter 5 subsequently used this novel task to induce mental fatigue, with the effects of mental fatigue then investigated using a battery of tasks which allow an insight into both broad performance and lower-level sensorimotor processes. Finally, Chapter 6 induced neuromuscular fatigue using a well-validated protocol, and investigated the effects of neuromuscular fatigue on the same battery of dexterity tasks used in Chapter 5.

Chapter 3 trialled existing mental fatigue protocols and investigated their effects on dexterity. Whilst prior research had identified some possible effects of mental fatigue on dexterity and other performance outcomes such as physical endurance, the replicability of these results, as well as the merits and limitations of different existing approaches to inducing mental fatigue, were unclear. It was also unclear how best to assess the efficacy of different methods used to induce mental fatigue. Consequently, three different methods to induce mental fatigue were explored and examined in a sequential-task paradigm. Study 1 used a total of one hour of the stroop and n-back tasks to induce mental fatigue, and explored its effects on accuracy and duration in a submaximal grip endurance task. Study 2 used a ten-minute letter-crossing task and examined the perceptual and behavioural effects of mental fatigue on an object lifting task. Study 3 used a 40-minute mental rotation task to induce mental fatigue and closely examined the subjective effects, as well as the behavioural effects on a subsequent cognitive task task. All three approaches to inducing mental fatigue examined in Chapter 3 had no effect on subsequent tasks. Following mental fatigue interventions, participants in study 1 did not have poorer or more variable performance in an endurance hand-grip task, and participants in study 2 did not show behavioural or perceptual differences whilst lifting objects. The absence of differences from mental fatigue may have been due to a failure of the manipulation, but thorough manipulation checks were not conducted to determine whether mental fatigue had been successfully induced. In study 3, which focused on mental fatigue development, reports of perceived exertion were taken as a subjective indicator of mental fatigue, and behavioural performance in a subsequent cognitive task (the AX-CPT) as an objective indicator of mental fatigue. Whilst participants' RPE did significantly increase from before to after the mental fatigue intervention, participants' performance in the AX-CPT did not significantly decrease. At the individual level, multiple participants in study 3 showed improvements in performance on the AX-CPT.

The findings from Chapter 3 raised doubts as to the efficacy of existing paradigms for inducing mental fatigue for two reasons. Firstly, there is a lack of insight into the nature of mental fatigue induced by these paradigms. In comparison with expectations, study 1 found an improvement in participants' performance in the mental fatigue intervention over time, with no insight into participants' subjective experiences. Participants' improvement in performance in study 1 may be due to their exerting additional effort, which could cause mental fatigue to manifest, or their increased performance could be due to a learning effect which would not necessarily subjectively manifest in the same way. In study 2, there were no manipulation checks regarding the mental fatigue manipulation and no other measures indicating that participants were experiencing mental fatigue or any other subjective effects from the manipulation. Study 3 used a simple measure of mental fatigue in the form of an RPE scale, which was not validated. The RPE scale also does not give an insight into other emotional aspects of mental fatigue whereas other measures, such as the BRUMS, can give such an insight. As well as these issues, Chapter 3 raised doubt around the unclear implications of the variations in the duration and type of tasks which are used to induce mental fatigue (Holgado et al., 2020; MacMahon et al., 2021). The work in Chapter 3 therefore found that tasks which are used to induce mental fatigue need to be more thoroughly developed so that researchers can be more certain that they are inducing the intended type of mental fatigue in participants, and need to carefully consider the duration and type of task(s) used to induce mental fatigue.

Consequently, in Chapter 4, a novel battery for inducing mental fatigue was developed and validated to address the uncertainties raised in Chapter 3 and facilitate an experimental approach to investigating the effects of mental fatigue on dexterity. This battery aimed to address the limitations of existing paradigms discovered during the work described in Chapter 3, and to gain a more thorough understanding of the mental fatigue induced by the task. To achieve this, a two-hour battery comprising multiple tasks with different cognitive demands was developed. Participants' subjective state and cognitive task performance from before to after the battery were examined in-depth. The novel battery developed was found to be successful at eliciting mental fatigue as characterised by an increase in subjective feelings of fatigue and a performance decrement in a subsequent cognitive task. The outcomes and their relationship were closely examined at both the group and individual level to gain a comprehensive understanding of the mental fatigue elicited by the cognitive task battery. Whilst Chapter 4 found significant changes in subjective perception of fatigue and cognitive performance at the group level, the findings at the individual level were more variable: cognitive performance in the cognitive task improved for approximately 1/3rd of participants, becoming worse for the remaining 2/3rds.

There are many possible reasons for the variance in cognitive task performance found in Chapter 4. For example, it is well established that ageing results in changes in cognition (Anderson & Craik, 2017), and prior research has found that older adults report cognitive tasks as less tiring than younger adults (Dahm et al., 2011), both of which could result in differing task performance over time. A variety of other individual characteristics such as physical fitness, experience at self-regulation tasks, and mental toughness have also been identified as potential moderators for the effects of mental fatigue on other tasks (Habay et al., 2023). Alternatively, differences in performance may relate to external factors such as the environment in which the task is performed - in an online-based study, participants may be taking part whilst sitting alone in a quiet room, or may be in a shared room with other individuals contributing to environmental noise levels that prove distracting. This finding demonstrated the difficulty in inducing and studying mental fatigue in groups of individuals. There may be uncontrolled factors with unknown effects on the outcomes of research, and these are not always considered in research looking to understand the possible effects of mental fatigue (Hassan et al., 2023). This is especially important to consider as no significant association has been found between behavioural performance and subjective reports of fatigue, meaning that researchers cannot use either of these measures as a proxy for the other. In addition to individual differences in changes in behavioural performance, Chapter 4 found that participants' changes in emotional state were highly varied across various different factors. Participants' experiences of changes in anger, confusion, tension, depression were also highly varied, again with unknown implications for mental fatigue (O'Keeffe et al., 2020).

As the novel method caused an increase in subjective mental fatigue and a behavioural performance decrement in the majority of participants it was deemed suitable for use in examining the effects of mental fatigue on dexterity. The key findings of Chapter 4 relating to individual variability and possible extraneous factors were, however, carefully considered in Chapter 5, which used a similar approach to characterising mental fatigue so as to understand any possible impacts of individual variability in responses to the fatiguing cognitive task battery. Chapter 5's analysis of the subjective and behavioural indicators of mental fatigue had similar findings to Chapter 4: participants' reports of mental fatigue were consistently elevated from before to after the battery, but performance in the battery itself was subject to a greater variety of responses. The additional NASA-TLX ratings in Chapter 5 extended the subjective findings of Chapter 4. Participants reported that they did not only experience increases in fatigue as reported in the BRUMS, but also reported that they perceived the mental fatigue battery as being more mentally demanding than the control task, as well as being more physically and temporally demanding. Participants also reported that their performance in the mental fatigue battery was poorer than for the control task. These findings of Chapter 5 support the notion that mental fatigue and mood change may be interrelated, as discussed in Chapter 4. This again highlights the complexity and challenges of researching mental fatigue.

The key findings on the effects of mental fatigue on dexterity from Chapter 5 considerably enhance and extend prior research. At the time that this study was designed, there was no prior research which took an experimental approach to inducing mental fatigue and investigated its effects on a battery of tasks designed to assess fine manual behaviours. The methods were therefore developed within the constraints outlined in Chapter 2. Participants' performance in the Purdue Pegboard Test showed that the effects of mental fatigue appear to be highly specific, with mental fatigue resulting in poorer initial performance following a task-switch to a dexterity task from a cognitive task. Mental fatigue did not result in poorer performance when task-switching between different subtests, however, despite the fact that there were some task differences which could have placed additional cognitive demand on participants. The assembly task, for example, uses both hands, multiple different types of item, and has specific rules on how each hand must be used and what sequence must be followed. This indicates that mental fatigue's effects on dexterity could be mediated through specific cognitive effects, such as through an interaction with additional cognitive task demands arising from task-switching between two dissimilar tasks (Hinss et al., 2023). Task-switching was not the only cognitive demand that the Purdue Pegboard Test placed on participants. The results indicated that participants experienced a learning effect throughout the repeated trials, and it is unclear how this may have affected the test outcomes.

The object lifting task findings in Chapter 5 indicated that mental fatigue also has specific rather than general effects on the forces used during object lifting. The force rates used during the initial lifts of objects in the object lifting task were not significantly different between conditions, with participants retaining the ability to predictively scale their forces appropriately for the size of the object they were lifting when they were mentally fatigued. The ratio of different forces used during the object lifts was also the same regardless of whether participants were fatigued or not, and was in line with what has been previously established as normal lifting behaviour. Participants' perception of object weight was also found to be unaffected by mental fatigue, with participants reporting objects as being similarly heavy in both conditions. Whilst the force rates and magnitudes were similar between conditions, the results showed that the timing of forces was less closely coupled in the mental fatigue condition than in the control condition, indicating that temporal coordination is affected by mental fatigue. Together, these imply that the effects of mental fatigue on dexterity are not general. Feedforward or predictive behaviours appear to be unaffected, whilst high-level cognitive processes such as temporal coordination appear to be altered. This is the first study to find that mental fatigue may affect dexterity by impacting the cognitive processes involved in dextrous tasks.

Whilst force control was affected to a limited extent in the object lifting task, no effects of mental fatigue were found on the conscious control of fingertip forces in the force matching task. In line with prior research (Budini et al., 2022), mental fatigue did not affect the accuracy or variability of force production. Participants' performance was similar between the mental fatigue and control conditions, even when visual feedback about force was removed. This indicates that the ability to use visual and cutaneous sensory feedback to consciously control fingertip force to match a specific level is not affected by mental fatigue. Despite the apparent interaction between mental fatigue and the cognitive demands of dexterity tasks found in the results from the Purdue Pegboard Test and object lifting task, participants' performance in the force matching task was the same between conditions even when the visual feedback was removed and participants reported the task as more demanding.

Overall, the findings from Chapter 5 suggest that there may be specific aspects of dexterity which are sensitive to the effects of mental fatigue, and that the mediator could be mental fatigue's effects on cognitive processes. Throughout all three dexterity tasks, the effects of mental fatigue were limited to specific processes such as coordination and task-switching. When participants were mentally fatigued, they were able to assemble items, lift objects, and consciously control their fingertip forces similarly to when they were not fatigued, even though the underlying cognitive processes appeared to be affected. Differences in participants' subjective and behavioural indicators of metal fatigue were, however, identified. It is possible that where mental fatigue manifests differently in different individuals, the behavioural effects of mental fatigue on subsequent dexterity tasks could vary, and so the broad pattern of results here may not be generalisable to all individuals even where they emerge at the group level.

Chapter 6 was the first to examine the effects of neuromuscular fatigue induced through heavy-intensity endurance exercise on dexterity. To facilitate comparison between mental and neuromuscular fatigue, participants completed the same dexterity tasks as in Chapter 5. Prior research which induces neuromuscular fatigue in an experimental setting has typically investigated outcomes relating to sports performance, with limited evidence for how neuromuscular fatigue may affect fine dextrous movements. This paucity of prior research meant that there were a number of methodological challenges that needed to be addressed, and decisions on how to address these had to be made under numerous constraints as outlined in Chapter 2. Nonetheless, an approach was identified which would develop current understanding as well as facilitating iterative development of the methods and findings in future research. Chapter 6 found that Purdue Pegboard Test performance was similar between conditions. When participants were fatigued, they placed similar numbers of items to when they were not fatigued in all subtests. It therefore appears that, similarly to mental fatigue, neuromuscular fatigue does not affect dexterity at the broad behavioural level. As with mental fatigue, however, neuromuscular fatigue appeared to have some more specific effects on the control of fingertip forces during the object lifting and force matching tasks, and on perception.

The first effect of neuromuscular fatigue on dexterity that was identified in Chapter 6 was that fatigue resulted in a dissociation between perception and sensorimotor prediction. This was identified during the object lifting task, which found that the rate at which participants applied grip and load forces during their first lifts of objects was the same in both conditions. That is, participants' sensorimotor predictions about object weight were stable regardless of whether they were fatigued or not. Their perceptions, however, were not stable between conditions. When participants were fatigued, they reported that objects were heavier. This resulted in a dissociation between perception and sensorimotor prediction in the fatigue condition only. Perceptual/motor dissociations have been found in prior research using perceptual illusions and clinical populations (Flanagan & Beltzner, 2000; Grandy & Westwood, 2006), but this is the first study to find an apparent dissociation resulting from neuromuscular fatigue.

As well as the apparent perceptual/motor dissociation during object lifting in fatigued participants, the results in Chapter 6 indicated that the relationship between force timing and magnitudes was affected by neuromuscular fatigue. The time at which participants reached peak grip and load force was less closely coupled between the fatigue and control conditions, with fatigued participants taking comparatively longer to reach their peak load force magnitude following reaching peak grip force. When fatigued, participants also used significantly greater load force in relation to grip force. Taken together, the object lifting results in Chapter 6 suggest that participants' feedforward predictions about object weight did not differ between conditions (Flanagan & Johansson, 2002). When fatigued participants lifted the objects and erroneously perceived that they were heavier, however, they subsequently applied more load force during the lift, which took more time, resulting in less temporal coordination between load and grip force. These key findings imply that neuromuscular fatigue does not affect participants' initial feedforward predictions, but instead may affect perceptual feedback which can subsequently affect feedforward processes.

The effects of neuromuscular fatigue on force control found in Chapter 6 were not limited to the object lifting task. Neuromuscular fatigue also affected participants' conscious control of fingertip forces. When participants were fatigued and visual feedback about their force production was removed, they maintained their level of force for longer than when they were not fatigued. Participants' force variability and visual force matching task performance was otherwise no different between the fatigue and control conditions. Fatigued participants' behaviour with no visual feedback is similar to older adults' behaviour, and this has previously been attributed to differences in cutaneous sensory feedback and memory that are associated with age (Neely et al., 2017). Neuromuscular fatigue may therefore affect cutaneous sensation or memory in younger adults, or the outcome may be related to conscious or subconscious changes in strategy (e.g. a perception that they feel more weak, so disregarding cutaneous feedback to squeeze harder than they feel they need to).

Overall, the findings from Chapter 6 indicate that, similar to mental fatigue, the effects of neuromuscular fatigue on dexterity may be task-specific. Throughout all three dexterity tasks, the effects of neuromuscular fatigue were limited to temporal coordination, sensory perception, and subsequent feedforward processes. Initial feedforward predictive processes during object lifting as well as general performance in the object lifting task were apparently unaffected. Participants' ability to successfully execute dextrous tasks therefore appears to be preserved even when they are experiencing fatigue. It is unclear how replicable or generalisable these findings may be, particularly as additional methodological limitations were identified during the research process (as discussed further in Limitations).

There were some key differences between the findings in Chapter 5 and Chapter 6 that give an insight into the underlying mechanisms for these apparent effects of mental and neuromuscular fatigue on different aspects of dexterity. In the Purdue Pegboard Test, neuromuscular fatigue had no significant effects on performance. There were, however, significant effects of mental fatigue on initial performance in the Purdue Pegboard Test. This supports the premise that the effects of mental fatigue are related to cognition as opposed to another process that is common between the different types of fatigue, such as disruption to central nervous system transmission. The perceptual differences in the object lifting task that were found in Chapter 6 were also not present in Chapter 5, which indicates that these differences are specific to a change that occurs from neuromuscular fatigue such as a change in sensory feedback, as opposed to being from a more general effect that was present in both types of fatigue such as feeling more tired. As well as perceptual differences, Chapter 6 found that neuromuscular fatigue affected the ratio between grip and load forces used to lift objects, whereas this was not the case with mental fatigue in Chapter 5. As discussed previously, it is possible that there is a relationship between the increased perception of object weight and the comparatively increased load force used to lift objects in the neuromuscular fatigue condition. The fact that these outcomes were found together in the neuromuscular fatigue study but were both absent in the mental fatigue study supports that they may be interrelated, and that they are specific to an underlying change that occurs with neuromuscular fatigue development. The final key difference identified between the effects of mental and neuromuscular fatigue was that neuromuscular fatigue affected force production during the no visual feedback version of the force matching task, whilst mental fatigue did not. Similarly to the object lifting outcomes, this may also relate to alterations in sensory perception from neuromuscular fatigue, as in prior research, similar findings have been related to differences in cutaneous sensation. There was no such effect in Chapter 5, indicating that mental fatigue does not affect sensory processes in the same way.

There were also similar findings between the mental and neuromuscular fatigue studies, but these may be due to different mechanisms. Temporal coordination of grip and load force was affected in both Chapter 5 and Chapter 6, although this may be for different reasons. In Chapter 6, the differences in temporal coordination between the neuromuscular fatigue and control conditions were present alongside differences in perception and force ratios. As discussed in Chapter 6, these results appear to be interrelated, with neuromuscular fatigue resulting in a chain of events where, on perceiving apparently heavier weights, participants increased the amount of force they applied to lift the objects upwards but used the same force rates as they had in the control condition, resulting in it taking longer for them to reach their peak load force magnitude, and so decreasing the temporal coupling between grip and load force. Whilst a difference in temporal coordination between the mental fatigue and control conditions was found in Chapter 5, there were no significant differences found in perception and force ratios. The underlying cause of the difference in temporal coordination therefore must be different for mental fatigue than it is for neuromuscular fatigue. Given that mental fatigue affects cognition, it is likely that the effects of mental fatigue on temporal coordination that were found in Chapter 5 are of a cognitive origin.

In summary, Chapter 3 found that mental fatigue research is challenging due to the heterogeneity of methods and outcomes in the extant literature (Holgado et al., 2020). Carefully examining participants' subjective and behavioural responses to tasks designed to induce mental fatigue is a critical step that researchers should not neglect when examining mental fatigue and its effects (M. R. Smith et al., 2019). The novel approach developed in Chapter 4 addresses some of these limitations in the extant research and demonstrates how individual responses by participants can be examined and accounted for at the group and individual levels. Chapters 5 and 6 found that both mental and neuromuscular fatigue affect dexterity, but that these effects are task-specific. The effects of mental fatigue on dexterity appear to be due to fatigue's effects on cognitive processes, with mental fatigue affecting temporal coordination and task-switching. Neuromuscular fatigue did not affect task-switching, but did affect temporal coordination and sensory perception, and this appears to be related to alterations in sensory processing. Notably, the research described in this thesis is some of the earliest research in an undeveloped area. At the time of study design there was therefore little extant research which could be used to guide methodological decision-making. Consequently, it became clear as the research developed that there are a number of challenges with inducing both mental and neuromuscular fatigue in an experimental setting, many of which appear to relate to participants' individual differences. This may have added variability to participants' behaviour in the dexterity tasks which was not accounted for in the study design.

7.2 Implications

The findings of Chapters 3 and 4 indicate that existing mental fatigue research is subject to some flawed methodological approaches. Pre-existing mental fatigue paradigms are often unvalidated for use as mental fatigue protocols (with some exceptions such as the TLoadDBack (O'Keeffe et al., 2020)), having originally been developed to understand cognition (e.g. Stroop, 1935). Research often does not carefully consider whether mental fatigue is manifesting as expected or intended, often relying on subjective measures. For research which examines the effects of mental fatigue on concurrent or subsequent tasks, using ineffective methodological approaches to induce mental fatigue and not properly assessing the outcomes of these approaches in participants' experience and behaviour could result in spurious outcomes (Holgado et al., 2020).

The examination of performance at the individual as well as the group levels in Chapters 3 and 4 demonstrates the importance of considering individual differences in mental fatigue research. Where there are individual differences in mental fatigue outcomes - whether due to individuals' state or trait differences - researchers are not inducing similar subjective or cognitive states between different participants. This may explain some of the heterogeneity which other researchers have found in the literature (Holgado et al., 2020).

Chapters 4 and 5 found that there is a wide range of emotional responses to mental fatigue, with participants also reporting different demands from a mental fatigue battery in comparison to a control task. Overall, these outcomes point to mental fatigue being an emotional state (O'Keeffe et al., 2020) as much as one of tiredness or lack of energy (Marcora et al., 2009). This has interesting possible implications for researchers interested in mental fatigue, as many do not examine or control for the possible effects of emotional state or perceived task demands. Participants who report greater emotional responses to a mental fatigue task may manifest mental fatigue differently to those who do not, and vice versa. Different emotions could also have unknown effects on subsequent tasks depending on the demands of those tasks, with anxiety, for example, having been shown to affect responses in a go/no-go test (Grillon et al., 2017).

The results in Chapter 5 indicate that the effects of mental fatigue on dexterity could be mediated through the cognitive processes required in the dextrous tasks, with mental fatigue's effect on Purdue Pegboard Test performance limited to trials where participants had switched to the test from a dissimilar task. This implies that researchers interested in mental fatigue and its possible effects on other outcomes should consider focusing on tasks or outcomes which have an established cognitive component. This is in agreement with prior research which has found that the effects of mental fatigue are specific to complex movements which have a cognitive component (Halperin et al., 2015; M. R. Smith et al., 2016), or on endurance exercise which requires cognitive control of effort (Marcora et al., 2009; Pageaux et al., 2015; Van Cutsem et al., 2017; though see also Clark, Goulding, et al., 2018; Holgado et al., 2023). This apparent task-specificity may partly explain the heterogeneity in the current literature (Holgado et al., 2020).

Similar to Chapter 5, Chapter 6 indicated that the effects of neuromuscular fatigue on dexterity are task-specific and could be mediated through specific processes e.g. by affecting perception. It is well-established in the physiology literature that fatigue development is highly task-specific (Burnley & Jones, 2018; Burnley et al., 2012; Poole et al., 2016), and so it is unsurprising that the subsequent effects of fatigue appear to be similarly task-specific. The neuromuscular fatigue protocol used in Chapter 6 was chosen to target central fatigue development, with similar protocols found to affect central mechanisms (Black et al., 2017; Clark, Goulding, et al., 2018). The task outcomes suggest that this specific type of fatigue can affect dexterity through its impact on central nervous system functions such as perceptual feedback processes, sensorimotor integration, and/or propagation of signals from the sensorimotor cortex. These findings imply that the motor system's susceptibility to fatigue is highly related to the type of fatigue that has developed - the apparent disturbances in dexterity caused by fatigue were all linked to central mechanisms. If participants had exercised at a different intensity - leading to differences in central fatigue development - or using an upper-limb task - leading to differences in peripheral fatigue development - the patterns of behaviour in the dexterity tasks would perhaps have differed, as the types of fatigue that had developed would challenge the sensorimotor system differently.

The object lifting results in Chapter 6 indicated both a dissociation and a possible relationship between the perceptual and sensorimotor processes underpinning object interaction. Fatigued participants perceived objects as heavier than when they were not fatigued, but did not use different force rates between conditions. As force rates are a measure of prediction (Flanagan & Johansson, 2002; Hermsdörfer et al., 2011), this indicates that prediction was not affected by participants' general perception that the objects were heavier. Whilst participants' force *rates* were not affected by fatigue, participants used higher load force *magnitudes* to lift objects when they were fatigued and took longer to reach their peak load force magnitude. As force magnitudes are updated during the lift in a reactive manner based on sensory feedback (Buckingham & Goodale, 2010; Scott, 2012), this indicates that the perception that objects were heavier is what mediated this behaviour.

The apparent relationship in Chapter 6 between perception and some behavioural aspects of object lifting emphasises the importance of concurrently investigating both subjective and objective measures in fatigue of all types (see also Behrens et al., 2022). The interaction during object lifting between conscious perception of object weight and altered sensory feedback has, in Chapter 6, given rise to highly specific behavioural changes under fatigue.

The investigation into participants' dextrous ability and fingertip force control in Chapters 5 and 6 found that mental and neuromuscular fatigue may have highly specific and quite limited overall effects. Whilst there were some small differences in coordination detected during object lifting in both Chapters, participants were still able to perform at normal levels in the Purdue Pegboard Test, lift objects normally, and achieve good accuracy in the force matching task when they were fatigued. This indicates that the sensorimotor system is highly capable of performing simple tasks even when participants report being greatly fatigued. The neural and muscular processes that underlie movement in Chapters 5 and 6 were not monitored, and so there is no insight into what low-level adaptive processes may have taken place in the sensorimotor system to manage any possible impacts of fatigue. Prior research shows that, whilst mentally fatigued, participants can produce the same maximal power as when they are not fatigued, but this requires increased muscular recruitment (Ferris et al., 2018), showing that lower-level processes can be adjusted under conditions of fatigue to maintain outcomes at the behavioural level. The timing difference between grip forces and load forces found in Chapter 6 could be an example of such an adjustment - the increase in the time that grip force preceded load force could reflect a low-level adaptation to changes in central nervous system function that ensure that an object has been grasped fully prior to being lifted. Overall, it appears that even when fatigue development is intentionally maximised in a controlled setting, there is little meaningful impact on simple dextrous behaviour. For more complex tasks such as the fine movements used during surgical suturing, however, different force magnitudes and timings (as found during object lifting and force matching), or very small changes in speed and accuracy (as reflected by the Purdue Pegboard Test outcomes) may have serious meaningful impacts.

7.3 Future Research

The research in Chapter 3 identified existing limitations of mental fatigue research. Some of these limitations were addressed in Chapter 4. Additional possible limitations were, however, revealed, with participants showing variable responses to the mental fatigue protocol. Future research should aim to address these limitations but, more importantly, aspects relating to these limitations should be assessed thoroughly by researchers regardless of their choice of method to induce mental fatigue. It is methodologically challenging to ensure that all participants have both a subjective experience of mental fatigue as well as other objective markers such as neural activity or behavioural performance, and impossible to ensure that the subjective experience is qualitatively the same or to the same degree between participants. As long as experimenters are, however, aware of which participants are experiencing mental fatigue in which way, they can take this into consideration in their protocol and/or analyses. This investigation and awareness of possibly confounding factors is crucial to enhance the value of future research and to reduce the likelihood of spurious interpretations.

The novel method to induce mental fatigue developed in Chapter 4 was also validated and its effects on subjective and objective outcomes were thoroughly quantified. As discussed in Chapter 4, however, it is difficult to ascertain how this novel method compares with others, and what implications this may have for the relevant research. If research does not move towards a consensus on how to induce mental fatigue, it would still be beneficial for researchers to consider in detail and report more specifically on: their chosen definition of mental fatigue; how this is being operationalised; individual and group-level responses to mental fatigue protocols; and theoretical implications of response variability. These steps would enhance transparency, allow researchers to compare and contrast different methods of inducing mental fatigue, and help them ascertain which was most suitable for their given area of interest. It would also give additional insight into the phenomenon of mental fatigue itself by elucidating quantitative and qualitative differences in mental fatigue development arising from different task types and in different individuals.

Chapters 5 and 6 did not examine whether there was any interaction between individual differences such as age or gender, fatigue, and dexterity. The variety of cognitive responses to mental fatigue found amongst participants in Chapters 4 and 5 emphasise the heterogeneity of responses by different individuals in experimental tasks. Age is particularly pertinent for research into dexterity and fatigue, as age-related changes in sensation, muscle physiology, and movement are well-documented (e.g. Brunner et al., 2007; Cicerale et al., 2014; Ketcham and Stelmach, 2001), and ageing also affects fatigability (Callahan et al., 2016; Christie et al., 2011). Future research should investigate these individual differences in more detail, as they have particular relevance for the ageing global population. Examining the effects of individual differences between young, healthy individuals may also give an insight into how characteristics which are amplified with ageing may interact with fatigue and dexterity.

In comparison with mental fatigue and as outlined in Chapter 1, neuromuscular fatigue is well-understood. The neuromuscular fatigue protocol in Chapter 6 was consequently highly specific and controlled. As outlined in the implications, there are a large variety of possible alternative methods for inducing different levels and loci of neuromuscular fatigue, with different possible outcomes for dexterity. For example, peripheral muscle fatigue in the upper limb induced through short-duration muscle-damaging weightlifting exercise places different challenges on the sensorimotor system in executing dexterity tasks than the exercise undertaken by participants in Chapter 6, as it directly damages the muscles and inhibits their contractile function, but would not necessarily result in the same level of central fatigue development as two hours of heavy-intensity cycling exercise. Similarly, endurance exercise which placed greater demands on the upper limbs, such as hand cycling, would result in different upper-limb peripheral fatigue development than a two-hour bout of cycling with the legs, but could still generate similar central fatigue development. Future research should seek to investigate how dexterity can be affected by different types of fatigue, as this has the potential to give fundamental insights into how the sensorimotor system works.

To increase the likelihood of participants developing mental and neuromuscular fatigue in Chapters 5 and 6, the approach was taken to maximise fatigue development using controlled long-duration challenging tasks. When fatigue manifests as a part of daily life, it may be from a 30 minute run, a 90 minute weightlifting session, or a particularly trying day at work. These activities, however, do not occur in isolation. There are many other factors which can contribute to a general sense of mental or physical tiredness. Chronic emotional stress, low-level physical stress, sleep disruption, illness, and disease can all result in what the lay population might describe as fatigue. Whilst the research reported in Chapters 5 and 6 demonstrates the effects of state fatigue arising through heavy-intensity exercise or two hours of a mix of challenging cognitive tasks, it gives no insight into the effects of these other aspects of individuals' lives which can arise independently, limiting the generalisability of the findings. Future research could take a more observational approach by assessing subjective and objective outcomes to identify individuals' level of fatigue, and seeing how these affect or relate to different dexterity outcomes. For example, participants' sleep quality and/or quantity could be recorded, and this could be related to perceptions of object weight or force rates during object lifting.

Defining and operationalising fatigue was a challenge throughout the research in this thesis. As discussed in Chapter 1, the word 'fatigue' has many different meanings and associations, both in scientific research and in lay terms. All types of fatigue have both a perceived and a performance component (Behrens et al., 2022), and the underlying physiological and cognitive processes relating to these are still not fully understood. Whilst peripheral neuromuscular fatigue has been studied at the biochemical level and so can be well-quantified (e.g. by examining metabolite accumulation), central fatigue remains less well-studied, and the many different subjective sensations that can fall under the umbrella term 'fatigue' - including mental fatigue, cognitive fatigue, ego depletion, sleepiness, tiredness, or the recently emerging Zoom fatigue which refers to the tiredness felt by many after an extended time using video conferencing software - do not have such consensus. To address this challenge future research should aim for more precision in its use of the word ‘fatigue’.

There is a wide range of different methods and measures for assessing dexterity that were not used in the present work, but could give additional insight into the effects of different types of fatigue on dexterity. Kinematics and eye tracking have been used extensively to examine sensorimotor control in different populations (e.g. Arthur et al., 2021). Other measures such as muscular electromyography, neural activity, and reaction time could give additional insight into the lower-level physiological changes that underlie any changes in dexterity outcome measures. For example, by adding eye tracking, kinematic analysis, and muscular electromyographic outcomes in the object lifting task, additional insight could be gained into participants’ predictions, speed and rate of movement, and underlying muscular activity that could be related to perceptual differences. Additionally, whilst the research in this thesis focused on direct interaction of the hands with objects in the environment, many of the activities that humans perform on a day-to-day basis involve the use of tools, and this has additional relevance for people who use tools in complex tasks such as surgeons or electrical engineers. Future research should expand on and complement the methods in this thesis using these additional measures and types of dexterity tasks. When analysing outcomes, researchers should ensure that they are using multiple approaches which provide different kind of insights so that subtle task-specific effects like those identified in Chapters 5 and 6 are not overlooked.

The approach to examining the subjective experience of both mental and neuromuscular fatigue in Chapters 4-6 was limited to numerical rating scales. As identified in Chapter 6, however, there may be some relationship between perceived fatigue and subsequent behaviour that could be related to conscious processes like applying more caution or experiencing greater uncertainty. Without asking participants, it is impossible to gain much insight into their conscious experience of completing the different dexterity tasks. Indeed, participants in Chapters 5 and 6 frequently spontaneously reported their experiences of completing the different tasks and often reported conscious decisions on strategies to help them perform ‘better’. For example, when participants were fatigued, they repeatedly reported frustration during the Purdue Pegboard Test with the perception that their performance was worse, and would often try and use strategies such as rhythmic talking to help them complete the task. Future research should consider using a mixed-methods approach to analyse such outcomes. This would allow researchers to gain a deeper insight into the perceptual experience of completing different tasks, and would identify whether - regardless of performance - participants adopt different strategies in different conditions. It could also be associated with quantifiable outcomes such as the timing of different forces during object lifting so that the hallmarks of, for example, uncertainty during an object lifting, could be identified. This knowledge could then be applied in interventions for people whose movements are of a lower quality.

Finally, the generalisability of these research findings is limited in two main ways: due to the experimental approach taken; and due to limitations which may have affected the study outcomes (discussed further in Limitations, below). The standardised experimental approaches taken to inducing fatigue were highly controlled and in this sense, not naturalistic. Future research could consider taking a more observational approach to fatigue and dexterity using more naturalistic situations. For example, researchers could compare surgeons' performance in simulated surgery tasks when they are less rested (e.g. on their first day shift after returning from night shifts) to when they are more rested (e.g. after a series of typical-length day shifts). This would enhance the generalisability of any findings from experimental to real-world settings. Alternatively, experimenters could address the limitations in the current research by more strictly controlling different aspects of the experiment (e.g. participant characteristics). This could elucidate which of the effects identified in the current research are most robust and thus most likely to be generalisable.

7.4 Limitations

When using hypothesis tests as in the current research, sample size is a crucial consideration. Where sample size is low and effect sizes are small, the risk of spurious findings increases. Given the lack of prior research into fatigue and dexterity, there was little available information about what effect sizes should be expected. A priori power calculations for Chapters 5 and 6 were therefore determined using a smallest effect size of interest approach (Lakens, 2014) for the Purdue Pegboard Test, which does not directly relate to the object lifting or force matching tasks. Furthermore, there were practical constraints on recruitment throughout. It is impossible to determine whether Type I or II errors are present in the current work, and so some caution should be used in interpreting the results. This work in its entirety does, however, represent an early exploration into the effects of fatigue on dexterity. The sample sizes were also either in line with or exceeded those in existing research into mental fatigue (Marcora et al., 2009), neuromuscular fatigue (Clark, Vanhatalo, et al., 2018), and how they relate to dexterity (Budini et al., 2022; Duncan et al., 2015; Valenza et al., 2020). Future research could use the effect sizes found here and the novel insights about which specific outcomes are affected by mental and neuromuscular fatigue to better inform power calculations. Future research could then replicate and extend the current findings using more robust sample sizes.

The manipulation checks in both Chapters 5 and 6 showed mixed results. In Chapter 5, mental fatigue did not manifest as both subjective and behavioural changes in all participants. In Chapter 6, participants' maximal voluntary contraction reduced regardless of whether they had undergone the fatigue intervention or control task. Maximal voluntary contraction therefore was not suitable as a specific measure of neuromuscular fatigue. In both Chapters, there were therefore no consistent objective outcomes that demonstrate that the specified types of fatigue were present to the same extent in all participants. Treating participants dichotomously as either 'fatigued' or 'not fatigued' may therefore be too simplistic, and also has other implications e.g. for statistical power (MacCallum et al., 2002). Future research could use alternative and more direct measures of mental and/or neuromuscular fatigue as manipulation checks, and could use a higher number of more nuanced groups of participants. For example, both mental and neuromuscular fatigue research could examine changes in neural activation as a consequence of the fatiguing interventions, and could categorise participants based on the presence or strength of these responses.

Individual differences in participants' characteristics may have influenced the outcomes of Chapters 5 and 6, where individual differences could have influenced the effects of the fatigue manipulations on participants' subsequent performance in the dexterity tasks. The inter-individual differences in behavioural performance in the cognitive task battery identified in Chapter 5 indicate that participants may have varied in characteristics such as their ability to quickly learn new tasks or switch between them. This could have resulted in different levels of performance in the dexterity tasks, particularly in the Pegboard Test where there was evidence of a learning effect. There may also have been an interaction where participants' individual characteristics may have resulted in differences in mental fatigue development, and these differences in mental fatigue may have resulted in differences in the dexterity task outcomes. A similar limitation may have occurred in Chapter 6. Participants' fitness levels and cycling experience varied which could have resulted in different physiological and perceptual responses to the exercise manipulation. This may have resulted in behavioural variance in the dexterity tasks. In Chapter 6, this heterogeneity across the sample may have interacted with the small sample size such that the variance was great enough to affect the power of the statistical analysis.

The findings in Chapters 5 and 6 may also have been influenced by participants' lack of familiarity with the dexterity tasks. Prior research using the force matching and object lifting tasks have not shown that familiarisation is necessary for these two tasks (Buckingham et al., 2016; Neely et al., 2017). In the Purdue Pegboard Test, however, participants showed a learning effect, indicating an ongoing increase in familiarisation throughout the study. This may have introduced variability to the Pegboard Test outcomes, making it more difficult to detect differences between the experimental and control conditions. Whilst this possibility was mitigated partly by the repeated measures design, an alternative approach which could have been effective would have been to use task familiarisation: participants could have practised the task until they reached a certain level of performance or a certain level of consistency, and this could have made it clearer to identify whether their performance was affected by fatigue.

The documentary-watching control task chosen in Chapters 5 and 6 also had limitations. As discussed in Chapter 5, a documentary was chosen for a control task so as to closely match prior research. Chapter 6 subsequently used the same task so as to be as closely matched as possible to Chapter 5. Prior research using documentaries has used films which have been shown to result in a neutral mood and no physiological response (e.g. raised heart rate; Marcora et al., 2009). These were not tested for the documentaries used in Chapters 5 and 6. The results of these two Chapters showed that participants' mood did not remain neutral during the control documentaries. Additionally, the original research examining the original documentaries from prior studies was produced some time ago before the commonplace use of smart phones and watches. Participants often spontaneously self-reported that it felt challenging, anxiety-inducing, and/or boring to not multitask using a smart phone or other personal device whilst watching the documentaries in Chapters 5 and 6. Many also reported that they habitually watch television in the evening and so had an association between documentaries and imminent sleep. Future research should consider using either a different documentary which has undergone testing similar to that in Silvestrini and Gendolla (2007), should make the environment less controlled to be more naturalistic for participants, or should use different approaches altogether e.g. a less challenging cognitive or physical task as a control.

Finally, the research reported in Chapters 4-6 was conducted during and in the wake of the global COVID-19 pandemic. The stressors experienced by participants both directly (e.g. from COVID-19 infection and recovery) or indirectly (e.g. chronic stress from social isolation and economic difficulties) have possible direct impacts on general feelings of fatigue. This could explain the differences in behavioural outcomes between Chapter 4 - where participants were at home amongst various nationwide lockdowns - and Chapter 5 - conducted when participants were able to live more normal lives again: participants in Chapter 5 were able to maintain or even improve cognitive performance to a greater extent than those in Chapter 4. The implications of this for interpreting the present results are unclear. Future replications of the current research could identify which outcomes replicate independent of the possible impacts of the COVID-19 pandemic.

7.5 Conclusions

This thesis identified existing limitations of mental fatigue research (Chapter 3) and developed a novel validated method to induce fatigue which addresses some of these limitations (Chapter 4). The thesis also comprises the first in-depth controlled experiments examining the effects of mental fatigue (Chapter 5) and neuromuscular fatigue (Chapter 6) on behaviour and perception in a battery of dexterity tasks.

The method developed in Chapter 4 to induce mental fatigue took the novel approach of using multiple different cognitive tasks which load on different aspects of executive function, with the aim of increasing the ecological validity of the protocol in comparison to extended-duration single-task approaches. The method was validated using both simple subjective ratings and behavioural indices to address extant issues of over-reliance on subjective ratings. Validating this method additionally provided novel insights into inter-individual subjective and objective responses to mentally fatiguing tasks. The novel method could be used in future research to test the effects, theoretical nature, and physiological markers of mental fatigue. Additionally, the novel method supports research to move towards a unified approach to inducing and measuring mental fatigue.

Chapters 5 and 6 both used an extensive battery of tests and a series of analyses to gain a deep insight into perceptual, performance, and force measures during dextrous tasks under fatigued and non-fatigued conditions. These pieces of research are the first to closely examine fatigue and dexterity using the object lifting and force matching tasks. The findings in these Chapters therefore provide a unique insight into participants' explicit and implicit predictive and reactive force control behaviours which can be extended upon in future research. In interpreting the findings, novel methodological insights were also gained, which can be used to enhance future research in this area. The research in Chapters 5 and 6 is also the first to employ the full Purdue Pegboard Test battery to examine mental and neuromuscular fatigue, expanding on prior research which used a more brief approach.

In Chapter 6, the effects of neuromuscular fatigue on dexterity were investigated for the first time by applying an existing neuromuscular fatigue protocol in a novel way. The outcomes of this research showed high task-specificity, with neuromuscular fatigue apparently having very specific effects on performance and force outcomes which can be attributed to known characteristics of neuromuscular fatigue which had developed in participants. The findings in Chapter 5 showed for the first time that mental fatigue appears to be similarly task-specific, with its effects on dexterity appearing to be mediated through alterations in cognitive processes.

Overall, this thesis developed and applied novel methods, and gained numerous insights into the effects of mental and neuromuscular fatigue on dexterity. These insights have extended existing knowledge about how the sensorimotor system is affected by and adapts to mental and neuromuscular fatigue. This extends prior research and provides a basis for future research to further investigate the meaningful impacts of different types of fatigue on different dextrous outcomes.

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