Shining a Light on Recovery: Investigating the Effectiveness of Bright Light Therapy in Mitigating Fatigue after Mild Traumatic Brain Injury

A thesis presented in partial fulfilment of the requirements for
the Degree of Doctor of Clinical Psychology at
Massey University,
New Zealand

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2023

Abstract

Fatigue is a common and debilitating symptom experienced by individuals following a mild traumatic brain injury (mTBI). Despite its prevalence, post-mTBI fatigue remains a challenging, and at times misunderstood condition, with a scarcity of scientifically evidenced treatment approaches. The complexity of fatigue's underlying causes in this population calls for further research. Recognising its significant impact on individuals' quality of life emphasises the need to identify effective interventions and enhance symptom management.

This study aims to investigate the potential effectiveness of daily bright light exposure as a non-invasive intervention to alleviate fatigue in the post-mTBI population. While existing research has shown positive outcomes for bright light therapy in managing fatigue in broader traumatic brain injury populations, the current study focuses on individuals with injuries at the mild end of the spectrum, offering valuable insights into the efficacy of this treatment in a more targeted context.

The primary objective of the research was to investigate whether daily bright light exposure effectively reduced fatigue symptoms in individuals with mTBI. Additionally, the study aimed to explore the impact of light exposure on secondary outcomes, including daytime sleepiness, sleep quality, depression, anxiety, stress, and circadian rest-activity cycles. To address recruitment challenges, a randomised multiple baseline controlled trial design was adopted.

The results revealed that all nine participants consistently experienced significant fatigue throughout the study. Fatigue levels appeared to decrease during the bright light therapy sessions suggesting a potential positive impact of bright light exposure on fatigue, although this reduction was not statistically significant across the group.

Due to limitations in data, the ability to confidently demonstrate efficacy was low and this prompted a shift in focus towards assessing the feasibility of conducting research of this nature. Moving forward, future studies can benefit from an understanding of the complexities involved in implementing intensive intervention protocols. The current study demonstrates a need for close collaboration with participants to monitor adherence and potential side effects, alongside coordination with colleagues in the mTBI field to ensure access to a sufficient participant pool for achieving statistically significant results.

Overall, this research provides some limited evidence of positive effects from bright light therapy for select individuals and contributes to the expanding body of evidence investigating

light as a potential intervention for alleviating fatigue symptoms post-mTBI. More importantly, by shedding light on the hurdles in implementing such interventions among individuals with mTBI, it contributes to the development of targeted and potentially effective interventions for improving the quality of life for individuals affected by this condition. It is hoped that this study contributes to the broader literature aimed at facilitating better outcomes for individuals with mTBI and related fatigue symptoms.

Acknowledgments

First and foremost, I would like to thank Prof. Janet Leathem, whose unwavering patience and kindness have guided me through the highs and lows of the past few years. Janet, your constant support and invaluable knowledge and insight have been instrumental in shaping both my academic and my personal journey. I feel exceptionally fortunate to have had you on my side.

I must also extend my sincere gratitude to all the research participants who generously took part in this study. Your willingness to share your experiences has been essential in making this research possible. I acknowledge the considerable time and effort you have contributed, and I am genuinely grateful for your support during a period in your lives when you were managing with depleted reserves due to your fatigue.

I am also immensely thankful to my second supervisors, Associate Prof. Mirjam Munch and Dr Stephen Hill, for your significant contributions to this work. Mirjam, your expertise in chronobiology has been pivotal in navigating a subject that I had limited knowledge of when embarking on this project. Your patience and willingness to share your knowledge has been truly appreciated, especially considering your shift across the globe to your current role in Switzerland, where you are actively engaged with many other students. And Stephen, thank you for always being approachable and accommodating. Given your late addition to the team, my questions often came at you with limited context, and despite this, you always graciously made time for me and provided valuable guidance.

I am forever grateful to my children, James, Zara, and Sophia, who have been my constant sources of motivation. When I decided to recreate myself as a clinical psychologist, James was a wee baby, Zara was a growing bump in my tummy, and Sophia was just a twinkle in my eye. You three have never known a mum who wasn't at least in some way distracted by academic pursuit. I look forward to putting the books down for a while for your sakes.

Thank you also to Shaun, for being a supportive editor during my pre-clinical years, a wonderful dad to the kids, and a good friend to me. You may not be there all the time anymore, but you are when I need you – and I am grateful for that.

To my Mum (and Dave) and Dad (and Pip), thank you for your unwavering love and support. Dad, you have always believed I could do anything, and I am especially grateful for the gentle approach you took when enquiring about my progress with this. Mum, you have always been on hand to deprioritize your own work and activities so you could help me with the kids, and I feel very lucky to have had your support. You have both been wonderful role models for me.

A very special thank you to my Aunty Jo, who paved the way for me by traveling a similar journey before mine. Your guidance and support from day one has been immeasurable, and I honestly don't know that I would have made it this far without your wisdom. To my sister Julia, who has been there for me through thick and thin, thank you for everything (I want to put "everything" in uppercase, but I feel it wouldn't be very fitting for an academic document). And to my brother David, thank you for your frequent words of support from across the globe. Your encouragement has meant so much more to me than you would know.

To my wonderful cohort, Emma, Dasha, Caitlin, and Lucy, what a team we have been! Your camaraderie and support have brought a little bit of fabulousness to this journey. I'm sure we will continue to share war stories until we are little old people hobbling around. And of course Irie, I hope you know how instrumental you have been in my journey. Thank you for your academic insight but more so your excellent banter - I sincerely hope that we can share an office again one day soon.

Thank you also to Jimmie for exercising such patience as a manager in my parallel life as an employee. I am grateful that you've hung in there with me while I loitered on the wrong side of the finish line of this thesis. I look forward to being able to focus on just one thing at a time – if that is even possible in this line of work.

Lastly (but far from least), I want to thank all my wonderful friends and family who I have not yet mentioned. I am so very fortunate that there are too many of you to name, but your collective presence and care has not gone unnoticed. I can't wait to discover all the things we can talk about now that it doesn't have to be "*is your thesis finished yet*…"

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Chapter One: Introduction and Thesis Overview

1.1 Introduction

Traumatic brain injury (TBI) is a major global health burden (GBD 2016 Traumatic Brain Injury and Spinal Cord Injury Collaborators, 2019). Mild forms of these injuries (mTBI, concussion) account for more than 90% of TBIs, and although labelled as 'mild', increasing evidence suggests that the burden of persistent long-term symptoms of mTBI can be significant. One of the most commonly reported, pervasive, and debilitating consequences following mTBI is fatigue. A study by Norrie et al. (2010) examined the prevalence of fatigue following mTBI over time. They found an initial prevalence of 68% at one-week post-injury, which decreased to 38% after three months, and decreased only slightly to 34% after six months. Similar findings have been reported, indicating that 32% of individuals experience severe fatigue six months post mTBI, compared to only 12% of individuals with non-brain-related injuries (Stulemeijer et al., 2006). With more severe TBI, fatigue is often one of many ongoing symptoms, however, for mTBI it can be the primary contributor to a decreased capacity for both mental and physical activities, a decline in quality of life, interference with the ability to undertake paid employment, and problems with social functioning (Palm et al., 2017). As such, fatigue is defined as a multidimension experience which can consist of mental, physical, and/or cognitive impairments due to a reduced sense of energy (Sharpe & Wilks, 2002).

The underlying mechanisms that lead to fatigue following mTBI are not well understood but given its common presentation in neurological disorders (e.g., multiple sclerosis, Parkinson's disease, myasthenia gravis, stroke, and others), there is broad agreement that neuropathology is an important pathway to its development. However, beyond the primary injury itself, secondary psychological processes are also thought to contribute to the onset and severity of fatigue following mTBI. These psychological processes include bidirectional relationships between fatigue and psychopathology, which will further be discussed in Chapter Three.

To date, there is a dearth of evidence-based treatments for fatigue following mTBI. A growing body of literature would lay claim to the effectiveness of various interventions, but promising evidence suggests that scheduled blue light therapy may be helpful in reducing fatigue following TBIs of varying severities (Srisurapanont et al., 2022). Given that research on treating fatigue following mTBI is at a stage of preliminary understanding, the current study leverages off of the collated evidence for blue light therapy as an intervention for reducing fatigue following TBIs. As such, this study positions light-based treatments as a possible mechanism for mitigating fatigue. Further to the rationale of the current study, individuals who have specifically suffered a mTBI have largely been neglected within prior studies. Therefore, the current evidence base for light therapy as a treatment for fatigue in this population is limited. The goal of this study is to test the efficacy of this treatment modality with individuals who have brain injuries at the milder end of the severity spectrum. Prior research has indicated that there is no therapeutic difference between broad spectrum light and blue light (Smith et al., 2009), making it an informed choice to use broad-spectrum polychromatic white light source in place of the more commonly trialled, blue-enriched light, thereby also trial a more naturally appearing form of light therapy.

Recruitment challenges and other logistical limitations encountered during the project necessitated an evolution in its focus. Consequently, the study shifted its emphasis towards assessing the feasibility of conducting further research in this domain. Specifically, the results and discussion now include an exploration of the demand for light therapy within the mTBI population, the viability of executing the intervention as initially planned, and the pragmatic considerations surrounding the feasibility of future research endeavours in this space.

The current study was conducted with nine participants recruited through concussion clinics and other TBI referral pathways in Wellington, New Plymouth, and Hamilton, New Zealand. Prior studies have primarily used control groups who were either exposed to a dim light source (e.g., Sinclair et al., 2014), or who received no treatment at all (e.g., Quera Salva et al., 2020). In contrast, the present study intentionally utilised a multiple baseline design and allocated participants either to Group One who undertook treatment after a two-week waiting period, or Group Two who undertook treatment after a six-week waiting period. The full rationale for this study design will be discussed in Chapter Six.

The overarching goal of this research endeavour is to contribute to the body of knowledge on non-pharmaceutical approaches for mitigating fatigue following mTBI. By doing so, the current study sought to make a tangible difference in the lives of individuals grappling with the debilitating effects of post-TBI fatigue, thereby enhancing their quality of life and functional outcomes.

1.2 Thesis overview

Initially, a narrative review of relevant literature will be provided. *Chapter Two* covers an overview of the definitions and epidemiology of TBI, critiquing the nuances in how this is defined, and the interchangeable terminologies used in the field. Emphasis is placed on literature pertaining to mTBI, acknowledging the contention regarding whether mTBI is synonymous with concussion, or if concussion is better understood as a distinct subset of mTBI. An overview of the pathophysiological mechanisms of mTBI are also briefly explained, as well as the predominant assessment and treatment approaches post-injury. Additionally, contextualised information on TBI and mTBI within New Zealand is provided. When considering the content of Chapter Two, it is worth noting that service users often define recovery as "living well in the presence or absence of symptoms" however, this study focuses primarily on clinical recovery, defined as the absence of symptoms. This distinction is important to acknowledge as it underscores the multifaceted nature of recovery and situates the current research within a specific clinical context.

Chapter Three provides a detailed review of the literature pertaining to fatigue. Discussions on the definitions and implications of fatigue as a broad construct is followed by a shift to considering how and why this difficulty presents following mTBI. Further, the current treatment approaches for fatigue following TBI are critically appraised, including pharmacological, psychological, and physiological interventions.

A review of the use of light therapy in the treatment of fatigue is provided in *Chapter Four*. This includes a summary of the literature relating to its use among people who have sustained TBI, as well as an overview of the current understandings of why it is effective in fatigue reduction more generally. Factors that influence the effectiveness of light therapy are outlined, followed by sections regarding the efficacy and methodological approaches to light therapy use.

Chapter Five explains the study rationale, including the research questions, hypotheses, and recent advancements that occurred following the conception of the current study, circa 2018.

Subsequently, the research methodology utilised within the current study is outlined in *Chapter Six*, attending to the study design, recruitment processes, descriptors of the participants, measures implemented, and the procedure for the light therapy intervention. Further, ethical considerations are discussed within the context of the current exploratory research.

Chapter Seven details the results from participants' baseline measures and results produced from the light therapy intervention. Analytical results are presented at both the group and individual level and include consideration of any changes observed after a follow-up period of four weeks without treatment.

Finally, *Chapter Eight* provides a synthesis and discussion of the study findings, then focuses on the feasibility of employing broad-spectrum polychromatic white light therapy as a viable treatment option for fatigue following mTBI. These results are discussed within the framework of existing international research regarding interventions for fatigue and contemporary theories on the aetiology of fatigue post-TBI. The implications of the study results for clinical practice are discussed, and the strengths and limitations of the current study are outlined. Particular attention is directed towards the feasibility-related challenges encountered during data collection, which prompts a nuanced exploration of potential avenues for future research. This analysis offers valuable insights aimed at advancing the evidence base pertaining to light therapy interventions among individuals with brain injuries. The thesis concludes with a summary of key reflections and concluding remarks

Chapter Two: Mild Traumatic Brain Injury

2.1 Overview

The global pervasiveness of TBIs and their substantial negative health impacts contribute to the ongoing prominence of research in the fields of neuro and clinical psychology. There are significant socioeconomic implications for the individuals who sustain these injuries, as well as for their families, friends, and broader communities. A 2018 systematic review estimated that there is an annual global total of 69 million (95% CI 64-74 million) individuals who sustain a new TBI each year (Dewan et al., 2018). These injuries range from mild to severe, with the vast majority (up to 95%) of cases being mild (Feigin et al., 2013). Many cases of mTBI go unreported. This is especially true in sport with research suggesting that up to 82% of mTBI's incurred during sport do not get reported due to players not wanting to be ruled out of game time or training (Longworth et al., 2020). This is concerning because despite its name being suggestive of a more benign type of injury, mTBI can have serious and long-lasting effects on a person's quality of life, including physical, cognitive, emotional, and behavioural challenges. The following sections focus on defining the severity of mTBI, outlining mechanisms of pathophysiology, assessment considerations for mTBI, and the impacts of mTBI on contemporary New Zealand.

2.2 Severity of Traumatic Brain Injury

Due to the heterogeneous nature of TBI, it is challenging to find a universal definition, however, one that encompasses most aspects of TBI is "an alteration in brain function, or other evidence of brain pathology, caused by an external force" (Menon et al., 2010, p. 1637). As evident by the breadth within this definition, the symptomatology of TBIs encompasses variating presentations. Factors which contribute to such heterogeneity include, the degree of force exerted on the brain and the duration and magnitude of neurophysiological disruption, creating a spectrum of injury severity that can occur following a TBI. Specific to mTBI, there are several proposed definitions that have been published, which are summarised in Table 1.

Table 1

Definitions of mTBI

Criteria (year)	Definition of injury	Factors related to injury can include
Centers for Disease Control and Prevention (2003)	Blunt trauma to head or acceleration/deceleration forces results in a brief alteration of mental status or brief loss of consciousness	GCS 13–15, LOC < 30 min; PTA ≤24 h; non-penetrating cranio-cerebral injury
WHO (Holm et al., 2005)	Acute brain injury resulting from mechanical energy to the head from external physical forces	GCS 13–15*(a)*, LOC≤30 min; PTA < 24 h; and/or other transient neurological abnormalities,*(b,c)* and intracranial lesion not requiring surgery
Mayo (Malec et al., 2007): mild (probable) TBI	Traumatically induced injury that contributed to physiological disruption of brain function	GCS 13–15 (≥13 at 30 min); LOC momentary to 30 min; PTA momentary to 24 h; skull fracture with intact dura; EXCLUSION if death due to TBI, worst GCS in first 24 h < 13*(c)*, abnormal head CT
Mayo (Malec et al., 2007): symptomatic (possible) TBI	Traumatically induced injury that contributed to physiological disruption of brain function	*(d)* Symptoms must not be attributable to pre-existing or co-morbid diagnoses. EXCLUSION if criteria met for mild probable TBI
Department of Veterans Affairs/Department of Defence (2009)	A traumatically induced structural injury and/or physiological disruption of brain function as a result of an external force	GCS 13–15(e); LOC momentary to 30 min; alteration of consciousness/mental state (AOC) momentary up to 24 h; PTA < 24 h; neurological deficits*(f)* that may or may not be transient; normal structural imaging
Ontario neurotrauma (2018)	Concussion/mTBI denotes the acute neurophysiological event related to blunt impact or other mechanical energy applied to the head, neck or body (with transmitting forces to the brain), such as from sudden acceleration, deceleration or rotational forces	LOC < 30 min; any AOC at the time of the injury; PTA ≤ 24 h; physical symptoms*(h)*; normal standard imaging
American congress of rehabilitation medicine (Silverberg et al., 2021)	A traumatically induced physiological disruption of brain function	Symptoms following a head impact, without associated observable signs (in some instances), Recommendation (i) consider a probabilistic framework that weighs observable signs more than subjective

		symptoms and (ii) incorporate objective cognitive, balance and vestibular-oculomotor test findings. 1993 criteria*(c)*: initial GCS 13–15; any LOC; any AOC at the time of the injury and focal neurologic deficit/deficits that may or may not be transient; any PTA
1st International conference of concussion in sport (Aubry et al., 2002)	A complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces	(i) Direct blow to the head, face, neck or elsewhere on the body with an 'impulsive' force transmitted to the head. (ii) Rapid onset of short-lived impairment of neurological function that resolves spontaneously. (iii) May result in neuropathological changes, but the acute clinical symptoms largely reflect a functional disturbance versus structural injury. (iv) Results in a graded set of clinical syndromes that may or may not involve LOC. Resolution of the clinical and cognitive symptoms typically follows a sequential course. (v) Typically grossly normal structural neuroimaging studies
5th International conference of concussion in sport (McCrory et al., 2017)	Sports-related concussion is a TBI induced by biomechanical forces	Modifications to the above: (i) In some cases, signs and symptoms evolve over a number of minutes to hours. (ii) No abnormality is seen on standard structural neuroimaging (iii) Sports-related concussion results in a range of clinical signs and symptoms*(c)*. In some cases symptoms may be prolonged

Note. Adapted from Clark et al., 2022. AOC = alteration of consciousness; GCS = Glasgow coma scale; LOC = loss or decrease of consciousness; PTA = post traumatic amnesia.
any loss of memory for events immediately before or after the accident.
(a) Ideally at 30 min post injury or first opportunity presented to healthcare.
(b) Such as focal signs or seizure.
(c) The clinical signs and symptoms cannot be explained by alternate cause, e.g., drugs or other comorbidities (e.g. psychological factors or coexisting medical conditions).
(d) Blurred vision, confusion (mental state changes), dazed, dizziness, focal neurologic symptoms, headache, or nausea.
(e) Best available score <24 h.
(f) Weakness, loss of balance, change in vision, praxis, paresis/plegia, sensory loss or aphasia, etc.
(g) Stratified into high and low risk mTBI.
(h) Vestibular, headache, weakness, loss of balance, change in vision, auditory sensitivity, or dizziness.

Although the definitions of mTBI differ in regard to which symptoms and signs must be present for a diagnosis, there are some diagnostic criteria consistencies. For instance, all these groups agree that temporary loss of consciousness is indicative but not mandatory. However, there are significant discrepancies which limit interpretations of studies relating to mTBI. For example, the inclusion or exclusion of brain structure changes as part of mTBI diagnosis is not consistent, and the role of subjective symptoms like headaches, dizziness, and concentration difficulties are also debated. To highlight this issue, Crowe et al. (2018) applied multiple mTBI definitions to a single dataset and found very wide variation in which individuals were defined as having a mTBI.

Another confounding feature of the definitions for mTBI within existing literature is that the terms 'concussion' and 'mTBI' are at times used synonymously, or used as hierarchical terms, with concussion being seen as a subset of mTBI. This discrepancy in terminology will be discussed later in this chapter. Perhaps the most widely agreed upon diagnostic criteria for mTBI was proposed by the Mild Traumatic Brain Injury Committee of The American Congress of Rehabilitation Medicine (ACRM, 1993), reprinted in Table 2.

Table 2

ACRM, 1993 Definition of Mild Traumatic Brain Injury

A traumatically induced physiological disruption of brain function, as manifested by at least one of the following symptoms:
1. any loss of consciousness, 2. any loss of memory for events immediately before or after the accident, 3. any alteration in mental state at the time of the accident (e.g., feeling dazed, disoriented, or confused), and 4. focal neurological deficit(s) that may or may not be transient; but where the severity of the injury does not exceed the following: • loss of consciousness of approximately 30 minutes or less, • after 30 minutes, an initial Glasgow Coma Scale (GCS) of 13-15, and • posttraumatic amnesia (PTA) not greater than 24 hours.

The Brain Injury Special Interest Group (BISIG) (which consisted of 31 experts) commenced work in 2019 to update the 1993 ACRM definition of mTBI (Silverberg et al., 2021). They agreed that some individuals present with subjective symptoms in the absence of objective signs, and while the original ACRM definition did not explicitly include these subjective symptoms, these should be captured in diagnostic criteria moving forward – albeit with prioritisation given to observable signs rather than subjective symptoms (Silverberg & Iverson, 2021). The experts were mostly in agreement that acute symptoms are diagnostically important, but they acknowledged that symptom onset can be delayed in some cases. The consensus on this aspect of the review was that symptoms should only be causally attributable to mTBI if they present within three days of the injury occurring. The growing controversy around whether injury resulting in structural damage that is visible on computerised tomography (CT) or magnetic resonance imaging (MRI) scans should be categorised as a more severe injury was also addressed by this panel (Silverberg & Iverson, 2021). They concluded that it is likely that advances in neuroimaging technology will lead to a moving threshold for the severity of injuries that will be visible through such scans. If this were the case, the diagnostic grading of TBI severity might well be refined with time and advancements. Additionally, 17 of the 31 experts recommended that there should not be a minimum duration of symptoms for the classification of mTBI.

As evident within these debates concerning the ACRM redefinition of mTBI, points of contention were orientated towards which symptoms required prioritisation when establishing updated diagnostic criteria. Among the proposed objective symptoms, diagnostic importance was rated (range 1-10) highest for loss of consciousness, disorientation, confusion/inappropriate behaviour, and seizure with clonic movements (Silverberg & Iverson, 2021). The highest diagnostic importance ratings among the proposed subjective symptoms were feeling confused, disorientated, and/or dazed, balance problems, and difficulties remembering. As previously mentioned, the BISIG experts advocated for objective symptoms to be prioritised over subjective symptoms for diagnostic criteria (Silverberg & Iverson, 2021); a seemingly redundant notion given that it was recognised that mTBI could present as subjective symptomatology without objective signs and the ambiguity of what distinguished objective from subjective. For example, disorientation and confusion (second only to loss of consciousness) were both rated among the most important diagnostic symptoms for mTBI, irrespective of whether subjective reported or measured objectively (Silverberg & Iverson, 2021). As such, rather than distinguishing between the two symptoms profiles, a collated prioritisation of both subjective and objective symptoms may better serve the purpose updating the ACRM definition of mTBI.

Within the current study, mTBI was defined using the 1993 ACRM definition of mTBI (see Table 1) and the BISIG experts' perspectives regarding diagnostically important symptoms were also included (ACRM, 1993; Silverberg & Iverson, 2021). These symptoms include: loss of consciousness, disorientation, confusion, seizures with clonic movement, focal neurological deficits, tonic posturing, slow response to questions, feeling dazed and dizziness, balance problems, and difficulties remembering (Silverberg & Iverson, 2021). Concussion was also recognised as a form of mTBI and the contention between these two forms of brain injury are discussed in the following section.

2.3 Mild Traumatic Brain Injury versus Concussion

In both scientific literature and clinical practice, the terms 'mTBI' and 'concussion' are often used interchangeably. Neurologists have been reported to understand that the term concussion is a reassuring one for patients – reinforcing the benign nature of this type of injury (Sharp & Jenkins, 2015). The 2012 Zurich Consensus Statement on Concussion in Sport proposed that concussion and mTBI should be viewed as distinct phenomena, with concussion represented as a subdivision of TBI (McCrory et al., 2013). However, this consensus statement has been critiqued in the time since publishing, due to its biases toward elite athletes and more importantly, the concern that statements of this kind have failed to include experts with the diversity of training and experience who could give scientific rigour to the distinction (Casper et al., 2021). Additionally, the 2012 Zurich Consensus does not provide sufficient diagnostic specificity for the clinical diagnosis of a concussion, whereby the 'shaking' of one's head, and the emergence of one subsequent symptom out of a possible 22, are required (Carton & Leslie, 2014).

The later Consensus Statement (McCrory et al., 2017) addresses some of these concerns. While it still acknowledges a need for a distinction between sports-related concussion and other causes of mTBI, it does not decisively settle the ongoing debate over whether concussion should be considered as part of a spectrum of TBI (characterised by lesser degrees of diffuse structural change compared to more severe TBI), or if it primarily involves reversible physiological alterations. What it does emphasise though, is that regardless of the diagnostic labels these injuries are given, the separation of sporting versus non-sporting TBI should not be seen as a dichotomous or exclusive view of TBI. It highlights the importance of understanding that lessons from non-sporting mTBI research inform the understanding of sports-related concussion and vice versa. The engagement of experts from various fields in the consensus document, including TBI, dementia, imaging, and biomarkers, further supports the comprehensive approach to understanding and managing concussion (McCrory et al., 2017).

A contrasting view on terminology provided by the American Academy of Neurology guidelines on sports concussion, illustrates the discrepant use of these terms (Giza et al., 2013). While acknowledging the lack of consensus in the use of the term concussion, they do not separate concussion from mTBI. Collating evidence from the aforementioned literature, the term concussion is seemingly used in two ways:

1. to describe a distinct pathophysiological entity with its own diagnostic and management implications, mainly seen in the context of sporting injuries, and
2. to describe a constellation of symptoms that arise after mTBI (e.g., post-concussion syndrome[1]).

The interchangeable use of these separate diagnostic labels to describe injuries that may or may not be similar creates some complexity in reviewing literature. Some have argued that in order to reach a clear and consistent definition of mTBI, the term concussion should be retired from use (Sharp & Jenkins, 2015).

As it stands currently, there are no clinical or diagnostic criteria proposed to distinguish mTBI from concussion, nor is there any consensus on distinct symptom profiles that might classify these as separate injuries (Mayer et al., 2017). What does appear to be the case is that concussion is more broadly used in sport related research whereas mTBI is common terminology for non-sport injuries (Silverberg & Iverson, 2021). Weighing into the controversy surrounding the disagreements in diagnostic labels, the current study includes concussion under the umbrella of mTBI, recognising that these terms are used interchangeably within contemporary research. As such, though literature is divided as to whether these terms represent

[1] Post-concussion syndrome is considered to be an unhelpful and out-dated clinical construct. Symptoms that persist beyond three months are now described as "persisting concussion symptoms" (ACC Position Statement, expiry 30 September 2026)

synonyms, or distinctions, the current study makes no distinction between these terms and people with either diagnostic label were eligible to participate in the current research under the inclusion criteria.

2.3.1 Persistent Postconcussion Symptoms

Symptoms resulting from a mTBI are generally considered to be persistent if they are still present 3 months post-injury (American Psychiatric Association, 2000). Additionally, they need to have emerged within hours of the mTBI occurring, impact at least one aspect of daily life, and not be better attributed to a pre-existing condition (Lagace-Legendre et al., 2021). Previously, individuals experiencing persistent symptoms may have been given a diagnosis of post-concussion syndrome (PCS). However, as outlined in the recently released Position Statement from ACC, this is no longer considered to be a helpful or valid diagnosis. It is recognised that the underlying mechanisms for the persistence of symptoms following mTBI are poorly understood and likely influenced by interactions between pre-injury factors, psychological comorbidities, and the injury itself (Clark et al., 2022). Clark and colleagues suggest that grouping these individuals with a diagnostic label hinders the progression towards considering underlying causes of symptoms that have evidence-based treatments. The latest diagnostic manuals, DSM-5 and ICD-11, no longer include PCS, preferring terms like 'persisting concussion symptoms' and related diagnoses such as 'mild neurocognitive disorder' and 'neurocognitive disorder due to traumatic brain injury.' ACC’s Position Statement advocates for careful assessment of individual cases to identify appropriate treatment targets.

2.4 Pathophysiology of Traumatic Brain Injury

The pathophysiology associated with TBI is complex and thought to involve multiple injury mechanisms. In broad terms, the injury is thought to occur as a result of mechanical forces applied to the head, causing the brain to move within the skull and resulting in disruptions to normal neurological functioning (Giordano & Lifshitz, 2021). The symptoms following TBI are extremely diverse, even within each injury severity classification. This showcases the intricate nature of TBI and illuminates that a variety of factors contribute to the heterogeneity of the injury. While it is important to recognise the severity of the mechanical force, the site of impact, pre-existing lifestyle, and genetics - the intricacy of the underlying pathophysiology can make it challenging to predict which individuals will recover fully and which may experience ongoing health problems.

The neuronal tissue damage caused by TBI generally falls into two categories: (i) primary injury, which results directly from the mechanical forces during the impact, and (ii) secondary injury, which involves additional tissue and cellular damage that occurs after the primary insult (Ng & Lee, 2019). The immediate observable symptoms following TBI, such as loss of consciousness, vary based on the type, magnitude, and location of the mechanical force that caused the injury. These immediate symptoms, which may also include disorientation, dizziness, slurred speech, vomiting, and others, indicate a disruption to neurological function (Giordano & Lifshitz, 2021). The mechanical impact sets off a number of cellular processes thought to be aimed at mitigating the damage, but as TBI evolves, subsequent pathophysiological processes start to unfold. For example, damage to axonal membranes, known as diffuse axonal injury, leads to compromised axonal transport, which can cause varying levels of axonal swelling and disconnection (Giordano & Lifshitz, 2021). Depending on the severity of the injury, TBI's can also cause vascular damage such as haemorrhage, microhaemorrhage, and hematoma which can undermine neural function and exacerbate pathophysiological processes (Giordano & Lifshitz, 2021).

Inflammation is also understood to be a critical component of the pathophysiology of TBI. When the injury occurs, the mechanical impact triggers a series of cellular and biochemical responses that lead to the release of various inflammatory molecules. These molecules then activate immune cells such as microglia, astrocytes, and infiltrating peripheral immune cells to help remove damaged tissue and promote tissue repair. However, the inflammatory process in TBI is often excessive and can set of a deteriorative feedback cycle placing further stress on the brain (Mentzer, 2021). The prolonged activation of immune cells can cause further damage to healthy brain tissue and exacerbate the initial injury. Inflammatory molecules can also increase the permeability of the blood-brain barrier, leading to the infiltration of more immune cells, which can intensify the inflammatory response. Figure 1 (North et al., 2012) provides an illustration of the pathophysiology of brain injury.

Figure 1

The Pathophysiology of Traumatic Brain Injury

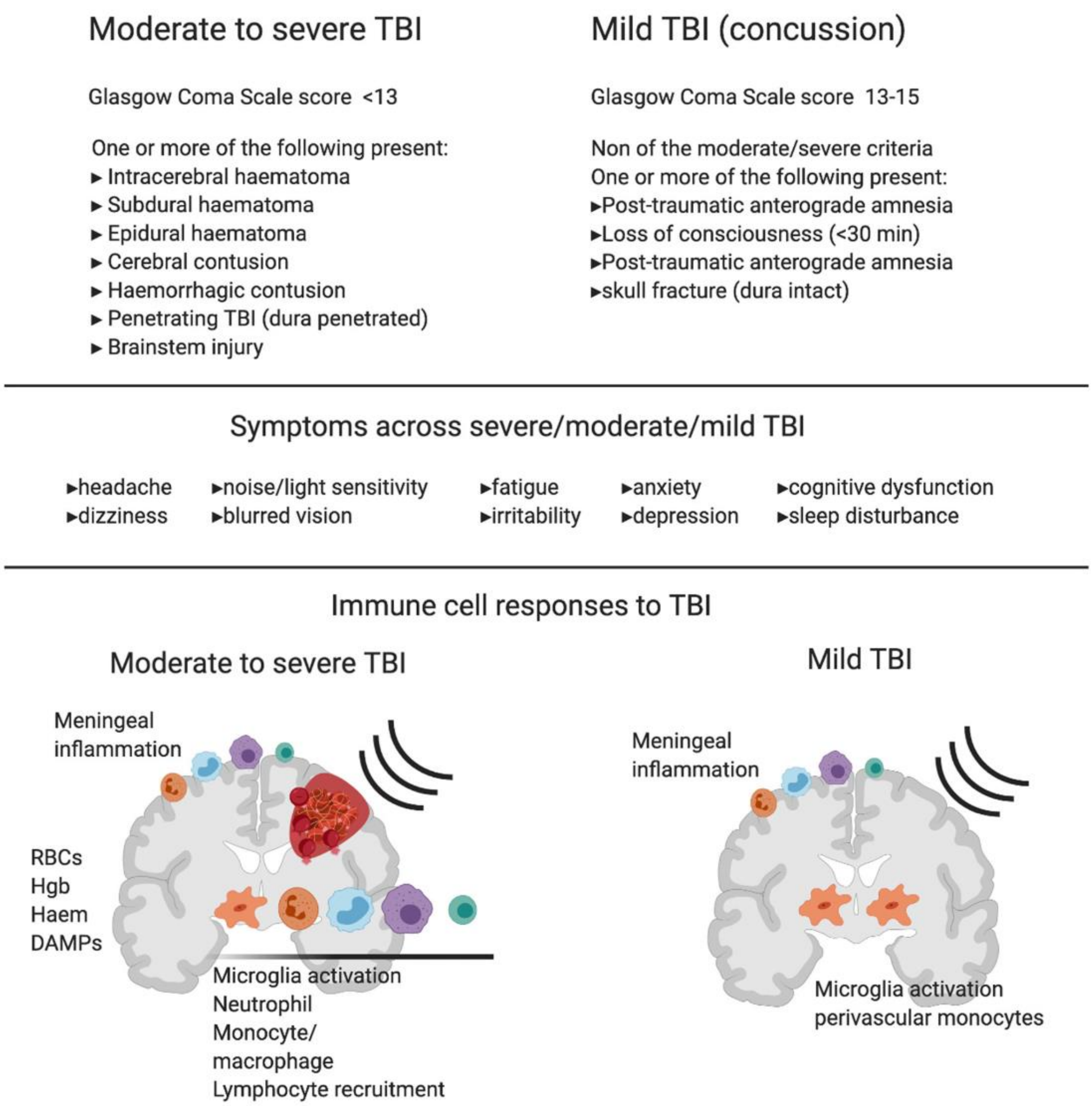
Notes. Sourced from North et al. (2012). CBF: cerebral blood flow; CPP: cerebral perfusion pressure; ICP: intracranial pressure. [*]The presence of ICP biomarkers C-tau, GFAP, and S100β.

The homogenous causal mechanisms (i.e., biomechanical traumas) across the spectrum of TBI severity adds complexity when attempting to understand the distinctive pathophysiology of mTBI. Further complicating differentiation between the severities of TBI are similarities in symptomatology, such as somatic (e.g., headaches), sleep disturbance (e.g., falling or remaining asleep), emotional (e.g., depression, irritability), and cognitive (e.g., poor memory and concentration) sequelae – suggestive of shared pathophysiological mechanisms (Petraglia et al., 2014). Numerous methods have been implemented to replicate mTBI under experimental conditions using animal models, such as fluid percussion, weight drop, and blast injuries, as well as controlled cortical impact (Petraglia et al., 2014). However, animal models of mTBI have limited utility in advancing understanding of the pathophysiology of mTBI. Firstly, successful treatments for mTBI in animal models do not inherently prove to be efficacious for human intervention; secondly, differences in human versus animal brain physiologies means that pathophysiological mechanisms are not directly comparable; and thirdly, animal models do not always exhibit the same functional impairments as would be expected in humans with mTBI despite sustaining physiologically similar brain injuries (Petraglia et al., 2014). As such, contemporary knowledge on the pathophysiology of mTBI remains within a stage of infancy and mirrors similar processes evident in moderate to severe TBI, though some distinctive features have been discerned.

Figure 2 has been included to highlight the distinct differences between moderate to severe TBI and mTBI. While moderate-to-severe TBIs are characterized by more severe symptoms and greater structural damage to the brain, there are certain features that overlap with mTBI. As is shown, symptoms are shared across all levels of TBI, however, they tend to occur more frequently and with greater severity as the severity of the injury increases. The accompanying illustrations in the figure depict the immune response in moderate to severe TBI (left) and mTBI (right). In moderate to severe TBI, there is evident activation of resident microglia and the recruitment of various immune cells, including macrophages, dendritic cells, neutrophils, B cells, and T cells, along with inflammation in the meninges. Moreover, in addition to active recruitment processes, peripheral immune cells can infiltrate the brain tissue alongside hemorrhage, red blood cells, and the release of substances like hemoglobin, Haem, and other damage-associated molecular patterns, which are known to trigger the immune response. Conversely, mTBI exhibits limited evidence of immune cell infiltration without the presence of hemorrhage or skull opening. Instead, mTBI is characterized by meningeal inflammation, activation of microglia, and some recruitment of monocytes/macrophages to the cerebrovasculature.

Figure 2

Diagnostic Criteria, Symptoms, and Immune Cell Involvement in mTBI in comparison to Moderate to Severe TBI



From "The immune system's role in the consequences of mild traumatic brain injury (concussion)," by L. Verboon, H. Patel, & A. Greenhalgh, 2021, *Frontiers in Immunology, 12.*

In summary, the pathophysiological processes that underlie the heterogeneous range of symptoms seen in TBI are first initiated immediately after the initial injury. However, these processes can be ongoing and result in persistent consequences for the injured individual. TBI pathophysiology is complicated by the overlapping feedback loops that contribute to injury and recovery, but are important to understand in order to accurately assess individuals and develop effective treatment pathways.

2.5 Assessment of Traumatic Brain Injury Severity

TBI severity is typically classified as mild, moderate, or severe based on clinical presentation. In categorising the severity of TBI, a comprehensive approach is often necessary to ensure the most proficient diagnosis. As it stands currently, the key clinical indicators used to determine the severity of injury in TBI are alteration in consciousness, loss of consciousness (LOC), and post-traumatic amnesia (PTA) following the injury (Teasdale & Jennett, 1974). These are considered to be important areas to focus on in assessing and diagnosing brain injuries, and while the definitions of TBI severity vary across different organizations and expert groups (Kraus, 2023), the broadly agreed upon criteria to classify TBI severity are as follows:

- Mild TBI: LOC <30 minutes; PTA 0–1 day; GCS score 13–15
- Moderate TBI: LOC 30 minutes–24 hours; PTA more than one day and less than seven days; GCS score 9–12
- Severe TBI: LOC >24 hours; PTA more than seven days; GCS score 3–8

The Glasgow Coma Scale (GCS) has gained wide acceptance as a clinical tool for assessing the level of consciousness following TBI. It was initially described nearly half a century ago and is a robust assessment tool that has been shown to be highly effective when predicting injury outcomes (Iaccarino et al., 2021). The GCS consists of a series of tests that assess the person's motor and reflexive responsivity, such as their ability to open their eyes, respond to verbal commands, and move their limbs. The scores from these tests are then combined to give a total score, which ranges from 3 to 15. This scaling is designed to stratify TBI's according to the extent of injuries sustained; namely, mild, moderate, or severe TBI. A score of 3 indicates the deepest level of coma, while a score of 15 indicates normative consciousness. A score of 13–15 is considered mild, 9–12 is considered moderate, and 3–8 is considered a severe injury. The GCS is often considered "the gold standard" for diagnosis (e.g. In-Suk Bae et al., 2020) because it can help healthcare professionals quickly gauge the severity of a brain injury and guide initial treatment decisions. However, notwithstanding its usefulness as a validated and reliable assessment tool, it does have a number of limitations given that it does not provide a detailed assessment of brain function. Of relevance to the current study, the GCS has been shown to be less useful as a prognostic indicator for mTBI where symptoms may be subtle and consciousness may not be significantly affected (Leo and McCrea, 2016). This is likely due to several factors including that initial GCS scores can be confounded by extraneous factors such as alcohol or other drug intoxication which are common precursors to mTBI. An illustrative example of this is where drowsiness, confusion, or amnesia might be attributed to intoxication which could lead to an underestimation of TBI severity. Conversely, those same symptoms could lead to an overestimation of injury severity if they are present due to the overuse of drugs or alcohol. Table 3 has been adapted from Tenovou et al. (2021) to highlight some of the confounders of using the GCS for severity assessments.

Table 3

Recorded Confounding Features when using the GCS for Estimation Severity of TBI

Confounders for Glasgow Coma Scale
CNS-active medications (sedatives, opiates)
Hearing deficits
Hypovolemia
Hypoxia
Inebriation (alcohol, drugs), intoxication
Language problems
Orbital injuries
Psychic shock
Seizures
Sensory/motor loss (hemiparesis, spinal cord injury)
Sleep deprivation
Surgical measures

Note. Adapted from Tenovou et al. (2021).

PTA is recognised as the most reliable predictor of mTBI outcomes. This can be defined as "a complex clinical concept reflecting an acute transient cognitive dysfunction that presents not only as amnesia but more broadly as a period of inability to store new information, confusion, disorientation or behavioural changes" (Pozzato, et al., 2019, p. 2). Assessment of the presence and duration of PTA provides valuable information about the extent and duration of memory impairment after a brain injury. Alongside consideration of the loss of/level of consciousness, it can help identify the severity of the injury and guide decisions about ongoing care and prognosis. Integrating an amnesia score into the broader assessment for diagnosis of mTBI is particularly important to ensure that individuals with apparently normative levels of consciousness (e.g. GCS of 15), are not overlooked or misdiagnosed (Meares et al., 2015). The Galveston Orientation and Amnesia Scale is validated for use in the TBI population. It focuses on assessing orientation to person, place, and time, as well as new learning ability. However, it has been criticised for its limited focus on memory and learning ability. Therefore, the Westmead PTA Scale, which provides a more comprehensive evaluation of PTA including memory and learning ability, is commonly used in both clinical and research settings. However, clinical assessment and interpretation of PTA is challenging due to it encompassing a series of acute cognitive impairment signs and symptoms. Additionally, retrospective evaluations of PTA, commonly utilised in clinical settings, are susceptible to inaccuracies due to recall bias. This bias can lead to both overestimation and underestimation of PTA durations compared to prospective assessments (Tenovuo et al., 2021). An Australian study in a hospital setting found that the median time to the first PTA testing was 3.7 (2.3–6.1) hours post-injury (Pozzato et al., 2019). In that study, many individuals returned PTA scores indicating the absence of acute cognitive dysfunction at the time of assessment (i.e., they were not in PTA). However, it is notable that these scores could not have definitively rule out the possibility that PTA was present before that time, indicating that in order to provide informative data for diagnosis, PTA assessments should be employed as soon as possible following the injury event.

Referring back to Table 3, the process of disentangling symptoms resulting from confounders, rather than from the injury itself, is not straightforward. But that these can lead to erroneous severity classification gives weight to the importance of their consideration during assessment. Due to the limitations of the GCS in the ability to provide information to guide the clinical management needed to ameliorate the consequences of TBI, other assessment approaches have been suggested. One such approach is the use of biomarkers which can be useful in generating an objective understanding of the pathophysiologic mechanisms underlying symptoms. Biomarkers are measurable indicators or substances in the body that can provide information about a biological process, condition, or disease. Given the previously discussed challenges in diagnosing mTBI (where symptoms can be nonspecific, transient, or delayed) biomarkers show promise as a tool to determine those individuals who may benefit from neuroimaging. Blood-based biomarkers have also been suggested as a means of differentiating mTBI from intoxication which is a significant challenge to accurate mTBI identification (Pozzato et al., 2019). However, it is important to acknowledge the limitations of this in a population where milder injuries have occurred and the exact time of injury may be ambiguous (Posti and Tenovuo, 2021). In an effort to address gaps in the clinical understanding of the utility of biomarkers in the classification of mTBI, Reyes and colleagues (2023) undertook a study aimed at determining the optimal combination of blood based biomarkers in this population. Their findings suggest that multiple biomarkers had a high classification accuracy both in the acute stage (within six hours of mTBI) and seven days post injury.

The use of neuroimaging to characterise the extent of structural and functional damages following a TBI is a well-established practice within medical settings. In particular, neuroimaging provides an objective means of evidencing the extent of injuries in cases of moderate and severe TBIs, yet it is recognised that neuroimaging may not always detect subtle brain injuries. This is an important limitation because the absence of abnormal findings on imaging does not necessarily rule out the presence of brain injury. There is an increasing understanding regarding the metabolic and ultrastructural pathologies associated with mTBI, and so while neuroimaging is predominantly utilised with assessing moderate to severe forms of TBI, it can also be indicated for use in assessing mTBI.

The most common types of neuroimaging techniques that are used to assess TBI, include computed tomography (CT) and magnetic resonance imaging (MRI). When applied to mTBI however, only a small percentage of scans (10-30%) reveal abnormalities (Koerte et al., 2016). There have been promising advances in neuroimaging techniques including functional MRI (fMRI) and diffusion tensor imaging (DTI) with mTBI populations, which provide greater sensitivity than conventional neuroimaging. fMRI techniques have shown promise in providing an indirect measure of neuronal activation, with studies indicating increased activation during moderate task difficulty and decreased activation during complex tasks in mTBI patients (Koerte et al., 2016). While promising, neuroimaging is understandably used selectively for symptomatic cases of mTBI. The results of these techniques can provide valuable information regarding structural changes in specific brain regions, global brain alterations, and their relationship to neuropsychological outcomes in mTBI (Bigler, 2023). Still, just finding these kinds of abnormalities in cases of mTBI has not consistently shown any clear links to how the brain functions afterward. All of this points to the need for more advanced brain imaging techniques that provide detailed information about brain structure, along with a better understanding of the differences in mTBI cases and how brain communication and networks are affected by injury. This idea is supported by a meta-analysis by Wallace et al. (2018), whose presented investigation of DTI showed this to be a promising tool in the detection of microscopic alterations in the white matter. DTI is not routinely done but is available in New Zealand. However, in spite of its ability to detect structural change resulting from mTBI, the causal relationship between DTI changes, symptoms, and neuropsychological performance remains uncertain (Worthington & Moore, 2022).

While brain imaging may be enticing for making informed diagnoses, microscopic brain changes identified through sophisticated technologies may not necessarily have behavioural implications. Because of the limited sensitivity for detecting mild injuries, as well as difficulties with cost and accessibility of these technologies, imaging is not yet a standardised assessment tool for the mTBI population (Mentzer, 2020). As technology advances with time, this approach may become more common, but it's still unclear if imaging can directly link identified lesions with clinical symptoms (Worthington & Moore, 2022).

Clinical interview is a key component of the assessment of patients with mTBI, as it can provide valuable information about the individual’s symptoms, medical history, and functional abilities. Typically, the interview will consist of several components, including a review of the individual’s medical history, a discussion of the injury event, and an assessment of their neurobehavioural symptoms (e.g. depression, anxiety, cognitive difficulties, poor sleep, irritability, headaches etc). These may be supplemented with self-report questionnaires such as the Rivermead Post Concussion Symptoms Questionnaire (RPQ), and Sport Concussion Assessment Tool (SCAT-3), however, clinical interviews are considered more sensitive in detecting symptom nuances and contextual data required to distinguish between pre-injury and injury-related symptoms (Emmert et al., 2021). Gathering details about the injury includes ascertaining any LOC, duration of PTA, and any associated symptoms experienced immediately after the injury. Commonly, individuals will be asked about headaches, dizziness, nausea, visual disturbances, noise or light sensitivity, and psychological symptoms. If cognitive symptoms are present, the data gathered during clinical interviews can be supplemented with neurocognitive assessment.

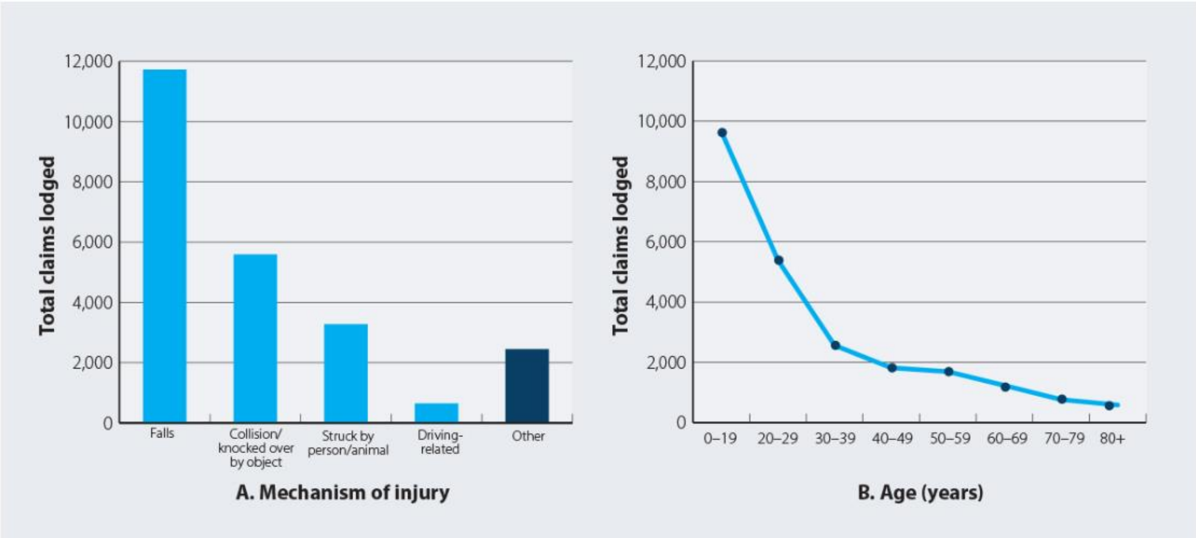
In summary, assessment for the presence and severity of TBI, particularly mTBI, presents diagnostic challenges requiring a comprehensive and often multi-faceted approach. Key severity indicators such as alteration in consciousness, LOC, and PTA play crucial roles in determining TBI severity, however, there are inherent limitations when each factor is considered in isolation. Additionally, diagnostic protocols can be confounded by factors like intoxication. Therefore, while technology and research are advancing, it might be that the way forward for TBI assessment and diagnosis is to steer away from oversimplified concepts in which a diagnosis provides a singular, mutually exclusive explanation for an individual's experience following injury (Zogas, 2022). Despite limitations, as it stands currently, the assessment of duration of loss of consciousness, presence and duration of PTA, and initial scores on the GCS remains the gold standard for assessing TBI. While there are known biomarkers for TBI and mTBI, their clinical utility is not readily accessible outside of hospital settings. Neuroimaging techniques are still in the early stages of development and are most effective for detecting features of moderate to severe TBI, although efforts are underway to refine these tools for the identification of mTBI-related changes (e.g., DTI and fMRI). Finally, it is important to emphasise that clinical interviews, where individuals are directly asked about their experiences, continue to be the most effective means of gathering information on mTBI. Therefore, to ensure optimal assessment practices, a combination of utilising diagnostic tools such as the GCS and PTA measures alongside engaging in direct conversations with individuals should be employed.

2.6 Mild Traumatic Brain Injury in the New Zealand Context

There are multiple mechanisms by which mTBI are incurred. In the New Zealand context, the most common pathways to injury are falls, colliding with an object, being struck by a person or animal, and driving/bike riding related accidents. Figure 3 provides the prevalence of both mechanism of injury and age at which they occurred.

Figure 3

New Concussion Injury Claims made to ACC between 1 July 2020 – 30 June 2021 by (A) Mechanism of Injury and (B) Age Group in New Zealand.



Note. This time period falls between the first and second nationwide lockdowns associated with the COVID-19 pandemic, and therefore data is not expected to be significantly affected by corresponding restrictions on people's activities and daily living. The data and associated trends for this period are similar to observations for previous years. Retrieved from: https://bpac.org.nz/2022/concussion.

The Accident Compensation Corporation (ACC) is a no-fault insurance scheme in New Zealand that extends coverage to all residents if they are injured in an accident. It also extends to visitors to the country. This comprehensive coverage addresses various aspects of injury recovery, encompassing financial support for treatment, assistance at home and work where required, and aid in managing income disruptions. As has been noted earlier in this chapter, the terms "concussion" and "mTBI" are often used interchangeably. ACC recognises this linguistic convention and acknowledges that, while "mTBI" is the technically accepted term, they employ "concussion" to describe the interdisciplinary 'Concussion Service' dedicated to supporting recovery from mTBIs (ACC, 2023).

ACC estimate that 36,000 people in New Zealand sustain a traumatic brain injury (TBI) each year, with younger males at the highest risk. Similar to global estimates, the vast majority of these (95%) are mild in severity. To understand the financial burden of such injuries, it is reported that, an average of approximately 21,000 new concussion-related claims per year were lodged with ACC in New Zealand (Kara, 2022). This is a unique population when compared to those reporting many other medical conditions in New Zealand because prior to injury, these are typically active and otherwise healthy individuals (Sussman et al., 2016).

Māori and Pacific peoples have a reported 23% higher risk of mTBI compared with NZ Europeans (Lagolago et al., 2015). This inequity is common across many medical conditions and provides clear rationale for providing culturally appropriate care in the New Zealand context. As has been discussed more broadly, management of the consequences of mTBI is not a one-size-fits-all approach. The Traumatic Brain Injury Strategy and Action Plan (2017–2021) (ACC, 2017) notes that education, management and service provision following a mTBI should be culturally responsive for Māori in particular. ACC encourages the use of Māori centred models such as the Whānau Ora model which provides a framework for addressing the comprehensive needs of individuals and their families affected by mTBI in a culturally safe way. Guidelines published by ACC (2021) stress the importance of "addressing individual needs in the context of their whānau as a whole. For example, consider how the concussion management advice of "rest to re-engagement" will impact on the role and responsibilities of the patient within their whānau and conversely, the important role that whānau has in providing strength and support for their recovery. This process may be aided by involving a Māori health provider in the care plan, and including relevant cultural practices into a tailored rehabilitation strategy". Encouragingly, ACC now funds traditional Māori approaches to care and healing depending on the cultural need (ACC, 2021).

2.6.1 ACC Concussion Service

The Concussion Service is an interdisciplinary service designed to provide assessment and therapeutic support following a mild to moderate TBI with the goal of facilitating recovery. Its primary goal is to prevent long-term consequences and to provide early intervention so that injured individuals can get back to their everyday lives as quickly as possible. The Concussion Service operates under three core philosophies: recognising individual needs, employing an interdisciplinary team approach, and prioritising strong relationships between ACC, suppliers, clients, and their families. Individuals who meet the criteria outlined in Table 4 can receive specialised care through the Concussion Service. When referred to this service, individuals are assigned a dedicated key worker who coordinates their assessment and treatment. The

Operational Guidelines for the Concussion Service (2023) detail the provision of a holistic approach to care, involving medical evaluation, physiotherapy, and psychology review to address the multifaceted nature of mTBI injuries. Evaluation through a neuropsychological screen is available when deemed necessary, and if recovery does not progress within the scope of the Concussion Service, clients can then be referred to additional services offered by ACC or external agencies. Whilst not a rigid or inflexible process, Figure 4 shows the general pathway through the Concussion Service in New Zealand.

Table 4

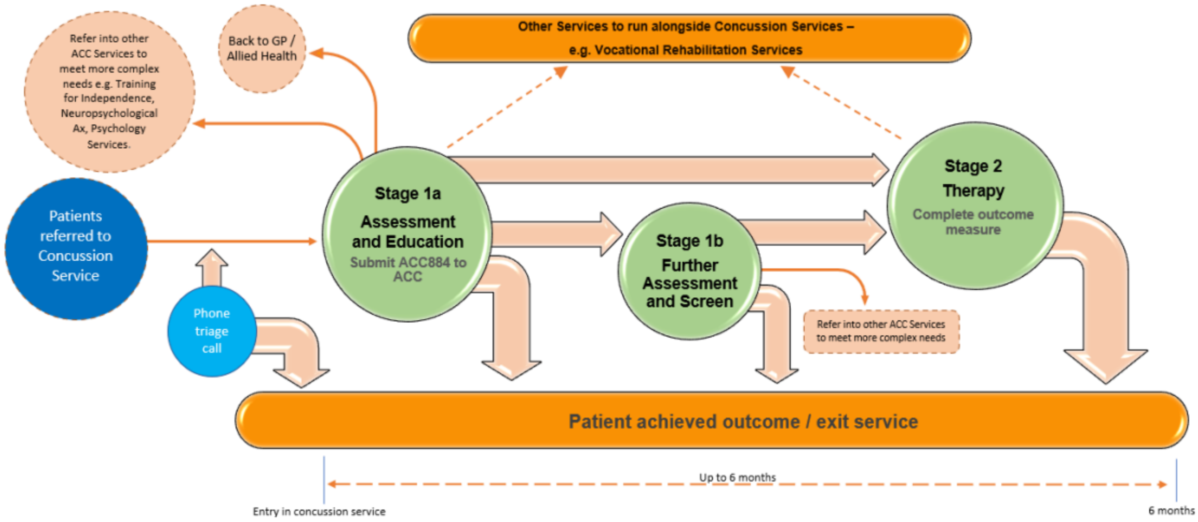
Concussion Service Eligibility Criteria

Client must…	And	And
• Have sustained a TBI (or suspected TBI) • Have an accepted ACC claim • Be diagnosed with or be suspected of having a mild TBI, moderate TBI or persisting concussion symptoms	Has at least one of the following on-going signs and symptoms such as: • mood changes • memory problems • fatigue • difficulty concentrating • loss of balance • headaches • visual disturbances • nausea • muscular aches • dizziness	Have at least one of the additional risk factors such as: • the inability to work or attend school for more than one week • second or subsequent mTBI within six months • post traumatic amnesia lasting more than 12 hours • a requirement to operate machinery at work • a pre-existing psychiatric disorder or substance abuse problem • a high functioning job such as engineer, medical practitioner or lawyer • currently attending secondary or tertiary education

Adapted from The Operational Guidelines for the Concussion Service (2023)

Figure 4

Suggested Pathway Through the Concussion Service



Note. Retrieved from: https://www.acc.co.nz/assets/contracts/concussion-og.pdf

2.7 Management and Rehabilitation of Mild Traumatic Brain Injury

Literature has historically reported that the majority of people with mTBI recover within the first few weeks postinjury. For example, Mayer et al. (2017) report that in 80-95% of mTBI cases, impairment is indetectable on neurobehavioral measures 3–6 months postinjury. Other research challenges this, suggesting that almost 50% of the mTBI population experienced postconcussion symptoms 1 year post injury (Theadom et al., 2016). These discrepancies in the literature pose significant challenges for individuals who continue to suffer prolonged consequences following mTBI. On one hand, the prevailing narrative of rapid recovery may undermine their experiences, leading to a lack of recognition and support for ongoing symptoms. Conversely, those who do not fit the expected trajectory of recovery may feel isolated and invalidated by research suggesting that they should have recovered by a certain timeframe. Several factors may contribute to these discrepancies in the literature. Methodological differences, such as variations in sample characteristics, outcome measures, and follow-up periods, can lead to divergent findings. Additionally, the heterogeneity of mTBI itself, with variations in injury mechanisms, severity, and individual characteristics, may contribute to disparate recovery trajectories among patients. Furthermore, factors such as pre-injury mental health, socioeconomic status, and access to healthcare may influence recovery outcomes but are not consistently accounted for in research studies. Despite the challenges in navigating discrepant research findings, it is now widely acknowledged that the consequences of persistent postconcussion symptoms are significant, impacting various aspects of individuals lives. Therefore, the primary rehabilitative goal following mTBI must be to maximise quality of life and improve functional outcomes where possible (Mee et al., 2021). As has been discussed throughout this chapter, mTBI's by nature are heterogenous and so individualised approaches are necessary to address the functional consequences that are most impactful.

For mTBI, where symptoms may be subtle, symptoms usually fall into three main categories: physical, cognitive, and behavioural/emotional. Acknowledging that in the majority of cases, recovery occurs rapidly, the focus of treatment should begin with the provision of education on mTBI, including its signs, symptoms, and the expected recovery timeframe. This education has been associated with improved symptom management (Eapen et al., 2022). Providing individuals with an understanding of the impairments that have resulted from their injuries assists them to comprehend the pathology of mTBI and to consider and employ compensatory strategies that can mitigate functional impairments (Goka, 2000). Furthermore, this knowledge can ameliorate the anxiety and frustration that individuals experience when managing post-mTBI symptoms – which in turn promotes effective rehabilitation. Goka (2000) claims that "gaining an understanding of the problems is usually half the treatment" (p. 197).

Relating to the more practical approaches to managing symptoms that have arisen due to a mTBI; historically, recommendations have emphasized strict rest for both physical and cognitive activities until symptoms resolve (Carter et al., 2021). As will be discussed further in the following chapter relating to fatigue, evidence has challenged the efficacy of strict rest following mTBI. Rather, research has shown that strict rest does not provide any benefits in reducing symptom severity compared to no rest, and that it may even slow down recovery (de Kruijk et al., 2002; Howell et al., 2016; Silverberg et al., 2013; Thomas et al., 2015). Prolonged rest can lead to the exacerbation of secondary symptoms such as fatigue, reactive depression, anxiety, and physical deconditioning (Schneider et al., 2017). As a result, current recommendations encourage a return to light physical activity after an initial period of 24-48 hours of rest (McCrory et al., 2017).

A recent systematic review and meta-analysis of 23 studies relating to active rehabilitation on mTBI management provides compelling evidence supporting the benefits of physical activity interventions in the recovery phase following injury (Carter et al., 2021). The majority of these studies were reported to consistently show that physical activity interventions resulted in a significant decrease in post injury symptoms. Importantly, the review found no adverse events from physical activity reported in any of the studies, confirming the safety of physical activity interventions for this population. The studies also demonstrated that physical activity led to improvements across different symptom domains, including physical, cognitive, emotional, and sleep-related symptoms. These findings suggest that exercise can have a positive impact on various aspects of mTBI recovery.

When considering the findings of the aforementioned review by Carter et al. (2021), it should be noted that other published reviews in this area have highlighted the limitations of previous meta-analyses. For example, Vuu and colleagues (2022) have suggested that reviews are often specific to specific subgroups such as exercise type, injury cause, age, or time since injury, and that this leads to bias in the reported results.

The underlying mechanisms behind the positive influence of physical activity on Post Concussive Syndrome (PCS) reduction are not fully understood. Physiologically, exercise may improve cerebral autoregulation and promote neuron growth and repair. Psychosocial factors, such as reducing fear of physical activity and illness perception, may also contribute to symptom improvement. Furthermore, encouraging individuals to reengage in physical activity can promote re-integration into social environments, which is believed to be important for symptom recovery (Carter et al., 2021).

Currently, there is a lack of a definitive biomarker that can objectively determine the resolution of mTBI and so clinical recovery is best assessed based on the resolution of symptoms, and the ability to engage in regular daily activities, including vigorous exercise for athletes (Silverberg et al., 2020). In cases where symptoms do not resolve during the expected period, treatment should shift to target the specific symptoms that persist. Silverberg et al. (2020) reiterate that persistent symptoms typically have multiple contributing factors and do not stem from a single cause. The interplay of biopsychosocial factors plays a significant role in the manifestation of these symptoms, many of which are not exclusive to mTBI. Therefore, clinicians should prioritise the treatment of symptoms that are most amenable to intervention and likely to have a positive impact on other symptoms as well. A relevant example for the current research is that by focusing on the amelioration of fatigue, for example, other symptoms (e.g., headaches, anxiety, depression, irritability etc.) might organically improve, with flow of positive effects on the individuals overall quality of life.

2.8 Summary

This chapter has outlined the challenges associated with defining and assessing TBI, with a specific focus on mTBI and/or concussion. The heterogeneous nature of TBI and the interchangeable use of terms like "concussion" and "mTBI" were discussed, emphasising the need for clear definitions.

The pathophysiology of mTBI was explored, highlighting the distinction between primary and secondary injuries. Primary injuries result from the mechanical forces during impact, while secondary injuries involve the additional tissue and cellular damage that occurs afterward. Inflammation plays a critical role in the pathophysiology, with the mechanical impact triggering an inflammatory response that can lead to further damage to the brain.

The limitations of the Glasgow Coma Scale (GCS) as a tool for assessing TBI severity are acknowledged, although it remains the most widely adopted instrument for doing so. The potential of biomarkers and neuroimaging techniques for assessing TBI severity have also been discussed and show promise in diagnosing TBI, monitoring recovery, and predicting long-term complications. However, neuroimaging remains prohibitively expensive and may not always capture subtle injuries in mTBI. Advances in this area are likely, but it should be acknowledged that imaging cannot necessarily detect the primary cause of subjectively experienced symptoms, and so the clinical interview remains the most effective means of gathering information on mTBI at an individual level.

The consideration of mTBI in a New Zealand context was important for this research. Considering that of the estimated 36,000 people in New Zealand who experience a TBI each year the majority are classified as mild injuries, the need for further focus at this end of the severity spectrum is justified. It is also important to keep in mind the observed disparity in the risk of injury to Māori and Pasifika people – which highlights the importance of culturally responsive care in managing mTBI.

Finally, given the diverse symptoms and overlapping confounders, the need for taking an individualised approach to management and care post-mTBI is emphasised. Educating individuals on mTBI is considered to be a crucial first step in the management of all individuals, which can be followed up with treatment targeting specific persistent symptoms should that be necessary.

Chapter Three: Fatigue

3.1 Overview

Similar to other medical and neurological conditions, fatigue is a widespread and persistent sequelae of TBI, with a reported prevalence ranging from 20% to 75% (Ouellet et al, 2020). Studies have shown that while the prevalence of fatigue decreases with injury severity, a significant proportion (29-59%) of individuals with mTBI experience problems with fatigue three months post-injury (Norrie et al., 2010). Similar to many other symptoms of TBI, fatigue tends to decrease in the first year following injury and remains relatively unchanged in subsequent years after injury (Khan & Bhasker, 2018).

The purpose of this chapter is not only to explain definitions of fatigue within the context of TBI, but also to explore the physiological and psychological mechanisms that contribute to this symptom, and the impact it has on the daily life of individuals who have experienced TBI. The chapter will then explore the available assessment tools for measuring fatigue in individuals with TBI, and the current treatment options for managing and reducing fatigue. This will include a discussion of the use and effectiveness of medications, physical therapy, and psychological interventions. The chapter will conclude by highlighting the current gaps in knowledge and the need for further research in this area.

3.2 Understanding and Defining Fatigue Following Traumatic Brain Injury

As a multidimensional construct that denotes a primarily subjective experience, there is no current, universally accepted definition of fatigue (Cantor et al., 2013). This has implications when reviewing extant literature because divergent attempts to define fatigue mean that it is often difficult to accurately measure its prevalence (Phillips, 2015), and therefore there is uncertainty relating to the overall health burden of this symptom following TBI (Mollayeva et al., 2014). One of the more commonly adopted definitions of fatigue in literature relating to TBI is the definition proposed by Aaronson et al. (1999) who conceptualise fatigue as "the awareness of a decreased capacity for mental and/or physical activity, because of an imbalance in the availability, utilization or restoration of resources needed to perform activities" (p46). This definition is considered to be useful because it acknowledges the subjective nature of fatigue, and positions it within a self-monitoring framework.

Adding to the complexity of describing fatigue, and understanding its nuances in literature, is the tendency to categorise it in varied ways. For example, in colloquial language, fatigue is often used to describe a feeling of tiredness or exhaustion resulting from physical or mental exertion (Phillips, 2015). However, research literature naturally leans towards more formal definitions which propose various categorisations of fatigue to explain the phenomena more clearly within the context of specific populations. For example, within the context of TBI populations it is common for authors to separately describe physiological fatigue (referring to the state of general tiredness due to physical or mental exertion, which can be ameliorated by rest) and pathological fatigue (referring to a weariness unrelated to previous exertion level, and not ameliorated by rest) (Mollayeva et al., 2014). Fatigue can be further categorised as either peripheral or central fatigue, depending on the origin of the dysfunction. Peripheral fatigue typically refers to impaired muscle performance secondary to physical exertion, whereas central fatigue is perceived at the level of the central nervous system and can be defined as the failure to initiate and/or sustain attentional tasks and physical activities that require self-motivation (Chaudhuri & Behan, 2004; Ezekiel et al., 2021).

Further adding to the complexity of describing fatigue is its relationship with phenomena such as apathy. Like fatigue, apathy is a common sequela following TBI, reportedly affecting up to 70% of individuals (Lane-Brown & Tate, 2009). Apathy denotes a lack of interest, motivation, or emotion, and while sometimes considered related, the concepts of fatigue and apathy represent distinct affective states with different underlying mechanisms. While fatigue pertains to a decreased capacity for activity due to resource imbalance, apathy encompasses a lack of motivation or interest in engaging in activities. Despite their differences, these phenomena frequently co-occur, complicating their assessment and management in clinical settings. In their research, Lacourt et al. (2020) shed light on the intricate relationship between apathy and fatigue following mTBI and showed that it is possible to distinguish apathy from constructs with overlapping symptomatology, such as depression and fatigue. This underscores the importance of conducting simultaneous assessment of constructs with overlapping symptomatology and aligns with the holistic approach advocated in my research. While apathy has not been directly measured in my study, the importance of considering overlapping conditions like depression and fatigue is evident.

It is also common for authors of literature related to TBI populations to differentiate between primary and secondary fatigue. When referring to primary fatigue in a broad sense, fatigue is understood to be caused by a specific disease/disorder. Therefore, primary fatigue following a TBI is considered to be directly caused by the brain injury itself. Examples of primary fatigue in individuals with TBI are thought to be related to disruption or damage to circuits that connect the basal ganglia, amygdala, thalamus, and frontal cortex (Chaudhuri & Behan, 2004). In contrast, a broad definition of secondary fatigue refers to fatigue caused by exacerbating factors that cannot be directly attributed to a specific disease/disorder/brain injury. These factors can include sleep disorders, pain, depression, and a decrease in the ability to tolerate physical or mental activity (Bushnik et al., 2008). These varied categories of fatigue are useful to understand within the context of TBI because they allow consideration of the experience of fatigue acknowledging multiple aetiological pathways.

Kuppuswamy (2022) perhaps describes fatigue most pertinently as the ‘Cinderella’ of affective symptoms. By this, it is implied that fatigue is often considered a secondary symptom due to its frequent association with various other affective symptoms. However, as Kuppuswamy has identified, treatments aimed at addressing the potential ‘primary’ issue have not always proven effective in reducing fatigue, leading to the hypothesis that fatigue may be a primary problem driven by its own distinct causes. And additionally, despite its complexity, it is possible to consider the existence of a shared mechanism rooted in the impaired functioning of a fundamental aspect of brain processing. Without discounting academic debate, on a basic level, it seems universally accepted that fatigue is a multidimensional phenomenon that is likely to require diverse approaches to effectively address it. Interventions should therefore acknowledge the potential complexities of its origin so as to best address fatigue in a comprehensive way, considering the physical, cognitive, and psychosocial components.

3.3 Adverse Impacts of Fatigue Following Traumatic Brain Injury

The consequences of fatigue for individuals with TBI are multi-dimensional, adversely affecting physical, cognitive, and emotional functioning, as well as impeding the individual's quality of life and their ability to participate in daily activities (Khan & Bhasker, 2018). Because of these wide-ranging impacts, as well as its persistent duration, fatigue is considered to be one of the most distressing symptoms following TBI (Lannsjö, 2009). It is thought to interfere considerably with the ability to resume work post injury, and to be a barrier to engagement in social activities with family and friends (Ezekiel, 2021). By limiting their engagement in social and physical activities, individuals with fatigue post TBI have been found to increase sedentary and home-based activities (Theadom et al., 2017). Considering the benefits of engaging in physical and social activities for overall health and wellbeing in the general population, it is of concern that individuals post TBI experience difficulties in these areas. A study by Cantor et al. (2008) suggested that it is the quality of participation in activities of daily life that are most negatively impacted – more so than the frequency with which one engages. For example, while a person may still be able to attend social events or prepare meals for their family, they may experience less enjoyment or satisfaction from these activities than they did prior to injury - due to the increased difficulty resulting from fatigue.

It has been reported that many individuals with fatigue following TBI engage in compensatory strategies such as staying in bed for long periods, taking naps during the day, and/or avoiding or abstaining from certain activities (Norrie et al., 2010). While these strategies may provide temporary relief in the moment, there is a risk that they lead to a further decline in functioning. This is especially relevant considering the benefits of physical and social activity which ultimately contribute to improved quality of life. Additionally, mTBI is associated with a significantly increased risk of having subsequent depression and anxiety (Delmonico et al., 2021). Fatigue is a known symptom of depression and is also associated with anxiety, possibly by contributing to insomnia. However, it should also be considered that the experience and consequences of fatigue may have a causal contribution to depression and anxiety.

3.4 Aetiology of Fatigue Following Traumatic Brain Injury

The underlying causal mechanisms of fatigue following TBI are not currently well understood, and this has obvious implications for progressing the development of effective treatment approaches (Zgaljardic et al. 2014). Many hypotheses have been presented which explain some aspects of the experience, however there is still a lack of understanding of the specific clinical, behavioural, and physiological factors that are associated with its presence, development, and amelioration post injury (Mollayeva et al., 2014).

3.4.1 Neuropathology and Genetics

Given that fatigue is a common sequela of a large number of neurological conditions (e.g., multiple sclerosis, Parkinson's disease, myasthenia gravis, stroke, and others), it is largely acknowledged that it has a neuropathophysiological basis (Kluger et al., 2013). This neuropathological pathway to fatigue following TBI has been supported by several studies. For example, in their meta-analysis, Cantor et al., (2008) found that a significant amount of fatigue post TBI is caused by the injury itself and is not related to comorbid conditions such as pain, depression, or sleep quality. In a cohort of 88 individuals with TBI, fatigue was found to be a predictor of depression and sleepiness. The authors of this study suggest that fatigue therefore likely has a neurological basis and can be considered a primary problem after TBI (Schonberger, Herrberg, & Ponsford, 2014).

The neuropathology of fatigue post mTBI is complex and not fully understood, but research has suggested that post mTBI fatigue is significantly correlated with the observation of aberrant functional connections of the thalamus and medial frontal gyri (MFG) (Nordin et al., 2016). Due to the thalamus having a key role in motor control, regulation of autonomic processes, and processing of sensory signals, thalamic injuries can impair the efficiency of these operations and lead to fatigue. Likewise, the MFG is a critical area where dorsal and ventral attention networks converge, playing a central role in attentional control. If disrupted following mTBI, it is plausible to expect that individuals will be required to exert more mental effort to perform complex tasks and eventually lead to fatigue (Ziino & Ponsford, 2006).

Additional theories propose that an imbalance between effort and reward, along with dysfunction within the cortico-striatal network, significantly contributes to cognitive fatigue following brain injury (Dobryakova et al., 2013). This imbalance reflects the discrepancy between the effort exerted in tasks and the expected rewards or outcomes. In contrast, alternative proposals suggest that fatigue may originate from basal ganglia dysfunction, disrupting the integration of limbic input and motor functions, consequently affecting the striatal-thalamic-frontal cortical system (Chaudhuri & Behan, 2004)

Genetics have also been posited to play a role in the development of fatigue following TBI, with studies showing that individuals who carry the APOE epsilon4 allele experienced twice as much fatigue after a mTBI compared to before the injury. No increase in fatigue was found in the control group with the APOE epsilon4 allele without TBI (Sundstrom et al., 2004).

3.4.2 Cognitive Impairments

Van Zomeren et al. (1984) proposed the coping hypothesis to explain fatigue following TBI. According to this theory, fatigue arises from the additional effort individuals must exert to compensate for cognitive impairments linked to TBI, such as slower information processing and attention difficulties. They suggest that the ongoing and heightened effort needed by TBI patients to manage daily tasks could account for their experience of fatigue. Several authors have investigated this concept experimentally, with some studies showing associations between mental effort and subjective fatigue (Azouvi, 2004; Ziino & Ponsford, 2006). However, other studies have not demonstrated a decline in performance over time compared to controls, thus failing to support the idea that fatigue is solely a result of cognitive impairment (Belmont, 2006; Van Zomeren, 1998).

3.4.3 Psychological Factors

Psychological factors are thought to have an impact on the presence and severity of an individual's experience of fatigue (Anderson et al., 2009). Depression and anxiety are commonly comorbid with TBI, and because fatigue is widely understood to be a symptom of these disorders, it is thought that psychological factors can exacerbate fatigue following a TBI. This can work in a bidirectional manner, because while fatigue and psychopathology clearly occur separately from one another and may have distinct contributory factors following TBI, they also commonly co-occur and are interrelated. Put more simply, depression and anxiety can exacerbate fatigue, and fatigue in return may lead to the consequential development of those disorders (Ymer et al., 2021).

In addition to depression and anxiety, PTSD is a prevalent psychological comorbidity following TBI and has been linked to heightened fatigue levels. The intrusive memories, hypervigilance, and avoidance behaviours characteristic of PTSD can exacerbate cognitive and emotional fatigue, complicating the clinical presentation and management of fatigue in TBI survivors.

3.4.4 Demographic Factors

Whether or not there are demographic predictors of the presence and/or severity of fatigue following TBI has been debated in literature and requires further investigation. However, findings from Andelic et al's, (2020) study support earlier literature suggesting that females experience greater levels of fatigue post TBI when compared to males. One explanation of why this gender disparity may exist is discussed in a broader study of gendered TBI outcomes which suggests women have higher propensity to self-report symptoms more generally following TBI (Alves, 2020). Other research has looked more broadly at this issue, suggesting that differing responses to outcome measures following TBI may be somehow impacted by gender differences in socialization as well as gender-role expectations, and that as these constructs shift and change over time, the relationship between gender and the experience of fatigue following a TBI may also shift (Colantonio et al., 2010; Niemeier et al., 2014).

It has been reported that people with higher levels of education tend to experience more severe fatigue following TBI (Andelic et al., 2020; Ziino & Ponsford, 2006). This may be linked to a general trend where individuals with higher education tend to report more symptoms, potentially due to their greater knowledge of health issues and their use of healthcare services (Cutler & Lleras-Muney, 2010). It has also been suggested that because individuals with higher levels of education often have jobs that require greater cognitive effort, the subjective experience of fatigue may feel more detrimental to them when compared with people who have a job requiring relatively less cognitive effort (Andelic et al. 2020).

3.4.5 Premorbid Variables

Finally, premorbid variables such as emotional and mental health issues, personality characteristics, pre-existing fatigue, and other health conditions may contribute to an individual's vulnerability to post TBI fatigue. A recent study found that trait extraversion, conscientiousness, and optimism were found to be protective in building resilience and mitigating fatigue, while trait neuroticism, loneliness, behavioural inhibition, and psychological distress were associated with vulnerability to post TBI fatigue (Loke et al., 2022). This has also been demonstrated in an earlier study which reported associations between high neuroticism, low extraversion and low conscientiousness and fatigue (Merz et al., 2019).

3.4.6 Aetiological Summary

In summary, the aetiology of fatigue post-mTBI involves neuropathological, cognitive, psychological, demographic, and premorbid factors. Aberrant functional connections in brain regions like the thalamus and medial frontal gyri, along with cortico-striatal network dysfunction, contribute to fatigue. Genetics, cognitive impairments, psychological factors (e.g., depression, anxiety, PTSD), demographics (e.g., gender, education level), and premorbid variables (e.g., personality traits, mental health issues) also play significant roles. Understanding these factors is crucial for tailored interventions and effective management of post-mTBI fatigue.

Overall, understanding the multifaceted etiology of fatigue post-mTBI involves considering a wide array of factors, highlighting the complexity of this symptom and the need for comprehensive assessment and tailored interventions. Additional research is required to better understand the interactions of the factors that are likely to be contributing to fatigue following TBI. This will benefit the development of evidence-based approaches to its management (Bay & Xie, 2009; Bushnik et al., 2008).

3.5 Assessment of Fatigue Following Traumatic Brain Injury

Given the general lack of consensus in the literature on a definition of fatigue, it is not surprising that measuring post TBI fatigue continues to challenge both researchers and clinicians. Not having a universally accepted definition or standardized measurement tool for fatigue in this population leads to variability in how it is reported. The extant literature reviewed for the current study is generally explicit on the definition and methodology utilised within those specific scientific investigations, but divergent definitions of fatigue can make it difficult to compare findings and establish a clear understanding of the prevalence and impact of fatigue after mTBI. Furthermore, the subjective nature of fatigue means it is difficult to measure and challenging to investigate empirically (Aaronson et al., 1999).

While some research groups have attempted to quantify fatigue objectively after TBI using neuropsychological tests (e.g., Ashman et al., 2008; Johansson & Ronnback, 2015; Ziino & Ponsford, 2006), the use of self-reported measures is likely more effective at capturing the subjective nature of the fatigue experience following TBI. Visual analogue scales (VAS) are commonly used, and in studies relating to the efficacy of light therapy, the Fatigue Severity Scale is predominant. However, Mollayeva et al. (2014) have highlighted the fact that several other self-assessment scales for fatigue have been utilised in the investigation of fatigue post TBI. They suggest that variability is inevitably introduced across studies based on the unique objectives, and importantly on the measures used. Mollayeva et al. reported that in studies where fatigue was not the main focus, it was often measured through a single item within a checklist that covered a wide range of symptoms. However, when fatigue was studied more extensively, standardized measures looking at different aspects of fatigue were employed.

The most common approaches reported in this systematic review were the use of multi-item scales, such as the fatigue severity scale (FSS), short-form health survey-36 (SF-36) vitality subscale, visual analog scale (VAS) for fatigue, and profile of mood states (POMS) fatigue-inertia scale (Mollayeva et al., 2014). These scales provided insights into fatigue perception, chronic characteristics, impact on function, intensity/severity ratings, and dimensions of fatigue.

The FSS has gained widespread acceptance in TBI research due to its ease of administration and sensitivity in distinguishing fatigue levels between brain-injured individuals and controls. Studies by Belmont et al. (2009), LaChapelle and Finlayson (1998), as well as Ziino and Ponsford (2006), have highlighted the FSS's ability to effectively differentiate fatigue in TBI populations from that in control groups. This differentiation underscores the scale's utility in capturing the unique fatigue experiences of individuals with brain injuries. Moreover, the FSS has shown promise in assessing treatment response in TBI populations (Sinclair et al., 2014; Nguyen et al., 2017). Its sensitivity to changes in fatigue levels over time suggests its potential utility in monitoring therapeutic interventions and evaluating their effectiveness in alleviating fatigue symptoms post-TBI. However, despite its widespread use and demonstrated effectiveness, the FSS is not without limitations. One notable concern is that while the FSS provides valuable insight into the impact of fatigue on daily activities, it may lack specificity in distinguishing between different dimensions of fatigue (e.g., physical vs. cognitive fatigue) (Schiehser et al., 2015). Additionally, alongside many other measures of fatigue, the FSS relies on self-report, which introduces the possibility of response bias and subjective interpretation of fatigue severity. For example, individuals may vary in their perceptions and expressions of fatigue, potentially influencing the reliability and validity of FSS scores. Finally, cultural and linguistic factors may influence the interpretation of FSS items, potentially impacting the scale's cross-cultural validity and generalisability across diverse populations.

Importantly, there is currently no universal consensus regarding the best-practice assessment tools for fatigue in the TBI population, and therefore heterogeneity is high between studies (Johansson, 2021). The wide array of assessment tools and approaches used to measure fatigue in TBI cohorts has an impact on the ability to generalise results from research in this population, and the field would benefit from improvements in recommended assessment guidelines.

Using brain imaging as an assessment tool for fatigue after TBI is an emerging research area, and although altered activity and connectivity has been demonstrated in relation to fatigue following TBI, results are not consistent. Johansson (2021) has summarised the study characteristics of research relating to brain imaging techniques, and these can be found in Appendix A.

3.6 Current Treatment Approaches for Fatigue Following Traumatic Brain Injury

Variability in the definition and assessment of fatigue following TBI arguably creates difficulty in the development of effective treatment approaches. Recent reviews investigating the efficacy of interventions for fatigue in this population have noted these shortcomings and highlighted the need for a clearer definition of post TBI fatigue. They also suggest a need for research to strive for larger sample sizes and the replication of results (Shuman-Paretsky et al., 2017; Xu et al., 2017).

In an attempt to update and expand upon these reviews, Ali et al., (2022) broadened their inclusion criteria to provide a comprehensive systematic review of 37 publications exploring the efficacy of treatment approaches for post TBI fatigue. Even in doing so, they reported several limitations to their review, the most notable being the methodological variations among studies that has meant quantitative meta-analyses could not be conducted. Considering this, future research should focus on investigating potential interventions with larger sample sizes, more rigorous methodologies, and replication to strengthen initial indications of effectiveness. Until such a time, Ali et al. suggest that given the multifaceted nature of fatigue following TBI, it is advisable to employ multimodal clinical treatment approaches that encompass sustainable levels of physical exercise, medication, and therapy delivered by a multidisciplinary rehabilitation team. This recommendation remains pertinent until more specific mechanisms and treatments pertaining to fatigue are elucidated.

3.6.1 Exercise-based interventions

Many clinicians encourage their clients with TBI related fatigue to incorporate exercise into their recovery plans. There are several published studies that provide an evidence-base for this (e.g., Chin et al., 2015) but as is the case with much research in this field, small sample sizes and inconsistent methodology make it difficult to draw clinical recommendations (Shuman-Paretsky et al., 2017). The caveat surrounding the evidence for physical activity treatments in Cantor et al.'s review was that the included studies were generally underpowered. Consistent with those findings, a review by Xu, Li, Wang and Cao (2017) also concluded that the efficacy of exercise-based interventions required further investigation.

It appears that a bidirectional relationship exists between activity and fatigue. From one perspective, fatigue following TBI can contribute to a loss of motivation and decrease in activity which likely disrupts the daily routine and contributes to an exacerbation of fatigue. This is a problematic interplay because it is considered that maintaining a regular routine and staying active are factors that enhance motivation and general well-being, and therefore decrease fatigue. This means that fatigued individuals are at an additional disadvantage in not having the required capacity to engage in the activities which have been shown to ameliorate their symptoms. There is a natural temptation to rest in response to fatigue, but how much rest is most advantageous remains a controversial topic after TBI.

As has been discussed earlier in this thesis, in the acute phase of the injury rest is promoted. However, in the long-term, replacing activity with rest probably contributes to perpetuating fatigue and may hinder recovery (Ouellet & Morin, 2006). In a study comparing outcomes between individuals who undertake prolonged and strict rest for five days following TBI and those who engage in some form of physical activity after 24 – 48 hours, it was found that the strict-rest group took an average of three days longer than the activity group to report that they had recovered (Thomas et al., 2015).

The mechanisms by which exercise is thought to promote recovery post TBI include improving cerebral blood flow and promoting production of brain-derived neurotrophic factor (BDNF).

Cerebral blood flow is linked with promoting cellular repair by increasing the delivery of oxygen and glucose to the brain. BDNF is an exercise dependent protein that functions to support the survival of existing neurons and encourages the growth and differentiation of new neurons (bpac.org.nz, 2022).

As well as it's efficacy in mitigating fatigue, Bellon et al., (2015) have demonstrated a relationship between physical exercise post TBI and symptoms related to depression and stress. This might suggest that physical exercise is an appropriate intervention for those individuals whose fatigue relates to secondary causes.

3.6.2 Pharmacological Interventions

Pharmacological interventions have been shown to have mixed efficacy in treating fatigue post TBI. Positive effects from methylphenidate have been shown (Johansson et al., 2014; Johansson et al., 2015), however, these studies have been limited by small sample sizes. Ali et al., (2022) considered pharmacological interventions in their review. They found that methylphenidate demonstrated significant reductions in fatigue symptoms post TBI across multiple studies, while the results for modafinil were mixed. Other pharmacological interventions, such as melatonin and creatine, showed significant improvements compared to controls, while some agents did not demonstrate significant improvements. Overall, Ali et al. concluded that more research is needed to establish the efficacy of pharmacological interventions for fatigue in this population.

When considering the efficacy of certain pharmacological treatments prescribed post mTBI, it is important to consider that some can potentially worsen fatigue. The impact of medications like antidepressants remains a subject of controversy in the literature. Some studies have reported an improvement in cognitive functions through the reduction of depression, while others have found an increase in both fatigue and cognitive dysfunction following antidepressant use (Heslot et al., 2021).

3.6.3 Psychological interventions

In the literature reviewed, various psychological interventions have been proposed as potential strategies for individuals who have experienced TBI. Cognitive-behavioural therapy (CBT) can help individuals with TBI identify and change negative thought patterns and behaviours that may be contributing to their fatigue. Hodgson et al., (2005) evaluated the efficacy of a 9-14 session CBT intervention which reduced fatigue, with a medium effect size (0.4) when compared with controls. Ali et al, (2021) considered nine studies their review focusing on various therapeutic interventions for post-TBI fatigue. The psychological interventions included cognitive behavioural therapy (CBT), client-centred therapy, psychoeducation, behavioural activation, and pacing. Only one of the studies in this review primarily targeted fatigue, while the others had broader targets. Most studies were randomized controlled trials, but all had small sample sizes with fewer than 50 participants and short follow-up periods of up to 4 months. Three studies were uncontrolled, including a case series, case study, and single group study. The studies used different measures to assess fatigue, with only two studies using the Fatigue Severity Scale. The evidence regarding the efficacy of psychological interventions for ameliorating fatigue was mixed, with only two studies reporting clear improvements after intervention.

Relaxation techniques are another effective intervention for reducing fatigue in individuals with TBI. Relaxation techniques such as deep breathing, progressive muscle relaxation, and yoga can help reduce muscle tension and stress, which can contribute to fatigue. These techniques can be learned and practiced at home, making them a convenient and accessible intervention. While there is not a current evidence base for the use of relaxation techniques in mitigating fatigue post mTBI, it has been shown to reduce fatigue and improve quality of life in other populations such as individuals on dialysis (Ghozhdi et al., 2022).

Mindfulness-based interventions have shown promise in alleviating fatigue symptoms in the mTBI population (Acabchuket al., 2021). Their findings provide encouraging evidence that practices such as meditation, yoga, and mindfulness-based interventions were associated with statistically significant yet modest improvements in various symptoms, with particular emphasis on fatigue, depression, and overall quality of life. Mindfulness-based interventions focus on helping individuals become more aware of their physical and emotional sensations and on helping them to learn to respond to them in a more effective way. Evidence for the efficacy of mindfullness in reducing fatigue post TBI has been published by Johansson et al.

(2012a), however, the sample size was small, and the authors acknowledged that more research is needed.

3.6.4 Light therapy

The search for effective treatment options to address post-mTBI fatigue has been ongoing, and one emerging area of investigation is the use of light therapy. In 2014, Sinclair et al. embarked on specific investigations into the use of light therapy for treating fatigue post mTBI. Their pioneering work shed light on the potential benefits of this non-invasive intervention. Building upon their initial findings, a meta-analysis conducted in 2021 revealed a significant benefit of light therapy for alleviating fatigue in individuals with TBI (Srisurapanont et al., 2021). The results appeared promising and hinted at the potential of light therapy as a viable treatment option. However, the significance of these findings was revisited in a subsequent review conducted by the same research group (Srisurapanont et al., 2022). In this review, the researchers noted that two recent trials reported less favourable outcomes (Bell et al., 2021; Connolly et al., 2021), leading to a re-evaluation of the overall efficacy of light therapy for fatigue post mTBI. The researchers suggested that while the initial meta-analysis demonstrated a statistically significant positive trend, the inclusion of the less favourable trial outcomes diminished the significance of the findings. Thus, the overall outcome for fatigue was better explained as a "beneficial trend" rather than a conclusive effect (Srisurapanont et al., 2022).

Despite the complexity of the findings, it is worth noting that light therapy has shown promise in addressing other related symptoms commonly experienced after mTBI. For instance, the most recent meta-analysis by Srisurapanont et al. (2022) revealed significant treatment effects of light therapy in reducing depressive symptoms and relieving sleep disturbances in individuals with mTBI. The meta-analysis highlighted that short-term light therapy is well accepted and may be effective for certain behavioural symptoms commonly found in patients with mTBI. Specifically, moderate certainty evidence supports the large treatment effect of light therapy in reducing depressive symptoms, while low certainty evidence suggests a moderate treatment effect in relieving sleep disturbance. Preliminary evidence also suggests that light therapy may better address sleepiness following mTBI compared to severe TBI.

This updated meta-analysis, which included a larger sample size than its earlier iteration and employed a Pooled Meta-Analysis (PMA) approach instead of Network Meta-Analysis (NMA), provided valuable insights into the effectiveness of light therapy. Notably, it found that light therapy was effective for depressive symptoms, with only one out of four trials failing to demonstrate its superiority over other interventions. Furthermore, Srisurapanont et al. (2022) revealed benefits of light therapy for sleep disturbance and a trend towards improvement in sleepiness, which were not fully elucidated in previous analyses. These findings align with previous research indicating that light exposure is associated with improvements in subjective and objective alertness. However, it's essential to note that while their previous meta-analysis (2021) reported a statistically significant benefit of light therapy for fatigue, this was observed as a "beneficial trend" in the updated analysis, likely due to less favourable results in recent trials. The 2022 meta-analysis provides valuable insights into the potential benefits of light therapy for post-TBI behavioural symptoms; however, several limitations need to be considered. The small sample size and heterogeneous data across trials raise concerns about the robustness of the findings, particularly for outcomes such as sleepiness and fatigue. Additionally, the relatively short duration of the included trials underscores the need for further research to examine the long-term outcomes of light therapy in individuals with mTBI..

The following chapter (*Chapter 4*) will delve further into the mechanisms of action underlying light therapy, examining the methodological considerations of relevant studies. The extant literature will be reviewed to provide a comprehensive understanding of the current state of light therapy as a treatment modality for fatigue post mTBI.

3.6.5 Electrotherapeutic interventions

Schoenberger et al., (2001) evaluated the potential efficacy of electroencephalographic biofeedback in treating TBI. They used the multidimentional fatigue inventory to measure five dimensions of fatigue: general fatigue, physical fatigue, mental fatigue, reduced motivation, and reduced activity. The results showed that the group receiving the intervention showed significant improvements in both general and mental fatigue, compared to the control group. Smith et al. (1994) investigated the effects of cranial electrotherapy stimulation on participants who had sustained closed head injuries. They found that the treatment group showed significantly greater improvements on a measure of fatigue when compared to controls. More recently, Ali et al. (2021) identified two articles and one abstract that examined the effectiveness of electrotherapeutic interventions on fatigue post TBI. The identified publications focused on two specific interventions: electroencephalographic biofeedback and cranial electrostimulation. Results from all three studies consistently demonstrated decreases in fatigue symptom ratings post TBI. Furthermore, the cranial electrostimulation study revealed significant reductions in post-TBI symptoms among the intervention group, but not in the control group, following the intervention.

3.6.6 Multimodal interventions

Fatigue can be conceptually considered to be a multimodal construct that includes physical, emotional, and cognitive components. Therefore, taking a multimodal approach to intervention planning appears sensible. Ali et al. (2022) reviewed three multimodal studies and found that all of them reported positive results in reducing fatigue following treatment (Gagnon et al., 2016; Gauvin-Lepage et al., 2020; Rytter et al., 2019). While these studies had a focus on ameliorating post injury symptoms more broadly, fatigue was one of the targeted treatment areas. Each of the three studies included in the review incorporated a unique combination of psychoeducational, psychotherapeutic, and exercise-based interventions, demonstrating the diverse approaches employed across the research.

3.6.7 Other Considerations

Loke et al. (2022) discuss the importance of considering protective factors which might buffer against fatigue when developing treatment protocols for individual’s post TBI. Research suggests that rehabilitation efforts that incorporate an emphasis on developing self-efficacy, building a positive future focus, and strengthening social support can temper the perpetuation and exacerbation of fatigue in this population (Loke et al., 2022). As discussed above, previous research has established a correlation, though not necessarily a causal one, between psychological consequences and post-mTBI fatigue. This suggests that gaining a thorough understanding of psychological status both pre and post-injury is important to incorporate into assessment prior to intervention. It should also be considered that fatigue indicators may fluctuate alongside alterations in other factors such as the severity of pain, the quality of sleep, lifestyle adjustments, and/or the degree of self-sufficiency (Zgaljardic et al., 2014).

3.7 Summary

Fatigue is a common and often devastating symptom that has broad impacts on an individual's quality of life following TBI. It presents with heterogeneous aetiologies and consequences, thus effective amelioration of fatigue remains an ambiguous pursuit. The available treatment options for addressing post-TBI fatigue are currently unsatisfactory in terms of effectiveness and outcomes (Srisurapanont et al., 2022).

This chapter has explored several interventions for fatigue and their limitations. Exercise-based interventions show promise in mitigating fatigue, with potential benefits for physical and mental health post-mTBI. However, evidence is limited due to small sample sizes and inconsistent methodologies. While rest is crucial in the acute phase, prolonged and extensive rest may hinder recovery. Pharmacological interventions like methylphenidate have shown positive effects but suffer from small sample sizes. Antidepressants remain controversial due to conflicting evidence regarding their impact on fatigue and cognitive function. Psychological interventions, including CBT and relaxation techniques, offer potential for fatigue management, but evidence is mixed, with many studies also reporting small sample sizes and varied methodologies. Electrotherapeutic interventions, such as electroencephalographic biofeedback and cranial electrostimulation, have demonstrated decreases in fatigue symptoms, suggesting potential avenues for treatment. Multimodal interventions that incorporate various approaches like psychoeducation, psychotherapy, and exercise have shown positive results in reducing fatigue post-mTBI. Finally, light therapy was introduced as a novel intervention, showing promise in reducing fatigue, depressive symptoms, and sleep disturbances post-mTBI. However, recent meta-analyses have cast doubt on its efficacy, requiring further investigation.

The primary emphasis in the treatment of mTBI should be on providing education about mTBI, its signs and symptoms, and the expected recovery timeline (Eapen et al., 2022). When addressing impairments, activity limitations, and participation restrictions resulting from mTBI, treatment should be guided by the specific symptoms experienced. Considering protective factors like self-efficacy and social support may also play a role in mitigating fatigue in mTBI rehabilitation.

There is a vast amount of literature relating to fatigue after TBI, but a relative dearth of large-scale, long-term studies examining how fatigue evolves over time, and how individuals respond to treatment. Therefore, there remains a clear need for more research in this space, both to refine and develop clear terminology and standard definitions of fatigue, and to test and develop successful preventative measures and interventions (Andelic et al., 2020). Ultimately, to establish a solid evidence base from which to guide clinical practice, it is essential to have valid methods of measuring fatigue that can be used in evaluating research.

Chapter Four: Light therapy

4.1 Overview

In the early 1980s, Czeisler et al. (1981) first showed that light has the ability to shift the circadian phase and rhythms in humans by modifying the light–dark cycle. This finding provided the basis for subsequent research piloting light therapy interventions with individuals who developed depressive episodes related to decreased seasonal exposure to light, termed seasonal affective disorder (SAD) (James et al., 1985; Rosenthal et al., 1984). One suggested approach was that the decreased light exposure in winter, due to shorter photoperiods played a role in phase shifting of circadian rhythms, resulting in alterations to the phase relationship of melatonin, and serotonin secretion with diurnal mood modulation and the sleep wake-cycle (Quera-Salva, 2011).

Two Cochrane reviews assessing the efficacy of light therapy in both the treatment and prevention of SAD found limited evidence for its effectiveness compared to placebo (Nussbaumer et al., 2015; Thaler et al., 2011). However, a more recent meta-analysis across the 19 studies found that despite a need for larger and higher quality clinical trials, light therapy is considered an efficacious treatment for SAD (Pjrek et al., 2020). Light therapy has subsequently also been successfully applied to treatment in nonseasonal depression, as well as several other clinical populations (Paino et al., 2009). Relevant to the current study, several studies have found beneficial effects of light therapy on fatigue post-TBI (Killgore et al., 2020; Raikes et al., 2020; Sinclair et al., 2014; Quera Salva et al., 2020). Treatment with light therapy with SAD as well as other conditions will be reviewed later in this chapter, however, this is preceded by exploration of what is known about light exposure, as further research is required to clarify the mechanisms of light therapy and how it improves symptoms of fatigue within the context of mTBI.

4.2 Mechanisms of Light Exposure

It is well known that sufficient daily light exposure is one of the strongest synchronizers of the human circadian clock (Gooley, 2017; Münch & Bromundt, 2012). That is, bright light therapy serves to entrain the endogenous human biological clocks to the 24-hr “solar” day. It has therefore been hypothesised that the mechanism by which light therapy might reduce fatigue symptoms is related to the resulting impact on this entrainment of the biological clock when light enters the eye (Küller, 2002). As well as its impact on the circadian system, light has been shown to have acute alerting effects that are distinct from its effect on the circadian system (e.g., Cajochen et al. 2009). For example, research suggests that light exposure can enhance alertness, performance, attention, and cognition (Okamoto & Nakagawa, 2015; Okamoto et al., 2014; Sahin & Figueiro, 2014; Vandewalle et al., 2006; Lockely et al. 2006).

Light in the visible range is used to both enable vision of motion, colours and contrasts and to facilitate important non-visual physiological and behavioural functions. For example, in humans, light exposure has been shown to shift circadian rhythms, enhance subjective ratings of alertness, and impact sleep architecture (Khalsa et al. 2003, Münch et.al. 2006, Cajochen et al. 2005). These non-visual light responses involve the photopigment melanopsin, found in intrinsically photosensitive retinal ganglion cells (ipRGCs; Provencio et al. 1997), which convey light information to the core biological clock in the suprachiasmatic nucleus (SCN) via the retino-hypothalamic tract (Stephan & Zucker, 1972). The SCN is located in the hypothalamus of the brain and generates circadian rhythms which then synchronizes the circadian clocks of each cell of the brain and the body to the 24-h day.

The role of melanopsin is supported through the results from research initially conducted with mice (Keeler, 1927). Findings demonstrated that visual blindness is not necessarily associated with a weakening of circadian responses, and that non-image-forming responses to light persist in the absence of rod and cone photoreceptors.

As has been mentioned, light plays an important role in the synchronization of the circadian rhythms within the organisms and entrain to the external 24-h day. Therefore, controlled exposure to light can impact on circadian amplitude and phase shifts which could also lead to a reduction in fatigue and sleepiness, as it was suggested by Maanen and colleagues (Maanen et al., 2016). The magnitude of the effect of light exposure is dependent on the wavelength, lux (or illuminance), duration of exposure, and time at which it is applied (Duffy & Czeisler, 2009). The neural mechanisms responsible for the alerting effects of light have garnered significant attention, leading to investigations employing positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) (Tam et al., 2020; Vandewalle et al., 2009). These studies demonstrate activation in a multitude of brain regions within minutes of light exposure during auditory cognitive tasks. Regions include the hypothalamus, thalamus, hippocampus, amygdala, and brainstem (Vandewalle et al., 2009). Notably, when comparing light of different wavelengths, blue light often elicits stronger regional activation than light of other photon-matched wavelengths (Vandewalle et al., 2007a; Vandewalle et al., 2007b). This observation suggests that the sensitivity of melanopsin-expressing intrinsically photosensitive retinal ganglion cells (pRGCs) may play a role in mediating the alerting effects of light. One case study that has shed light on the potential involvement of pRGCs in light-induced alertness reported that three individuals, despite a complete loss of rod/cone responses and visual perception, exhibited similar increases in brain activity within cortical and thalamic regions following exposure to blue light to what we would expect when visual perception is intact (Vandewalle et al. 2013). This finding suggests that intact pRGCs may be driving the observed cortical and thalamic responses to light, emphasizing their potential significance in mediating light-induced alertness in humans, as it was recently shown in animals and humans (Hattar et al. 2023), that light impacts the pre-frontal cortex also directly. Further research is warranted to explore the precise mechanisms by which light influences brain activity and elucidate the specific contributions of pRGCs in mediating the alerting effects of light in humans.

4.3 Factors influencing Light Therapy

4.3.1 Spectral sensitivity

It is broadly agreed that ipRGCs are particularly sensitive to blue light and that the impact of light on the circadian process and its immediate alerting effect predominantly relies on light in the blue spectrum of the visual wavelength range (Brieann et al., 2013). For this reason, short wavelength light (i.e., blue, and blue-enriched polychromatic white light) has been used in several of the previously cited studies in the area of light intervention for fatigue following TBI. However, polychromatic white light has some advantages in that it is deemed to be a more natural light from a visual perspective. Being a broad-spectrum polychromatic bright light, the benefits of ‘blue’ light via the circadian clock remain whilst appearing more natural to the users. In a study comparing the effectiveness of different polychromatic lights in shifting human circadian rhythms, it was found that the use of a bright blue-enriched light did not lead to larger advancements of the circadian clock compared to a bright white light (Smith et al., 2009). These results were obtained using light levels commonly employed for therapeutic circadian phase shifting and support the use of a broad spectrum polychromatic white light.

4.3.2. Duration

A 2016 review looking at the effects of light therapy in relation to sleep has highlighted the importance of gaining further insight to identify the specific factors that influence the effectiveness of light therapy (van Maanen et al., 2016). Their findings suggest that there are several important treatment characteristics that could impact treatment effects when using light therapy. These include the number of treatment days, daily treatment duration, and the intensity and spectral characteristics of the light. Gooley et al. (2010) also found treatment effects were dependent on the intensity and duration of exposure to light.

Previous studies investigating the efficacy of light therapy in treating fatigue post TBI have adopted protocols of daily exposure to light of 30 minutes in duration (e.g. Killgore et al., 2020; Raikes et al., 2020; Quera Salva et al., 2020) and reported significant effect sizes in reducing fatigue and increasing alertness.

4.3.3 Time of administration

Early literature on the timing of light exposure sparked a debate regarding its importance in regulating circadian rhythms and sleep. Controlled trials conducted during that period yielded mixed results, with some suggesting that morning light exposure was most effective, while others found efficacy in the middle of the day or even in the evening (Partonen et al., 2010). However, current understanding in the field has evolved, and it is now widely accepted that light exposure in the morning is the most beneficial. Several studies have provided evidence supporting the notion that light exposure is most efficacious near the time of awakening (Buysse et al., 2010; Lewy et al., 1985). Wu et al. (2022) tailored their study, investigating fatigue in breast cancer survivors, on the knowledge that morning light exposure is associated with phase advances of the circadian rhythm, and evening light exposure has been found to delay the circadian phase. Wu et al. found that the timing of light exposure plays a crucial role in optimizing the therapeutic effect of light therapy.

In the modern world, where there is typically access to electricity, humans can use artificial light to increase the flexibility with which they can schedule activities. There is a tendency to keep the lights on many hours after dusk, but rarely to turn the lights on many hours before dawn, which leads to a net delay in the circadian system and the rhythms it sustains (Wu et al., 2022). An important biological sleep cue is the nocturnal release of melatonin a few hours before bedtime, and exposure to artificial light in the evening delays this release of melatonin by the pineal gland (Casiraghi & de la Iglesia, 2022).

4.4 Efficacy of Light Therapy

Light therapy has been trialled in many varied populations. The first use of light therapy in psychology was shown to have a significant antidepressant effect on individuals with SAD (James, Wehr, Sack, Parry & Rosenthal, 1985). More recently, evidence has also been found for its efficacy in treating nonseasonal depression (Lam et al. 2016). Non-clinical populations have also been researched. For example, light therapy devices have long been commercially marketed as being useful in alleviating fatigue resulting from jet lag and shift work (Lam & Chung, 2021). This is because research has shown that timed exposure to light can help resetting circadian rhythms in individuals (thereby alleviating symptoms of fatigue) due to shift work (Griepentrog, Labiner, Gunn & Rosengart, 2018) and jet lag (Bin et al., 2019). Limitations of studies with jet lag related fatigue were detailed as being due to a combination of poorly designed interventions, as well as a neglect of other contributors to fatigue that result from jet lag, such as the effects of sleep deprivation that arises from travel itself.

Perhaps more pertinent to the current study, light therapy has been trialled in other clinical populations such as with individuals who have Parkinson’s disease (PD) and varying types of cancer. Alterations to the circadian system are increasingly recognised in the manifestations of PD and this determines the rationale underlying the use of light therapy to improve symptoms such as insomnia, fatigue, motor function and mood (Fifel & Videnovic, 2019). There have been mixed findings relating to whether PD-related excessive daytime sleepiness is reduced by administering light therapy. The outcome of some studies suggests that there are significant improvements (e.g., Videnovic et al., 2017; Willis & Freelance, 2018), whereas others found no significant difference between light therapy and placebo treatment groups (e.g., Paus et al., 2007; Raymackers et al., 2019). An interesting finding from Raymackers et al.

(2019) was that in a subgroup analysis of the PD patients with the highest reported difficulties with excessive daytime sleepiness prior to treatment, a significant difference was shown post-intervention. This indicated that there was a greater benefit for these patients with more extreme difficulties with excessive daytime sleepiness highlighting the importance of considering the severity of fatigue.

A recently published meta-analysis reviewing treatment effects of fatigue on PD patients did not reveal any significant effects from bright light therapy (Folkerts et al., 2023). Included in that meta-analysis were the above mentioned studies as well as another conducted by Rios Romenets et al. (2013) who compared the efficacy of combined CBT and 30-minute sessions of bright light therapy administered either in the morning or afternoon for 6 weeks. The study primarily focused on assessing the effects of the interventions on insomnia in PD patients and the results indicated a significant improvement in the insomnia severity index with bright light therapy. However, despite the positive impact on insomnia, there were no observed improvements in daytime sleepiness, fatigue, depression, or sleep quality.

The lack of improvement in fatigue despite successful treatment of insomnia could be attributed to several factors. Firstly, fatigue in PD may have multifactorial causes beyond insomnia, such as neurodegenerative processes, medication side effects, and disrupted neurotransmitter regulation, which may not be directly addressed by treatments targeting insomnia alone. Secondly, similar to individuals who incur mTBIs, fatigue in PD often involves complex interactions between physical, cognitive, and psychological factors, which may require comprehensive and multimodal interventions beyond sleep-focused therapies. Additionally, individual differences in response to treatment, variations in disease progression, and other confounding variables could have influenced the outcomes related to fatigue. Further research with a focus specifically on fatigue management in PD patients may provide deeper insights into effective treatment strategies.

When considering the implications of these research findings in relation to the proposed study, it is important to recognise that while there might be some overlap between fatigue symptoms, daytime sleepiness, and night-time sleep quality, there are also some distinct definitional differences. While fatigue is considered to be multidimensional and all-encompassing, daytime sleepiness is defined by The American Academy of Sleep Medicine (2014) as the inability to stay awake and alert during the major waking episodes of the day, resulting in periods of irrepressible need for sleep or unintended lapses into drowsiness or sleep.

Light therapy has also shown preliminary efficacy in reducing cancer-related fatigue (CRF), a prevalent symptom that is reported to occur with up to one third of survivors of cancer treatments (Johnson et al., 2018). Specific to CRF, light therapy has been shown to be beneficial both in preventing the worsening of fatigue during chemotherapy (Ancoli-Israel, 2012) and in reducing fatigue symptoms post-treatment (Johnson et al., 2018; Redd et al, 2014). As is the case with mTBI, there are no current evidence-based standard treatments for CRF and whilst other non-pharmacological interventions such as exercise and cognitive behavioural therapy (CBT) show promise for some individuals, they are not without limitation. A recent study evaluating the impact of physical exercise to reduce fatigue post-TBI reported a high dropout rate (30%) of participants in their study, indicating that this type of intervention is perhaps not realistically achievable for all individuals (Kolakowsky-Hayner et al., 2017). One salient example of the limitations of these interventions is that the experience of CRF can reduce motivation both for physical activity and for the time commitment required for completing CBT programmes (Matthews et al., 2012; Shang et al., 2012).

If motivation is indeed reduced by the experience of fatigue, one advantage of using light therapy as suggested by researchers in the CRF space, is its low behavioural demand relative to exercise and CBT (Johnson et al., 2018). Combined with being safe to use and easy to access, light therapy has been trialled with other populations such as individuals with Multiple Sclerosis (Mateen et al., 2017) and hospitalised patients with fatigue relating to severe burnout symptoms (Canazei et al., 2019).

4.4.1 Light Therapy and TBI - What has been done before?

Exploring the use of light therapy to alleviate fatigue following TBI has yielded interesting findings. Five studies focusing on traumatic brain injury (TBI), have examined its effectiveness. The initial study, a home-based light intervention for TBI was investigated, and the results were promising (Sinclair et al., 2014). Thirty participants experiencing post-injury fatigue and sleep disturbances underwent four weeks of treatment, with morning light exposure sessions lasting 45 minutes. The study revealed significant reductions in fatigue and daytime sleepiness, particularly in the group exposed to short-wavelength (blue) light therapy.

However, the effects diminished after treatment ceased and once the blue light was removed levels of fatigue returned to baseline levels. The same occurred for daytime sleepiness and depression – which also returned to baseline when the light was removed.

Subsequent studies on light therapy for TBI employed similar approaches, utilizing blue light therapy (Killgore et al., 2020; Raikes et al., 2020). Killgore et al. (2020) conducted a randomised, double-blind, placebo-controlled trial involving 32 adults recovering from mTBI. Researchers investigated the effects of 30-minutes of blue light daily compared to amber placebo light over 6 weeks. The study aimed to capitalise on blue-wavelength light's circadian resetting effect to shift sleep patterns and facilitate brain structure, connectivity, and cognitive performance recovery. Results showed that morning blue light led to phase-advanced sleep timing, reduced daytime sleepiness, and improved executive functioning compared to placebo. Raikes et al. (2020) conducted a very similar study with 35 participants who had suffered an mTBI within the past 18 months. They also used a placebo-controlled randomised trial aimed at identifying the treatment effects of 6 weeks of daily 30-minute sessions of morning blue light therapy compared to placebo amber light therapy. Whilst fatigue was not directly measured, the findings suggested that blue light therapy was a promising nonpharmacological approach to improve sleep-related complaints, post-concussion symptoms, and depression severity following mTBI.

While the aforementioned studies did not specifically focus on fatigue as an outcome, Quera Salva et al. (2020) have published findings suggesting that 30-minutes of exposure to blue-enriched white light for 4 weeks resulted in significant improvement in FSS scores in the light therapy group when compared to no light controls. Important differences between this and the current study include that these participants had all incurred a severe TBI with eligibility criteria including a GCS score of 8 or less. A total of 20 participants completed this study, with 10 in the light therapy group and 10 in the no-light control group.

While light therapy proved effective for addressing fatigue, sleepiness, and certain cognitive aspects in individuals with TBI, there were some limitations. The need for daily morning therapy sessions posed practical challenges, and fatigue levels often returned to baseline after treatment cessation. To overcome these limitations, researchers have proposed exploring ambient lighting interventions that provide therapeutic lighting throughout the day and evening in a more naturalistic manner. In the most recent study on light therapy to treat fatigue post

TBI, therapeutic lighting was provided as part of the ambient environment (Connolly et al., 2021). This was a pilot randomised controlled trial with 24 participants who had mild-severe TBI or stroke more than 3 months prior. The findings indicated a trend towards improvement in fatigue (medium effect size) and significant enhancements in sleep, reaction time, and productive activity during the treatment. Connolly et al. included only five stroke participants, but a larger study (n=90) in stroke patients using diurnal naturalistic light showed significant reductions in self-reported fatigue with no significant impact on sleepiness or subjective sleep quality (West et al., 2019).

While these individual studies have demonstrated positive effects of light therapy in mitigating the symptoms of mTBI and TBI more broadly, Srisurapanont et al. (2022) indicate that the certainty of evidence regarding fatigue reduction remains very low. Despite promising results observed in individual trials, the overall quality of evidence, as assessed through meta-analytic approaches, suggests a need for caution in interpreting the efficacy of light therapy specifically for alleviating fatigue associated with mTBI. Further research is warranted to establish a more conclusive understanding of the role of light therapy in managing fatigue in individuals with mTBI.

Addressing post-TBI fatigue is important, given its common occurrence in this population and its debilitating impact. Light therapy presents a focused, accessible, and low-demand strategy to ameliorating fatigue, potentially yielding positive outcomes and enduring improvements. Considering the interplay between fatigue, sleep, mood, and cognitive abilities, it is essential to continue to investigate the potential advantages and long-term effectiveness of light therapy in alleviating TBI-related fatigue.

4.4.2 Consideration of Other Light Wavelengths

In their review of existing literature on the effects of light on recovery from mTBI, Raikes and Killgore (2018) provide commentary on other light wavelengths. These include monochromatic red light and monochromatic green light. In the case of red light, research suggests that it may have powerful alerting effects without impacting melatonin secretion (in the way that blue wavelength light does). And while research in support of this is lacking, green light has also shown promise in promoting sleep. Green light may also alleviate migraine symptoms and provide antinociceptive benefits, making it potentially beneficial for individuals with post-traumatic headache or pain. Further research is needed to confirm the efficacy of red and green light with mTBI and to understand the underlying mechanisms.

In a recently published review, transcranial photobiomodulation (PBM) is suggested to hold potential as a promising treatment for the intricate pathophysiology associated with TBI (Lim, 2024). PBM utilises targeted wavelengths of red to near-infrared light to influence brain function. The application of such approaches differs to the light therapy proposed in the current study as PBM involves applying light to the brain either through the skull (transcranially) or through the nasal passages (intranasally). However, it is mentioned here to acknowledge concurrent research (e.g., Naeser et al., 2016) suggesting that exposure to red light has the potential to stimulate the growth of new neurons and the formation of new synaptic connections between neurons in the brain

4.5 Methodological Considerations for Light Therapy Use

The safety of participants needs to be a key consideration of any intervention trial. Literature published to date has not shown any obvious light-induced pathology or long-term sequelae resulting from light therapies, so long as the intensity of the light source is within recommended guidelines (Gallin et al, 1995). Treman and Treman (2005) highlight the importance of providing clear instruction on dose, timing, and method of exposure to avoid adverse responses or side-effects. Their earlier study using a downward-tilted fluorescent light box protected by a smooth diffusion screen, with 30-minutes daily exposures at 10,000 lux, is of particular interest to the current study due to the parallels in equipment and protocol (Treman & Treman, 1999). This study was investigating the efficacy of light therapy for seasonal and nonseasonal depression and they evaluated their 83 participants for 88 potential side effects. They identified a small number of negative effects which may have been induced by light administration. These included including nausea, headache, jumpiness/jitteriness, and eye irritation at a frequency of 6% to 16%. A more recent study reported the most prominent side-effects of light therapy (used to treat seasonal depression) to be headaches and blurred vision (Leichtfried et al., 2010). In this study, headaches were reported with prevalence rates varying between 8.4% and 21.4% and visual disturbances were reported in up to 18%. A 2022 study looked at the efficacy of bright light therapy in perinatal depression. They found that 20% of the participants reported headaches as a side effect of light administration. However, most completed the study expressing that it did not significantly affect their lives and that it was very mild (Donmez et al., 2022).

Unmonitored home-based intervention trials have some inherent limitations linked to the motivation and compliance of participants. This is particularly note-worth in a population of fatigued individuals who, despite agreeing to wake and administer light within 2 hours, may find it difficult to commit to this daily for the required four weeks. The behavioural investment of light therapy is considerable when compared to less arduous treatments such as pharmacotherapy (Treman & Treman, 2005). However, to balance this point, as has been stated earlier in this thesis, light therapy is considered to be less arduous than options like CBT and exercise.

Chellappa et al. (2017) sought to explore potential sex differences in response to light exposure. Their findings suggest that men exhibit a stronger response to blue-enriched light than women and highlight the potential significance of sex differences in light sensitivity for the success of personalized light interventions.

4.5.1 Compliance control of light exposure by using wearable light sensors

Finally, field research presents some limitations in terms of being able to control for variables, and being able to measure relevant physiological variables (Casiraghi & de la Iglesia, 2022). Data may be collected over years and across seasons when natural light exposure varies. Coupled with the fact that some participants naturally spend more time outdoors acclimating to the natural light/dark environment, total light exposure over the course of a study may be difficult to control. However, when used correctly, actigraphy data is able to monitor light exposure, as is discussed in the following section.

Actigraphic recording of sleep involves the wearing of a wrist mounted device which measures light exposure as well as rest and activity patterns across the 24-hour day via an accelerometer (Acebo et al., 1999). Software can then be used to score objective sleep onset and offset time. Commercial wearable devices, such as the Apple Watch or Fitbit and Jawbone, are also commonly used to measure sleep and activity, however, they are yet to be endorsed for scientific enquiry (Evenson, Goto, & Furberg, 2015). Topalidis et al. (2021) conducted an evaluation study to compare the performance of low-cost commercial smartwatches with scientific actigraphy devices. They found that step counts were highly correlated between devices, but that there was less accuracy in recording of total sleep-times. Overall, they suggest that affordable smartwatches can reduce the recall bias of subjective estimates of participant sleep-time.

The analysis of wrist actigraphy data can infer circadian changes, monitor activity levels (which may infer changes to alertness), and monitor exposure to light across the course of the day/night. These measures aid in the determination of the mechanisms underlying the efficacy of light therapy. The incorporation of an objective measure for sleep and activity can identify patterns of change that are reflective of alterations to the circadian system. Sleep diaries are important components of the assessment of sleep, but are sensitive to the subjective bias individuals are prone to when appraising their sleep duration and quality. Therefore, measures of subjective sleep (i.e., sleep diary) should be supplemented with measures of objective sleep (i.e., actigraphy) (Topalidis et al., 2021).

4.6 Summary

In conclusion, light therapy has emerged as a promising intervention for various health conditions, including fatigue. Pioneering research in the early 1980s demonstrated the ability of light to modulate circadian rhythms and treat seasonal affective disorder associated with decreased light exposure. Although early reviews found limited evidence, more recent meta-analyses support the efficacy of light therapy in treating seasonal affective disorder and nonseasonal depression. Additionally, light therapy has shown beneficial effects on fatigue post-TBI. The alerting effects of light may provide additional explanation for the reported reduction in fatigue in previous light therapy studies post-TBI.

The mechanisms underlying light exposure involve the synchronization of the circadian clock and the activation of melanopsin-expressing intrinsically photosensitive retinal ganglion cells (ipRGCs). These cells communicate with the suprachiasmatic nucleus in the brain, regulating circadian rhythms and sleep/wake cycles. The effects of light extend beyond the circadian system, influencing alertness, performance, attention, and cognition.

Several factors influence the effectiveness of light therapy, including spectral sensitivity, duration of exposure, and timing of administration. While ipRGCs are particularly sensitive to blue light, polychromatic white light offers advantages in terms of a natural appearance. The duration of light exposure and its administration in the morning have been found to be crucial for optimal treatment outcomes. Further understanding of the underlying mechanisms and optimization of treatment parameters will enhance the development of targeted and efficacious light-based interventions.

Chapter Five: Rationale for the Current Study

5.1 Overview

At the inception of this study, there had been two identified published studies that sought to specifically examine the effects of light therapy in reducing fatigue symptoms following TBI. Sinclair et al.'s (2014) trial of light therapy investigated the efficacy of daily blue light exposure in reducing fatigue for participants who had suffered from ranging severities of TBI. Quera Salva et al. (2020) explored the efficacy of face-mounted, blue-enriched white light therapy in reducing fatigue symptoms following a severe TBI. Both studies reported a significant improvement in self-reported fatigue symptoms during the 4-week treatment phase of their trials. However, it is important to note that the effects observed in both studies ceased after the cessation of treatment.

Participants in the Sinclair et al. (2014) study were aged 18-65 and had sustained a TBI at least 3 months prior to the study. Inclusion criteria included that participants scored 4 or more on the Fatigue Severity Scale (FSS) and/or scored 10 or more on the Epworth Sleepiness Scale (ESS) and/or scored 5 or more on the Pittsburgh Sleep Quality Index (PSQI). Notably, Sinclair et al. included participants with a range of injury severities. Severity was determined based on post traumatic amnesia (PTA), and 50% had a severe injury (PTA > 1 week), 27% had a moderate injury (PTA 1-7 days), and 23% mild injury (PTA <24 hours). Overall, the study included 30 participants who were randomly assigned to three groups of 10; one exposed to blue light, one exposed to a placebo of yellow light, and one which received no treatment at all. The full protocol extended over 10 weeks, with 2 weeks of baseline, 4 weeks of treatment and 4 weeks of follow-up. Those assigned to the light therapy groups were required to sit approximately 50 cm away from a 15cm x 15cm light therapy device for 45 minutes, within the first 2 hours of waking. Rather than staring at the device for the duration of therapy, participants were asked to look into the light for a few seconds every few minutes. The primary outcome of this study was that Sinclair et al. were able to demonstrate that daily exposure to blue-enriched white (but not yellow) light, reduced fatigue symptoms and daytime sleepiness during the treatment phase. Their data showed a return of fatigue symptoms to baseline levels after treatment cessation. There were no effects on self-reported symptoms of depression or reaction time in the Psychomotor Vigilance test.

Quera Salva et al. (2020) had very similar participant characteristics to Sinclair et al.'s groups. Participants were also aged 18-65 and whether they met fatigue criteria was primarily determined using the same cut off scores, on the same three measures cited by Sinclair et al. (4 or more on FSS and/or 10 or more on the ESS and/or 5 or more on the PSQI). In this study, participants had to have sustained their injury at least 6 months prior to inclusion. Inclusion criteria was very similar between these two studies, with the main deviation from the Sinclair et al. study being that Quera Salva et al. focused specifically on reducing fatigue for survivors of 'severe' TBI (where severity was determined based on an initial Glasgow Coma Scale score being 8 or less). Overall, this study included 20 participants who were randomly assigned to two groups of 10; one exposed to blue-enriched white light, and one which received no treatment at all. The duration of this study was 8 weeks, which included 4 weeks of treatment, and 4 of washout. Quera Salva et al. opted to use a face-mounted light therapy device in their study, rather than the more traditional light box that Sinclair et al. used. Participants were required to wear the light device for 30 minutes every day at awakening, and there were no adverse effects from the treatment reported during the study. Quera Salva et al. found that compared to their control group, participants receiving light therapy saw a significant reduction in fatigue as measured by the FSS. As was found in the Sinclair et al study, the positive effects of light stopped after the cessation of treatment, with FSS scores returning to baseline. This trend suggests that the mechanisms underlying the efficacy of light therapy rely on continued daily exposure to light, and for participants to continue to benefit from the intervention, they might have to commit to long term use of a light therapy device.

In support of the two studies mentioned above, a related study by Bajaj et al. (2017) found that six weeks of blue-enriched white light therapy significantly impacted the amount of water diffusion for multiple brain areas in individuals with mTBI. In this study the amount of water diffusion in the brain was measured using a method called Q-space diffeomorphic reconstruction (QSDR), which helps create detailed maps of how water moves in the brain. They looked at 11 specific areas of the brain, and by comparing brain scans before and after treatment, they could see if there were any changes in how water moved in the brain's nerve fibres following light therapy. Many of the observed changes were associated with improvements in sleep latency and delayed memory, although notably this study did not measure fatigue. Participants in this study were 28 individuals meeting criteria for mTBI. The injury had to have occurred within the preceding 12 months but no sooner than 4 weeks before screening. They all had to have some level of sleep problem and for these to either have emerged or worsened due to injury. Participants were separated into either a blue light treatment group or an amber light (i.e. longer-wavelength light) control group. Bajaj et al. suggest that their findings support that blue light exposure may facilitate structural and functional recovery following mTBI.

While these studies provide promising insights into the potential efficacy of light therapy for reducing fatigue post-TBI, the evidence is not conclusive. The limited number of studies, methodological limitations, and the transient nature of observed effects after treatment cessation suggest that further research is needed to establish the efficacy of light therapy in this context. Additionally, the question of whether these potential positive effects would translate to individuals who have incurred only minor injuries has not yet been answered. Sinclair et al. (2014) conducted their research with participants who had wide ranging injury severities. Only a handful (7 individuals) of those participants had sustained a mTBI, and it is unclear which group they were assigned to. Quera Salva et al. (2020) chose to focus on individuals with severe TBI, and while it is promising that the findings from their study have supported light therapy as an effective treatment for reducing fatigue post TBI, it remains unclear whether these benefits will also be recorded post mTBI. This gap in knowledge provided the primary rationale for conducting the present study which is focused on investigating the efficacy of light therapy with individuals who have sustained mTBI.

Additionally, one of the reported limitations of the Sinclair et al. (2014) study was that there was no comparison of light wavelengths of equivalent photon density. Because of this, they acknowledged that broad spectrum white light might also be effective. This is a suggestion that has also been supported by the recommendations resulting from a review of the potential of light therapies in mTBI treatment (Raikes & Killgore, 2018). This gap in the extant literature, alongside the aforementioned evidence to suggest it is therapeutically comparable (Smith et al., 2009), is what informed the choice of the more naturally appearing broad spectrum white light, rather than blue light in the current study.

Adding to the rationale that informed the current study, it was recognised that while the aforementioned published studies appear consistent in providing some limited evidence for their efficacy in reducing fatigue post TBI, the question of how this form of therapy works had received little attention. What has been agreed upon is that sufficient daily light exposure is one of the strongest synchronizers of the human circadian clock with the external light-dark cycle (Gooley, 2017; Münch & Bromundt, 2012). This led to the hypothesis that the mechanism by which light therapy might reduce fatigue symptoms is related to the resulting impact on the entrainment of the biological clock when light enters the eye in circadian systems (Küller, 2002). Based on this hypothesis, it is thought that the analysis of wrist actigraphy data to infer circadian changes would aid in the determination of what mechanisms underlie the efficacy of light therapy. Despite their subjective reports of adequate sleep quality, the incorporation of an objective measure for sleep and activity might identify patterns of change that are reflective of alterations to the circadian system and that might therefore allow us to target the intervention to those individuals it will be the most effective for.

In summary, the current study was informed by a promising but limited evidence base supporting light therapy as a treatment to ameliorate fatigue post TBI. Because it remains unclear whether light therapy will consistently yield meaningful benefits for individuals with mTBI, the current study is designed to further inform the evidence of the efficacy of the therapy. The pursuit of efficacious evidence-based treatments for fatigue in this population is important because, as outlined in chapter three, fatigue can significantly impact a person's ability to function in daily life. For those with more severe injuries, and a more complex array of impairment, fatigue can be a barrier to treatment for other symptoms. Therefore, reducing fatigue in these populations might have a secondary benefit in increasing participation in treatment that could aid their recovery process. For those with mTBI however, fatigue may be the most significant barrier to regaining the quality of life they had pre-injury. Therefore, rather than fatigue reduction serving as a positive catalyst for recovery in other areas, it may be that addressing fatigue is the final piece of the puzzle that allows them to return to work and to return to activities that support their long-term wellbeing.

5.2 Research Objectives:

5.2.1 Primary Objective:

The primary objective of the current research is to determine whether daily exposure to polychromatic bright white light is effective in reducing mTBI related fatigue symptoms as measured by the Fatigue Severity Scale and daily self-reports.

- Independent variable: Time (intake, baseline, treatment, no treatment)

- Dependent variable: Fatigue symptoms (as measured by the Fatigue Severity Scale and daily self-report)

5.2.2 Secondary Objectives:

1. To investigate the effects of bright light exposure on reducing daytime sleepiness and improving sleep quality in patients presenting with fatigue symptoms.
   - Independent variable: Time (intake, baseline, treatment, no treatment)
   - Dependent variables: Sleep Quality (as measured by the Pittsburgh Sleep Quality Index). Daytime sleepiness (as measured by the Epworth Sleepiness Scale)

2. To assess the impact of bright light exposure on reducing levels of depression, anxiety, and stress in individuals subjected to the intervention.
   - Independent variable: Time (intake, baseline, treatment, no treatment)
   - Dependent variables: Anxiety, Depression and Stress (as measured by the DASS-21)

3. To investigate the effect of bright light exposure on modifying circadian rest-activity cycles in study participants.
   - Independent variable: Time (intake, baseline, treatment, no treatment)
   - Dependent variables: Objective sleep and activity data (as measured by wrist actigraphy)

5.3 Research Hypotheses

Based on the research objectives, the hypotheses tested in the current study are:

Hypothesis 1:
Fatigue Severity Scale (FSS) scores will be lower at post-intervention and after follow-up than at baseline.

Hypothesis 2:
Daily Fatigue Ratings will be lower at post-intervention than at baseline.

Hypothesis 3:
Epworth Sleepiness Scale (ESS) scores for participants post-intervention will be significantly lower than at baseline.

Hypothesis 4:
Pittsburgh Sleep Quality Index (PSQI) scores for participants post-intervention will be significantly lower than at baseline.

Hypothesis 5:
Depression Anxiety Stress Scale (DASS-21) scores for participants post-intervention will be significantly lower than at baseline.

5.4 Post Hoc Research Objective

After the intervention phase, it became apparent that methodological limitations had influenced the study's outcomes and interpretations. In light of these insights, it was deemed valuable to incorporate a discussion on feasibility issues that emerged during the course of the research. This additional focus aims to provide a comprehensive understanding of the study's practical implications, acknowledging the challenges encountered and offering insights into the feasibility of implementing similar interventions in real-world settings. By addressing these feasibility issues, the study aims to contribute to the refinement of future research endeavours and the development of more effective intervention strategies tailored to the needs of the target population.

Chapter Six: Method

6.1 Chapter outline

This chapter outlines the design of the current study and the rationale for using a randomised baseline controlled trial. The recruitment, intervention, and data collection processes are explained. The data analysis process is described, ethical issues are explored, and consideration is given to relevant limitations.

6.2 Study design

A multiple baseline controlled trial was conducted with participants recruited through Concussion Clinics in Wellington and New Plymouth, as well as private referrals and the TBI network in Hamilton. Previous research in this area has used randomised controlled trials (RCT), however RCTs have limitations in their practicality, ethical appropriateness, and cost (Hawkins et al., 2007). Therefore, while acknowledging the gold standard status of RCTs in clinical research, the decision to employ a multiple baseline design stemmed from various considerations. Perhaps most importantly, conducting a sufficiently powered RCT would have required significant resources, including extensive participant recruitment and substantial funding. These resources were not readily available for the current study. Biglan et al. (2000) suggested that multiple baseline controlled trials can be used to develop and sort through potentially effective intervention methods which if successful can be followed by more extensive evaluation in RCTs. This indicates that there may be practical utility in using these study designs in the early stages of protocol development with interventions that, if successful, can be further tested through RCTs. It is considered that the multiple baseline design used in this study can demonstrate whether a measurable change has occurred in the relevant outcome measures, whether the change is a result of the light therapy intervention, and whether the change is statistically significant. Further rationale for using a multiple baseline controlled trial is that because participants may act as their own controls, all participants could access the treatment, a critical consideration given prior research indicated potential benefits from the intervention.

The initial design intended to utilise a randomisation procedure involving allocating participants to either Group 1, scheduled for treatment after a two-week waiting period, or Group 2, scheduled for treatment after a six-week wait. However, due to the diverse schedules of participants, including work obligations, travel plans, and personal commitments, it became evident that maintaining the randomisation procedure was not feasible. To ensure participants could effectively complete a four-week light intervention with minimal disruption, the waiting period was dictated through consultation with each participant. This meant that the baseline phase differed for each individual in the study. The specific timings for individual baseline monitoring will be reported in the results chapter.

Monitoring occurred at four crucial time periods:

Time 1: Intake measures were recorded for all participants.
Time 2: Participants are retested on all measures at the conclusion of the baseline period, immediately prior to the intervention phase.
Time 3: Participants are retested on all measures at the conclusion of the light therapy phase.
Time 4: Participants complete final survey after a four-week follow-up phase during which they have had four of weeks without light therapy.

This design facilitates the measurement of the overall efficacy of light therapy. It also helps to develop an understanding of whether light therapy generates lasting benefits in fatigue reduction. Having multiple baseline time periods is important in identifying possible waitlist placebo effects where part of the benefit of light therapy might relate to anticipation of the intervention, or by the natural passing of time.

6.3 Recruitment

As mentioned, participants were recruited through concussion clinics, private referrals, and the TBI network. Table 4 below provides information about the services and networks involved in recruitment. The process that was followed for the current study began with briefing supporting clinicians in these services on the eligibility (and exclusion) criteria of the study, as well as what participant involvement would entail. They would then identify clients that they thought might benefit from the intervention trial and seek permission for the researcher to contact them directly. In total 36 participants were contacted who expressed interest in participating in the study.

Table 5

Number of Interested Referrals by Source

Referral Source	**Count**
Talking Point Taranaki[2]	8
Private Referral[3]	17
Assessment Providers Taranaki[4]	8
Brain Injury Association[5]	1
TBI Network[6]	2
Total	**36**

6.4 Participants

Participants were eligible to take part in this study if they were between 19 and 65 years of age and had sustained a mTBI (or concussion injury) at least three months prior to recruitment. They were required to have cognitively recovered but meet the threshold for significant fatigue symptoms based on scores of 4 or more on the FSS. Consistent with the inclusion criteria used in prior studies, scores of 10 or more on the ESS and/or 5 or more on the PSQI also qualified individuals to take part.

Participants were excluded if they reported any other chronic or acute medical or psychiatric illness that might account for fatigue; if they had a DASS-21 depression score higher than 14[7];

[2] Talking Point is a private psychology practice providing psychological support to people post TBI
[3] Private referrals came from various practicing psychologists, and there were also referrals from participants already enrolled in the study
[4] Assessment Providers Taranaki runs a Concussion Service for ACC, and provides assessment and rehabilitation services to people of all ages, including those post TBI, referred through ACC and other funders
[5] The Brain Injury Assn is a service to support people in the community who are suffering from brain-related injuries
[6] The TBI Network aims to support better health and wellbeing for people with traumatic brain injuries by uniting people, services and research
[7] One completed participant had a score above this range on the DASS-21 but was included after further information was sought to understand that score

if they performed recent shift work[8] or travelled across multiple times zones; if they had current or historic sleep problems (such as sleep apnea or restless legs syndrome); if they were currently using sleep or sleepiness affecting medications[9]. Further exclusion criteria included cataracts, glaucoma, and other eye diseases as well as known pregnancy in women, migraine and photophobia (hypersensitivity to light). Exclusion criteria were particularly focussed on identification of those individuals whose reported fatigue symptoms were likely better understood as having causes secondary to the mTBI itself. Participants were also excluded if pre-assessment scores indicated that malingering, factitious disorder, or somatic disorder could be potential causes of fatigue. The structured approach to assess for these conditions involved considering administering the Structured Interview of Reported Symptoms, 2nd Edition (SIRS-2). However, due to the lengthy administration time of the SIRS-2 and the fact that participants were primarily recruited through concussion services where screening for these conditions had already been conducted via clinical interviews or objective measures, it was deemed redundant and unnecessary to administer the SIRS-2. Therefore, the assessment of malingering occurred prior to recruitment, and depending on the setting and client presentation, it included the Test of Memory Malingering, the Forced Choice Test from Advanced Clinical Solutions, or in some cases, the SIRS-2.

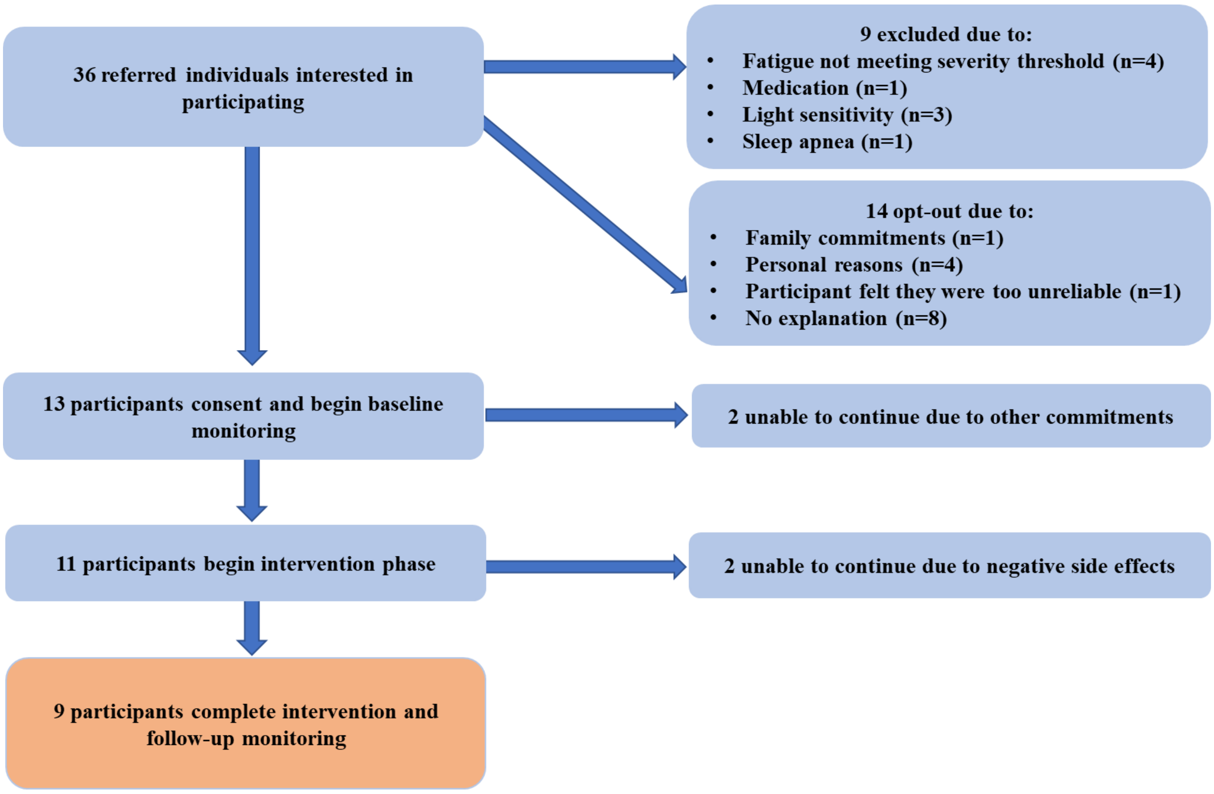
Of the 36 participants who were contacted after expressing interest in participating in the study 25 participants were excluded or removed from the main analysis because of a range of factors which are detailed in Figure 5 below. The final sample size was 11, however, two participants were unable to complete the four-week intervention phase due to subjective reports of adverse effects of the light, leaving a completed sample size of 9.

[8] One completed participant was a medical doctor who worked shifts but as these were consistent in pattern across time points, she was included for the purposes of this research

[9] Medications were considered on a case to case basis dependent on consistency of medication adherence and research relating to specific medication and its impact on sleep or sleepiness

Figure 5

Flow Diagram of Recruitment and Participant Retention



Despite the initial intention of the study design to randomly allocate participants to either a two-week or six-week period of baseline monitoring, it was observed that participants often faced various competing life demands (such as travel, work commitments, moving houses, etc.). This presented a challenge to strictly adhere to the predetermined allocation. Recognising the need to accommodate participants and ensure their continued engagement, a decision was made to allow flexibility in the baseline monitoring period. While this approach may introduce some impact on the scientific rigour of the study, prioritising participant retention and accommodating their individual circumstances was deemed necessary. By allowing flexibility, it was anticipated that participants would be more likely to remain actively involved, leading to a more comprehensive and representative dataset. Table 6 provides an overview of each of the participants who completed this study, including the period of time they were in the baseline monitoring phase, as well as when they started light treatment (time 2).

Table 6

Participant Overview

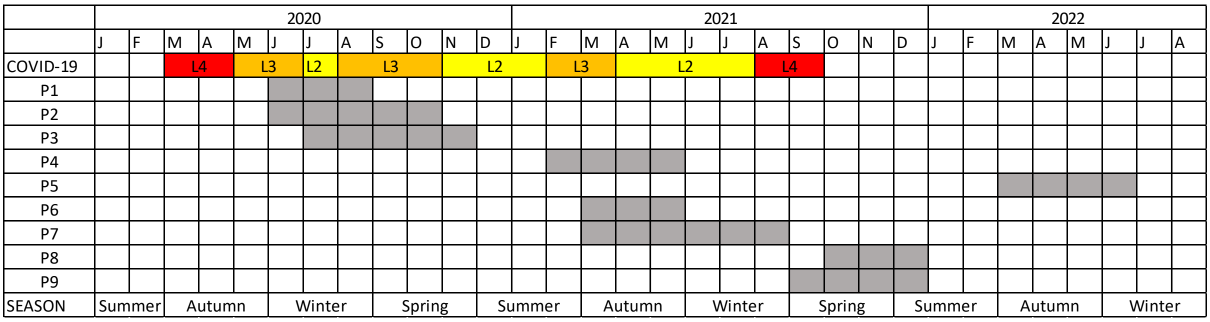
Participant	Sex	Ethnicity	Age	Injury	Referrer	Baseline	FSS *a*	Intervention start date
1	M	NZ Euro	42	April 2019	Talking Point	26/06/2020	5.67	07/07/2020
2	F	NZ Euro	43	August 2018	Private Psych	26/06/2020	6.22	01/09/2020
3	M	NZ Euro	52	March 2015	Talking Point	10/07/2020	6.22	21/08/2020
4	M	NZ Euro	21	July 2019	Private Psych	10/02/2021	6.78	06/03/2021
5	M	NZ Euro	46	March 2020	Self-Referral	10/03/2022	6.22	23/03/2022
6	F	NZ Euro	34	September 2019	APT	12/03/2021	6.33	31/03/2021
7	M	NZ Euro	57	October 2018	Private Psych	13/03/2021	6.78	10/05/2021
8	F	NZ Euro	36	August 2020	Private Psych	10/08/2021	5.67	22/09/2021
9	M	NZ Euro/Maori	33	May 2020	Private Psych	03/09/2021	4.44	01/11/2021

Note. a. denotes the FSS score at baseline

Figure 6, below, showcases the time period of participant engagement in the study, along with the season and COVID-19 lockdowns. This serves to provide important contextual information and potential influences on the data collected. The amount of natural light during different seasons can impact circadian rhythms, sleep patterns, and overall well-being, which could potentially influence the outcomes of the study. Additionally, COVID-19 lockdowns have had widespread effects on daily routines, including sleep patterns, activity levels, and mental health, all of which can directly or indirectly affect the variables under investigation.

Figure 6

Timeline of Participation including Season and COVID-19 Lockdowns



Note. COVID alert levels are shown in coloured blocks. Red depicts level four restrictions, orange depicts level three restrictions, and yellow depicts that level two restrictions were in place.

6.5 Sample Size and Statistical Analysis

To balance what is feasibly achievable, within the time and resource constraints of the current study, with the need to obtain sufficient participant data to conduct meaningful statistical analyses, it was planned that 20 participants would be recruited. This is comparable with both the Sinclair et al. (2014) and Quera Salva et al. (2020) studies which were conducted using randomized controlled trial study designs with sample sizes of 10 in the light therapy group, and 10 the no treatment control group (Sinclair et al. also had an additional 10 participants in a placebo light control group).

The decision to include 20 participants in this study was not primarily based on the fact that it aligns with the sample sizes of previous studies. Instead, the driving factor behind this choice was the presence of resource constraints which are common in experimental design, but often not explicitly acknowledged (Lakens, 2022). Traditional statistical methods often require larger sample sizes than what is feasible for research such as the current study, and so it is understood that group findings from this project are unable to be generalised to the wider mTBI population. Therefore, alongside providing visual representations of group-level changes, individual-level analyses will be provided to examine how the therapy intervention affected each participant. This pragmatic approach prioritises the demonstration of significant efficacy for the specific individuals involved.

6.5.1 Data analysis strategy

The data analysis strategy for the current study involves:

1. Visual inspection of time-series graphs, modified Brinley plots, and complementary statistical analyses. Visual inspection has traditionally been the primary method of multiple-baseline data analysis (Wolfe et al., 2019). This is a non-statistical method whereby data is plotted on a graph that visually represents changes to the dependent variable over time.

   Relative judgements relating to the efficacy of the intervention can therefore be made based on a straight-forward visual analysis. The pattern of results can be estimated to determine whether a potential relationship between the light therapy intervention and fatigue symptoms exists, and if so, the strength of that relationship, indexed by the distance to the mean value.

   Individual changes in outcome measures over baseline and intervention phases will be analysed using modified Brinley plots (Blampied, 2017). Modified Brinley plots provide a visual analysis of individual change over time so that intervention effects can be recognised, whilst also placing each individual participant's scores in the context of those of all other participants.

   The plots will be explained further in the following section, however, one of the advantages of using this form of analysis is that data points can be plotted to show not only whether change is statistically significant, but also whether outcomes have clinical significance. In other words, would we expect the reduction in FSS scores to be noticed by participants and to reflect a positive outcome in terms of their quality of life.

   It is increasingly recognised that statistical analysis can be used to complement the visual inspection techniques used in multiple-baseline data analysis (Bulté & Onghena, 2009). The intention for the current study is that a comprehensive view of the results will be built by combining visual analysis with both statistical significance and effect size measures. However, it was understood prior to analysis that statistical findings would need to be interpreted with caution due to the low sample size.

2. In order to assess the statistical significance of the observed changes, the data are primarily analysed using the Wilcoxon signed-rank test due to its robustness against outliers and non-normality, which aligns well with the limited dataset available for this study. Despite the acknowledged limitations stemming from the small sample size, this

approach will allow for a more comprehensive understanding of the outcomes while acknowledging the inherent caution required in interpreting results within this context.

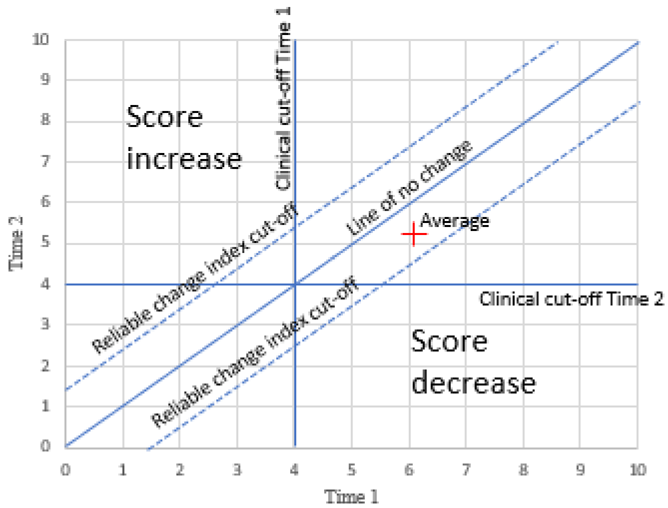
For all statistical analyses, the software JAMOVI (2023) was used. All data was visually inspected and processed for reliability before entering the analysis.

6.5.2 Brinley Plots Overview

The advantage of using Brinley plots to view the data from this study is that they directly show the direction and extent of change for each individual participant relative to that individual's pre-intervention score. For participants plotted below the line, the intervention has had a positive effect (reducing scores), and for those above the line, there has been a negative effect (showing an increase in scores). Because each plotted point represents one participant, the consistency of the intervention outcome, can be easily referenced viewing the group mean (identified by the red cross on the graph as seen in the example in Figure 7 below).

Figure 7

Example Layout of Brinley Plot



Note on the reliable change index:

Reliable Change Index (RCI) scores have been provided with the Brinley plots because they are commonly used in intervention studies using this form of analysis. Despite being a widely used statistical method in psychology, the application of the RCI continues to be critiqued (McAleavey, 2021). Within the current study, RCI scores should be interpreted with caution because there are several significant problems with them. Specifically, they are based on statistical calculations that assume that the measurement error remains constant both across all participants in this study, and that it is the same for the participants in the current study as it is in the sample the measurement error was calculated from (https://thepathologicalscience.blogspot.com). This assumption may not hold true in practice, especially where validation studies are not specific to mTBI populations. This estimation process introduces additional uncertainty and potential error into the RCI calculation. RCI scores do not take into account other sources of variability or confounding factors that may influence the observed change. They have been included to be consistent with the recommended approach to constructing Brinley plots, but will be interpreted in conjunction with other clinical and contextual information. They are not provided as the sole measure of treatment effectiveness.

The calculation to determine the RCI value uses the standard error of measurement (SEM) for each scale. The SEM for the FSS was provided in the paper by Learmonth et al. (2013). The SEMs for all of the other scales were estimated using the standard deviation (SD) and reliability (Cronbach's alpha) of the measure. Scale SDs and Cronbach's alphas were drawn from the following studies:

- PSQI: (Buysse et al., 1989; Mollayeva et al., 2016)
- ESS: (Johns, 1992; Kendzerska et al., 2014)
- DASS-21: (Randall et al., 2017)

RCI scores are not included in the analysis of daily fatigue ratings. This decision was primarily due to the limited availability of adequate validation studies specifically addressing the use of visual analogue scales as a reliable change measure for fatigue.

6.5.3 Alternative Measure of Clinical Significance

Due to the limitations discussed regarding the RCI, alternative measures of clinical significance were explored. Rooney et al. (2019) propose that interpreting meaningful changes in fatigue can be improved by establishing the minimally important difference (MID) for fatigue. The

MID represents the smallest difference in the outcome of interest that individuals perceive as beneficial, serving as a threshold value to determine the importance of change from the individual's perspective. However, it is important to note that the MID can only be utilised to interpret results if the sample size was predetermined based on the MID (King, 2011). While it may be tempting to calculate the MID as a supplementary statistic in the current study, it is acknowledged that it is an estimate and susceptible to sampling variation like any other measure. This holds particular relevance to the current study given its small sample size, providing the rationale for its exclusion as a supplementary statistic. However, in future larger-scale studies, its inclusion may prove advantageous.

6.6 Equipment

Much consideration was given to choice of device type, given that studies vary in terms of both the light source itself (generally either blue light, or bright white light) and in terms of the delivery of light (either face-mounted, or a therapy lamp that is positioned in close proximity to users). Whether using bright white light or blue light, the therapy is delivered by the blue spectrum, peaking between 435 to 485 nm and both blue and bright white light provide that (given that bright white light is a broad-spectrum light). While researching commercially available light therapy device types, it was recognised that one of the common products reported in extant literature (The Litebook) was no longer available to purchase through the company website. This triggered some concern around whether the device might have been withdrawn from the market due to any health and safety concerns.

Consultation was therefore sought with the General Manager of The Litebook Company Ltd regarding any inherent risk in asking people to use light therapy interventions (T. Cook, personal communication, August 27, 2019). The advice received was sufficient to allay those concerns.

A systematic review that synthesized the clinical literature on the ocular safety of light therapy determined that ocular complaints associated with this treatment are typically mild, and discontinuation of therapy due to ocular issues is rare (Brouwer et al., 2017). The review did not find any substantial evidence indicating ocular damage resulting from light therapy, with the exception of a single case report documenting the development of a maculopathy (Gallenga et al., 1997). However, a clear causal relationship between the maculopathy and light therapy was not established in that case. Overall, the review suggests that light therapy is generally safe for ocular health.

Because white appearing light seems more natural to users as it more closely resembles natural light (whereas blue light has a more unnatural appearance), a white light source was chosen for the current study. It was hoped that using a more natural light source might contribute to increased compliance to using the device on a regular daily basis. Additionally, results of a comparative study, revealed that participants allocated to use monochromatic blue low lux light generated a greater number of ocular complaints compared to the condition with white high lux light (Anderson et al., 2009). This finding suggests that selecting white light instead of blue light may be justified as it potentially reduces the occurrence of ocular discomfort or complaints associated with light therapy.

The light therapy device used in this study was the Carex Day-Light Classic lamp (Carex Health Brands, China). It was selected because it is a well-established and widely used device known for delivering the appropriate intensity and spectrum of light required for therapeutic effects. Amongst other uses, it has been shown to positively impact alertness (Monroe & Smith, 2021). The device's design successfully emulates the qualities of natural sunlight through a spacious screen, ensuring a therapeutic light output. Delivering 10,000 lux of glare-free lighting, the device provides an optimal level of brightness for light therapy sessions. Moreover, its ergonomic design allows for comfortable usage at a recommended sitting distance of approximately 30cm, further enhancing the user's experience (Carex, 2014). The Sleep/Wake Research Centre at Massey University, New Zealand kindly provided nine devices for the duration of the study.

Participants were asked to use the Carex Day-Light Classic lamp daily for 30 minutes within two hours of waking every day for 4 weeks. In accordance with product instructions, participants were instructed to angle the lamp head at approximately 30° from the vertical position and to direct their eyes towards the approximate centre of the lamp. Participants were asked to sit approximately 30 cm from the light to provide a vertical (photopic) illuminance at the cornea of approximately 7000-10'000 lux. This is a distance at which they could comfortably read or have breakfast, as shown in Figure 8 below.

Figure 8

Visual Example of Light Therapy Positioning

Note. This figure provides one example of lamp position. Participants were able to alter the angle of the light to a limited extent to align with what was most comfortable for them, and most user friendly for the activities they chose to do while using the light. Image retrieved August 29, 2022, from https://redlighttherapyguide.com/carex-day-light-classic-review/.

6.7 Questionnaires

The following section provides an overview of the measures used in data collection. The primary outcome measure in the current study was the Fatigue Severity Scale (FFS). Measures were selected based on their validity and use in previous studies, as well as by considering what would be most useful but least burdensome for participants.

Initially, to check demographic and clinical characteristics were not statistically different between participants, a brief questionnaire was also completed prior to the intervention phase. This asked participants to complete a range of demographic questions covering age, ethnicity, gender, employment status and socioeconomic status; as well as a range of clinically relevant questions covering date of injury, injury severity, previous head injuries, previous experience of fatigue, and any specific beliefs held around the permanence of their injury.

6.7.1 Fatigue Severity Scale (FSS; Krupp, LaRocca, Muir-Nash & Steinberg, 1989)

The Fatigue Severity Scale is a nine-item questionnaire that consists of statements that are scored on a seven-point Likert type scale ranging from 1 (“strongly disagree”) to 7 (“strongly agree”). The scores on all 9 items are averaged to produce a mean FSS which can be interpreted as a measure of unidimensional fatigue. While some measurement tools assess multiple dimensions of fatigue, such as mental and physical fatigue, the FSS is specifically designed to measure fatigue within a single dimension, taking into account the way in which fatigue affects motivation, exercise, physical functioning, carrying out duties, and interference with work, family, and social life. This average score provides a general indication of the individual's perceived fatigue severity during the past week, with higher scores reflecting greater fatigue severity. A mean score of 4 or above indicates moderate-high levels of fatigue. However, some studies now use a cutoff of 5 or above to categorise severe fatigue (e.g., Johansson et al. 2008; Tellez et al., 2005). The FSS has been used among people with conditions such as brain injury, cancer, chronic fatigue syndrome, fibromyalgia, hepatitis C, HIV/AIDS, multiple sclerosis, neuroborreliosis, kidney diseases, obesity, Parkinson’s disease, poliomyelitis, sleep disorders/insomnia, stroke, and systemic lupus erythematosus, as well with people receiving primary care and healthy controls (Lerdal, 2021). A single item visual analogue scale rated 0-10 (with 0 being normal and 10 being most severe fatigue) may also be completed within this measure. Cronbach's alpha coefficient was reported to range from 0.81 to 0.94 (Lerdal, 2021). Administration time is approximately 5 minutes.

6.7.2 Epworth Sleepiness Scale (Johns, 1991)

The Epworth Sleepiness Scale (ESS) is a widely used self-report questionnaire designed to assess daytime sleepiness and to quantify an individual's tendency to fall asleep or experience drowsiness in various daily situations. Respondents are asked to rate, on a 4-point scale (0-3), their usual chances of dozing off or falling asleep while engaged in eight different activities. Most people engage in those activities at least occasionally, although not necessarily every day. No specific timeframe is given, but administration instructions include “this refers to your usual way of life in recent times”. The ESS score (the sum of 8 item scores, 0-3) can range from 0 to 24. The higher the ESS score, the higher that person’s average sleep propensity in daily life, or their ‘daytime sleepiness’. Scores can be interpreted as follows: 0-5 lower normal daytime sleepiness. 6-10 normal daytime sleepiness. 11-12 mild excessive daytime symptoms (Johns, 1991). The questionnaire takes no more than 2 or 3 minutes to answer and has been used in a number of other studies with mTBI patients. Cronbach's alpha coefficient was reported to range from 0.73 to 0.86 (Kendzerska et al., 2014). Administration time is approximately 2-3 minutes.

6.7.3 Pittsburgh Sleep Quality Index (Buysse, Reynolds, Monk, Berman & Kupfer, 1989)

The Pittsburgh Sleep Quality Index (PSQI) is a self-rated standardised measure of subjective sleep quality (Buysse, et al., 1989). The questionnaire is comprised of 19 items which form a global composite score to assess sleep quality during the previous month. Participants are asked to estimate sleep duration, sleep latency, use of medications, daytime sleepiness that may impede functions such as driving or socialising, and also the presence and frequency of specific sleep related problems such as difficulty falling asleep and waking throughout the night. These items generate seven equally weighted component scores relating to subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction due to sleepiness. Component scores are totalled to yield a global PSQI score between 0 and 21, where higher scores relate to poorer sleep quality. A global score of >5 is indicative for disturbed sleep and worse sleep quality (Buysee et. al., 1989). The PSQI is favoured as a measure of subjective sleep quality in the proposed study because it is easy for participants to understand and can be completed within 5-10 minutes. The PSQI has been used in previously published papers relating to subjective reports of fatigue in the mTBI population (Sinclair et al., 2014; Quera Salva et al., 2020). Cronbach's alpha coefficient was reported to range from 0.70 to 0.83 (Mollayeva et al., 2016). Administration time is approximately 5-10 minutes.

6.7.4 Depression Anxiety Stress Scale (Lovibond & Lovibond, 1995).

The Depression Anxiety Stress Scale (DASS-21) is the short form of the DASS-42. The scale consists of 21 items that relate to three subscales for depression, anxiety and stress. Each subscale is informed by seven items for which participants are asked to indicate how much a particular statement applied to them over the past week from 0 (did not apply to me at all) to 3 (applied to me very much, or most of the time). The threshold values for depression are categorised as follows: 0-4 (normal), 5-6 (mild), 7-10 (moderate), 11-13 (severe), 14+ (extremely severe). The threshold values for anxiety are categorised as follows: 0-3 (normal), 4-5 (mild), 6-7 (moderate), 8-9 (severe), 10+ (extremely severe). The threshold values for stress are categorised as follows: 0-7 (normal), 8-9 (mild), 10-12 (moderate), 13-16 (severe), 17+ (extremely severe). Cronbach's alpha coefficients have been reported as 0.90 for depression scale, 0.82 for anxiety scale, and 0.89 for stress scale (Randall et al., 2017). The DASS-21 has been shown to be reliable and valid with non-clinical samples. It is also highly correlated to other validated measures of depression and anxiety, indicating a high convergent validity. Administration time is approximately 5-10 minutes.

6.7.5 Daily Fatigue Rating Scale and Sleep Diary

One of the questions in the FFS asks participants to rate their overall experience of fatigue. In order to track the subjective experience of fatigue in a more continuous way, participants in the current study were asked to complete a daily record of fatigue on a scale of 0-10, where zero is no fatigue at all, and 10 is the most severe fatigue they could imagine. Alongside this, they were required to keep a sleep diary, recording the time they went to bed (with the purpose of sleep onset) and the time they woke up in the morning. This was to help track any significant changes in sleep patterns, and to corroborate with sleep data from wrist actigraphy. The daily fatigue rating scale and sleep diary were also able to serve as a proxy measure for adherence to the research protocol. In the sleep diary, participants were asked to record their sleep and wake times alongside their daily fatigue rating and any notes to indicate significant events or activity/inactivity that day.

6.7.6 Rest-activity monitoring and sleep

Wrist-worn actigraphy recordings was used to monitor rest-activity cycles across the study period and to objectively assess sleep timing, duration and fragmentation. Additionally, wrist actigraphy facilitated the assessment of indicators for fragmented rest-activity cycles such as for example the inter-daily variability[10], intra-daily stability[11], and relative amplitude of rest-activity cycles[12] (see for example Münch et al. 2016; Bromundt et al. 2012). IV measures the fragmentation of activity-rest periods within a 24-hour cycle. Healthy individuals usually have one prolonged activity period and one prolonged rest period per day. Higher IV values, ranging from 0 to 2, indicate increased fragmentation, with values below 1 being typical for healthy subjects. IS quantifies the regularity in the activity-rest pattern with values ranging from 0 to 1. A value of 0 indicates no rhythm, while a value of 1 indicates a perfectly stable rhythm. Relative amplitude (RA) is calculated by first finding the difference between the average activity levels during the ten most active hours (M10) and five least active hours (L5) periods, called amplitude. To account for the overall activity level, RA is obtained by dividing amplitude by the sum of the L5 and M10 values. RA ranges from 0 to 1, with higher values indicating a rhythm with a stronger amplitude. Other outputs of actigraphy data include sleep efficiency, which is actual sleep time expressed as a percentage of time in bed. The Fragmentation Index reflects the degree of sleep period fragmentation and serves as an indication of sleep quality. Higher values suggest increased sleep disruption or poorer sleep quality (Camntech, The MotionWatch User Guide 2023).

Wrist actigraphy was included in the current study to help better understand participants' objective daily activity and sleep/wake patterns. Actigraphy provides objective data on individuals' activity patterns over time, allowing for statistical calculations to interpret and quantify those patterns, thus providing a comprehensive picture of physiological rhythms and behaviour.

For this study, two different devices were used. The reason for this was that the original devices were personally owned by one of the research supervisors overseeing the current study. Due to her relocating to Europe part way through data collection, comparable devices were loaned from the Sleep Wake Research Centre. Both are described below:

1) The MotionWatch8 (Camntech, United Kingdom) is designed to monitor daytime light exposure for quantifying exposure duration and intensity. Data related to daytime physical activity was intended to be used to monitor possible treatment effects on

[10] IV measures the fragmentation of activity-rest periods within a 24-hour cycle. Healthy individuals usually have one prolonged activity period and one prolonged rest period per day.
[11] IS quantifies the regularity in the Activity-Rest pattern.
[12] RA is calculated by first finding the difference between the average activity levels during the M10 (ten most active hours) and L5 (five least active hours) periods, called Amplitude.

mobility, and provide further evaluation of the efficacy of bright light therapy in reducing fatigue.

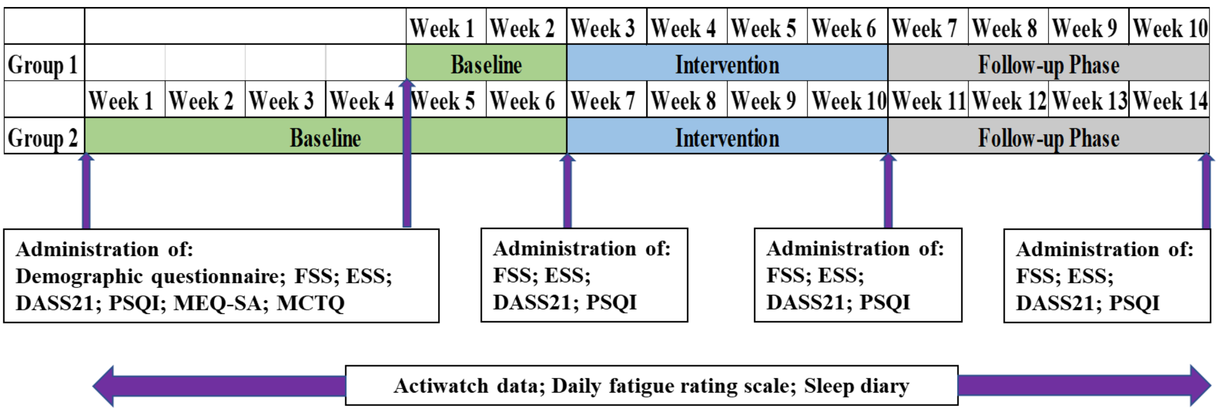
2) The Micro Motionlogger (Ambulatory Monitoring, United States) device, was considered to be a comparable alternative and was used as a substitute for the MotionWatch8 during the latter stages of the study.

6.8 Study Design and Protocol

The primary researcher was responsible for facilitating the completion of all measures outlined above. The relevant questionnaires were combined into one overarching online survey using the Qualtrics survey tool which is included as Appendix B and C. This allowed participants to provide responses to questionnaires in an efficient way, with a link being emailed directly to them at each stage. The survey was administered at four crucial timepoints which can be most clearly explained in the Figure 9 below. This figure illustrates the intended study protocol with two distinct groups, however, the practical execution deviated from this plan. Individual participant circumstances and the dynamic nature of the intervention led to variations in the timing of the baseline phase, blurring the distinction between the two groups originally envisioned. Consequently, the data collected cannot be neatly categorised into two separate participant groups for analysis. Instead, the results reported in the following chapter represent the collective outcomes of all participants, reflecting the holistic impact of the intervention across the entire cohort.

Figure 9

Administration Protocol. Design with Multiple Baseline.



Note. As previously explained, due to individual participant circumstances, the timing of each phase was not strictly adhered to as planned. However, the measures were administered at each timepoint as outlined.

6.8.1 Intervention phase

Following the baseline phase, participants were provided with a light therapy lamp and each given instructions and practical demonstration on its use. This included being sent photographic images of the correct positioning of the lamp, as well as written instruction. Participants were seen in person where possible, or spoken to over the phone to address any difficulties they had with set-up and/or questions about the process and timing of the intervention. Contact was maintained by email and phone throughout the intervention phase to make sure participants could ask questions or raise concerns when required.

6.9 Methodological Considerations for Light Therapy Use

The safety of participants is a critical consideration in any intervention trial. As mentioned in the literature review, previous studies have not shown any apparent light-induced pathology or long-term sequelae resulting from light therapies, as long as the intensity of the light source was within recommended guidelines (Gallin et al., 1995). However, possible side-effects were discussed with participants and they were encouraged to monitor for these and to communicate their experiences if anything was noticed.

6.10 Ethics

The trial was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving participants were approved by the New Zealand Central Health and Disability Ethics Committee (HDEC; 20/CEN/49). Written informed consent was obtained from all participants before the study began.

A submission of a Scope of Review form to the Ministry of Health was completed in October 2019. The outcome of the Scope of Review was that an application was needed to be completed, with the salient issue for consideration being the vulnerability of this participant group; that is, the capacity participants have to provide informed consent to participate in the research. It was considered by the researcher that these are people who are able to make informed decisions (e.g., they are not cognitively impaired), but it was ultimately something needing to be to delineated through the submission process. A decision was made through the HDEC-Expedited Review pathway on 22 April 2020 that the ethics application for the current study was approved.

Chapter Seven: Results

The final sample size in the current study fell short of the target, and while this was disappointing, it was deemed to be ethically necessary. In the earlier stages of data collection, one participant reported having some problems which he suspected was related to the use of the light. These included headaches, sore eyes, disrupted sleep, and early waking in the morning. After further discussions with this participant, he explained that he had found the light to have an “activating” effect, which in part led to him increasing his work hours. This increase in time at work, and increased responsibility he had taken on during the hours he was working was thought to be a contributing factor in the problems he was reporting. Therefore, at that time it was decided that he would cease the intervention trial, but that the study would continue with other participants. However, in the latter stages of data collection, a second participant reported subjective adverse effects which he believed resulted from his use of the light. This participant reported “severe fatigue” which had a detrimental effect on his mood. The severity of his fatigue following the light intervention was such that it needed to be followed up medically. In spite of a review of the literature on light therapy revealing no reports of severe adverse effects, the reaction experienced by these two individuals raised doubts as to the ethics of continuing the study. After discussion, a decision was made to stop further recruitment. Because multiple-baseline research allows for evaluation of data obtained from a small number of participants who act as their own controls (Hawkins et al., 2007), the data collected can still be usefully explored.

Of the participants who progressed to the therapy stage of this study, nine continued through to the follow-up phase. Results will be presented for each hypothesis, with group data presented initially in the form of Brinley plots. Due to the inherent limitations stemming from the small sample size, it is important to adopt a cautious approach in evaluating the significance and generalizability of these findings.

A subsequent section presents data for each individual participant. It was thought that consideration of each participant’s progress in this study could bring a richer meaning to group results and contribute to informing further research in this area.

7.1 Group comparisons

The group results were analysed via a threefold comparative approach. First, comparison is made between baseline measurements (mean of intake and pre-intervention scores) and post-intervention data to reveal immediate effects of bright light therapy. Second, comparison between baseline measurements and post-follow-up phase results, and third, comparison between post-intervention findings and post-follow-up phase results. This approach aids in the understanding of whether the effects induced by the intervention persist or dissipate after the cessation of light therapy. Collectively, these analyses provide a nuanced understanding of the efficacy and lasting impacts of the intervention.

7.1.1 Fatigue

The research question was whether daily exposure to bright light is effective in reducing concussion related fatigue symptoms as measured using the Fatigue Severity Scale alongside daily fatigue ratings. Results are presented at baseline, pre-intervention, post-intervention, and post follow up.

As stated earlier, mean scores of 4 or higher indicate clinically significant fatigue, and scores of 5 and above are thought to indicate severe fatigue. As shown below in Table 7, all participants were above a mean of 4, and remained so throughout, with only two exceptions (highlighted in bold).

Table 7

Fatigue Severity Scale Scores

	Intake	Pre-Intervention	Post-Intervention	Follow-up
P1	5.67	5.67	5.56	4.89
P2	6.22	6	6.22	6.33
P3	6.22	5.67	5.44	5.89
P4	6.78	6.67	6.67	Missing data
P5	6.22	6.22	6.22	7
P6	6.33	5.22	**1.56**	5.11
P7	6.78	6.33	6.33	6.22
P8	5.67	Missing data	5.11	5.11
P9	4.44	Missing data	4.11	**3.44**

Note. Values in bold indicate scores that no longer reach FSS threshold for significant fatigue.

Hypothesis 1 *Fatigue Severity Scale (FSS) scores will be lower at post-intervention and after follow-up than at baseline*.

A Wilcoxon Sign-Rank Test indicated that median post-test ranks for FSS scores decreased between baseline and post-intervention (*Meddiff* = 0.29). This difference is statistically significant (*W*=41.0, *p*=0.027, *rank biserial correlation*=0.82).

Baseline and follow-up comparison of FSS scores also indicated reduction in fatigue severity (*Meddiff* = 0.35) although the difference was not statistically significant (*W*=27.0, *p*=0.25, *rank biserial correlation*=0.50).

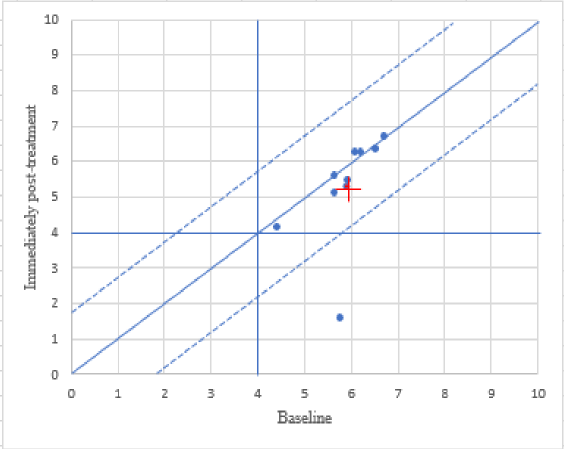
Immediate post-intervention and follow-up comparison of FSS scores revealed an increase in fatigue severity at follow-up (*Meddiff* = -0.14) although the difference was not statistically significant (*W*=10.5, *p*=0.611, *rank biserial correlation*=0.25).

Descriptive visual representation of these results is provided in Figure 10 below.

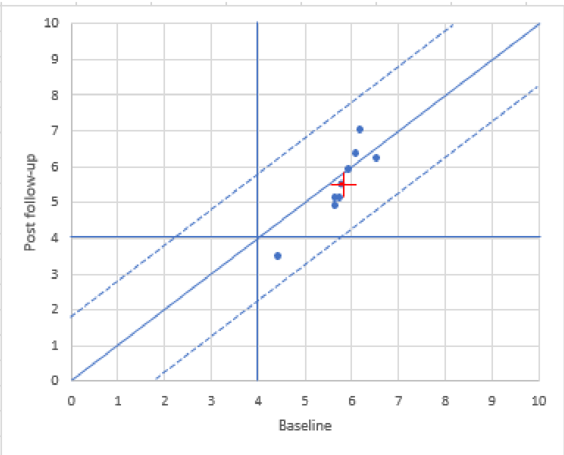
Figure 10

Brinley Plots for FSS Scale Score Comparisons: a. Baseline and Immediate Post-treatment and b. Baseline and Follow-up c. Immediate Post-Treatment and Follow-up

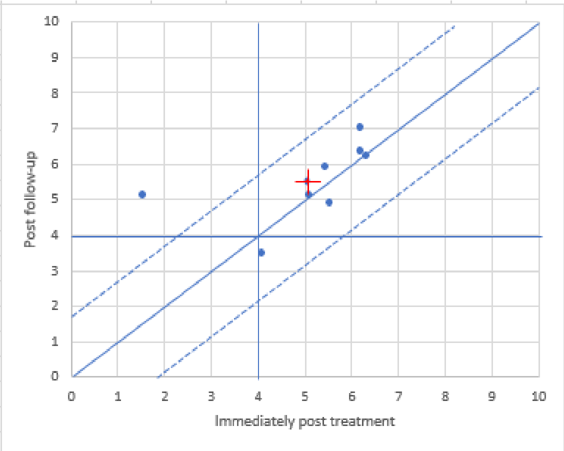
a.



b.



c.



Hypothesis 2: *Daily Fatigue Ratings will be lower at post-intervention and follow-up than at baseline*

A Wilcoxon Sign-Rank Test indicated that median post-test ranks for mean daily fatigue ratings decreased between baseline and post-intervention (*Meddiff* = 0.34) although the difference was not statistically significant (*W*=25.0, *p*=0.078, *rank biserial correlation*=0.77).

Baseline and follow-up comparison of mean daily fatigue ratings also indicated reduction in fatigue severity (*Meddiff* = 0.11) although the difference was again not statistically significant (*W*=17.0, *p*=0.688, *rank biserial correlation*=0.21).

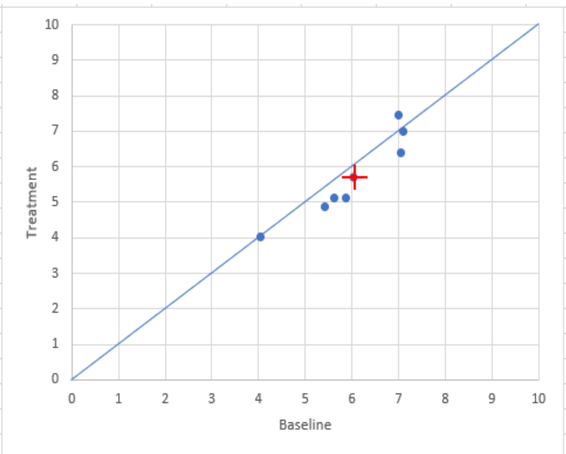
Immediate post-intervention and follow-up comparison of mean daily fatigue ratings revealed an increase at follow-up (*Meddiff* = -0.168) although the difference was not statistically significant (*W*=9, *p*=0.469, *rank biserial correlation*=0.36).

Descriptive visual representations of these results are provided in Figure 11 below.

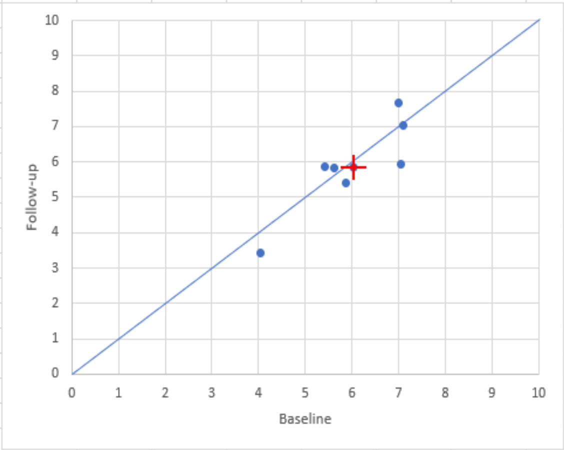
Figure 11

Brinley Plots for Daily Fatigue Comparisons: a. Baseline and Treatment and b. Baseline and Follow-up c. Treatment and Follow-up

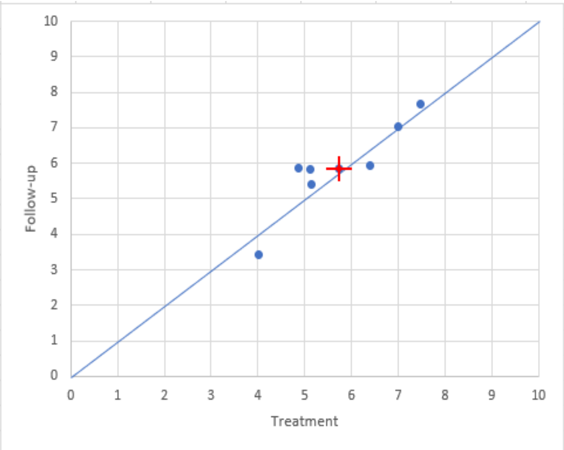
a.



b.



c.



7.1.2 Daytime Sleepiness and Sleep Quality

The question here was whether daily exposure to bright light is effective in reducing daytime sleepiness and/or improving sleep quality in participants with fatigue symptoms.

ESS scores can be interpreted as follows: 0-5 lower normal daytime sleepiness. 6-10 normal daytime sleepiness. 11-12 mild excessive daytime symptoms. As shown below in Table 8, prior to treatment, all participants were below 11 except for 2. This demonstrates that for most participants, excessive daytime sleepiness was not present.

A cut off on the PSQI global score of >5 indicates poor sleep quality. Furthermore, a score of >5 conveys that a respondent is having severe difficulties in at least two areas, or moderate difficulties in at least three areas measured on this scale (Buysee et. al., 1988. p.205). As shown below in Table 8, all participants scored above 5 across all data points indicating at least moderate difficulties.

Table 8

ESS and PSQI Scores

	Epworth Sleepiness Scale				Pittsburgh Sleep Quality Index			
	Intake	Pre-treatment	Post-treatment	Follow-up	Intake	Pre-treatment	Post-treatment	Follow-up
P1	8	8	8	10	**6**	**8**	**9**	**8**
P2	5	2	3	4	**7**	**10**	**9**	**8**
P3	**13**	6	4	8	**12**	**12**	**11**	**11**
P4	4	5	9		**12**	**12**	**12**	
P5	**24**	**24**	**24**	**22**	**11**	**11**	**11**	**11**
P6	3	4	3	2	**14**	**12**	**10**	**9**
P7	8	**14**	10	**12**	**11**	**10**	**9**	**10**
P8	2	missing	2	1	**10**	missing	**9**	**7**
P9	10	missing	6	7	**9**	missing	**12**	**13**

Note. All scores represented in **bold** indicate values above the clinical cutoff for the respective scale.

Hypothesis 3. *ESS scores for participants post-intervention will be significantly lower than at baseline.*

A Wilcoxon Sign-Rank Test indicated that median post-test ranks for ESS scores decreased between baseline and post-intervention (*Meddiff* = 0.75) although the difference was not statistically significant (W=16.0, p=0.293, *rank biserial correlation*=0.52).

Baseline and follow-up comparison of ESS scores also indicated sleepiness reduced between the two time points (*Meddiff* = 0.68) although the difference was again not statistically significant (W=26.0, p=0.292, *rank biserial correlation*=0.44).

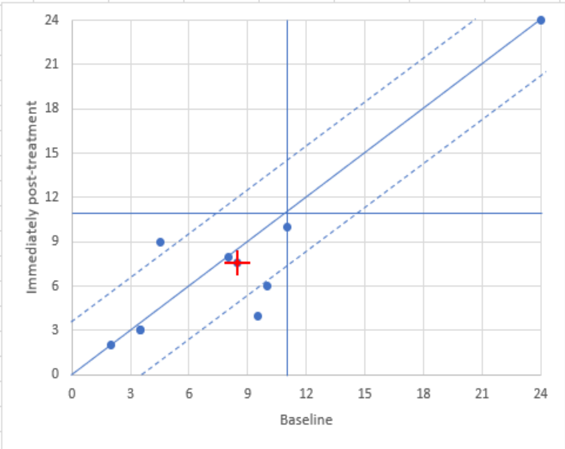
Immediate post-intervention and follow-up comparison of ESS scores revealed an increase at follow-up (*Meddiff* = -0.58) although the difference was not statistically significant (W=11.0, p=0.354, *rank biserial correlation*=-0.39).

Descriptive visual representation of these results is provided in Figure 12 below.

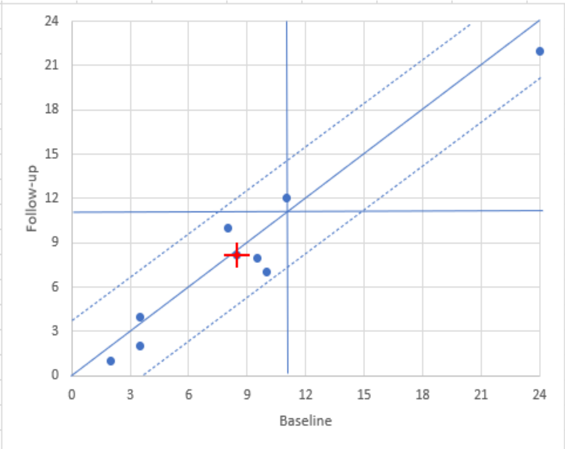
Figure 12

Brinley Plots for ESS Score Comparisons: a. Baseline and Immediate Post-treatment and b. Baseline and Follow-up c. Immediate Post-Treatment and Follow-up

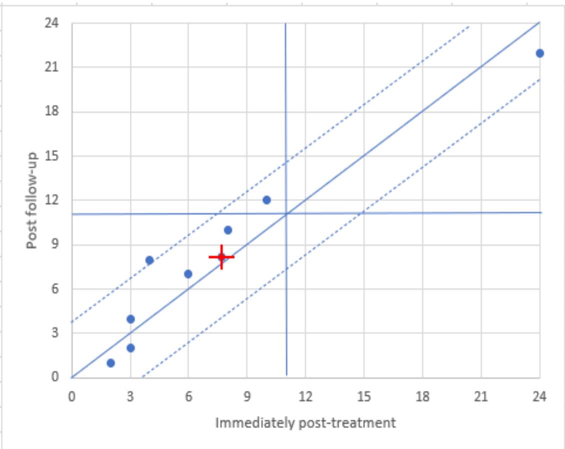
a.



b.



c.



Hypothesis 4. *PSQI scores for participants post-intervention will be significantly lower than at baseline.*

A Wilcoxon Sign-Rank Test indicated a slight increase in PSQI scores (worsening of sleep quality) between baseline and post-intervention (*Meddiff* = 0.25) although the difference was not statistically significant (*W*=15.5, *p*=0.865, *rank biserial correlation*=0.11).

Baseline and follow-up comparison of PSQI scores show a slight decrease in PSQI scores between the two time points (*Meddiff* = 0.63) although the difference was again not statistically significant (*W*=18.0, *p*=0.552, *rank biserial correlation*=0.29).

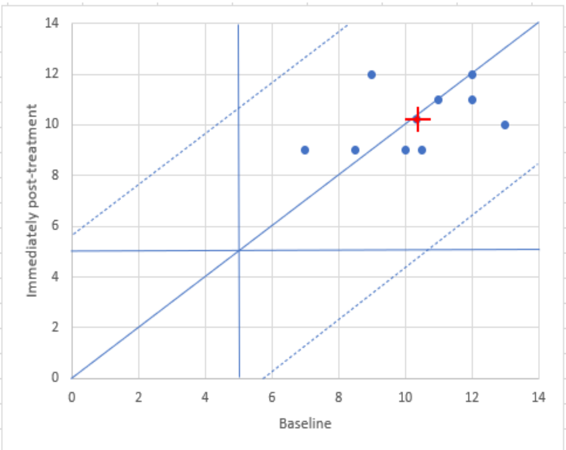
Immediate post-intervention and follow-up comparison of PSQI scores revealed a slight decrease post follow-up (*Meddiff* = 0.50) although the difference was again not statistically significant (*W*=15.0, *p*=0.374, *rank biserial correlation*=0.43).

Descriptive visual representation of these results is provided in Figure 13 below.

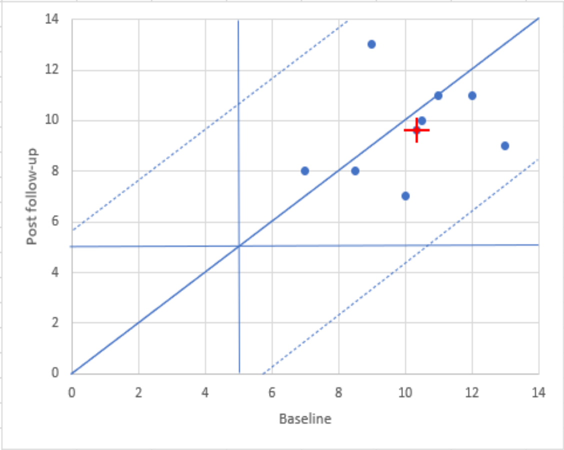
Figure 13

Brinley Plots for PSQI Score Comparisons: a. Baseline and Immediate Post-treatment and b. Baseline and Follow-up c. Immediate Post-Treatment and Follow-up

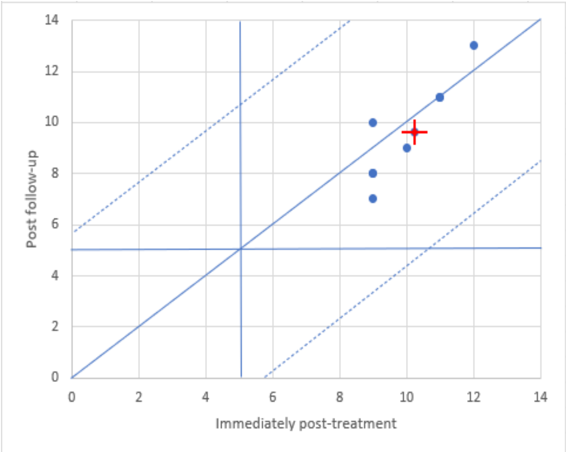
a.



b.



c.



7.1.3 Depression, Anxiety, and Stress

The research question was whether daily exposure to bright light is effective in reducing daytime sleepiness and/or improving sleep quality in participants with fatigue symptoms.

Score cut offs for the DASS 21 are as follows: mild depression 5-6; moderate 7-10, severe 11-13, extremely severe 14+; mild anxiety 4-5; moderate 6-7, severe 8-9, extremely severe 10+; and mild stress 8-9, moderate 10-12, severe 13-17, extremely severe 17+. A summary of detailed participant's results from the current study is shown in Table 9 below.

Table 9

DASS-21 Results

	DASS Depression				DASS Anxiety				DASS Stress			
	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
P1	**6**	**6**	**5**	**5**	**6**	**6**	**4**	**5**	7	7	7	**9**
P2	0	1	**6**	2	0	0	0	0	5	4	3	3
P3	2	1	1	2	**4**	3	0	2	**14**	**11**	6	6
P4	**14**	**12**	**10**		**7**	**4**	2		**11**	**11**	**10**	
P5	0	0	0	1	0	0	0	1	4	4	3	3
P6	4	3	**11**	**6**	0	0	0	0	**12**	**9**	**8**	7
P7	**5**	**6**	**5**	**5**	**4**	**4**	1	1	6	**10**	**9**	**8**
P8	0		0	0	0		0	0	2		1	2
P9	**6**		3	**6**	**9**		**4**	**4**	**11**		7	7

*Note.*T1 = Intake, T2 = Pre-intervention, T3 = Post-Intervention, T4 = Follow-up. Scores that are depicted in bold font indicate they reach cut-off for at least mild experiences of depression, anxiety, or stress.

As was acknowledged in the methods chapter of this thesis, the goal was to minimise the potential confounding factors that could be introduced if participants were experiencing significant challenges with mood at the time of recruitment. However, in the context of real-world clinical scenarios, individuals with mTBI will present with diverse and overlapping clinical profiles. The decision to include participants with elevated DASS-21 scores mirrors the complex realities encountered in clinical practice. With a larger scale study, subgroup analysis that is designed to specifically focus on fatigue among individuals experiencing co-occurring psychological distress would offer valuable insights into the unique manifestations of fatigue within this subgroup. Regrettably, due to the small sample size available for the current study, the implementation of a robust subgroup analysis is not feasible.

7.1.4: Group Data: DASS-21 Scores

Brinley plots are presented in the following section to visually represent DASS-21 data. The relevant RCI values are: DASS-21 Depression Scale, RCI = 4.42; DASS-21 Anxiety Scale, RCI = 4.73; DASS-21 Stress Scale, RCI = 4.74.

DASS-21 Depression

A Wilcoxon Sign-Rank Test indicated a marginal increase in DASS-21 depression scale scores between baseline and post-intervention (*Meddiff* = 1.00) although the difference was not statistically significant (*W*=15.0, *p*=0.932, *rank biserial correlation*=0.07).

Baseline and follow-up comparison of DASS-21 depression scale scores show a small decrease between the two time points (*Meddiff* = -0.50) although the difference was again not statistically significant (*W*=5.0, *p*=0.572, *rank biserial correlation*=0.33).

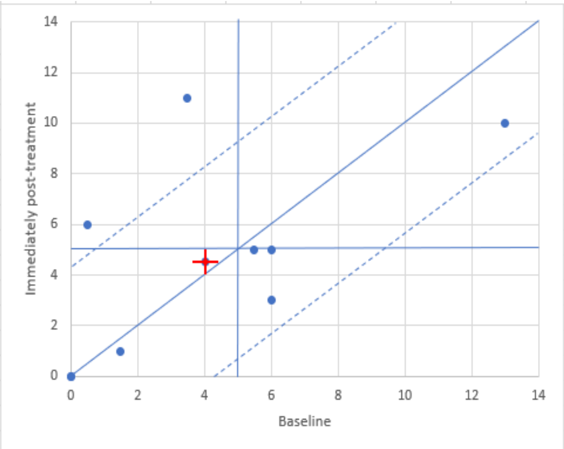
Immediate post-intervention and follow-up comparison of DASS-21 depression scale scores revealed a slight decrease post follow-up (*Meddiff* = 0.50) although the difference was again not statistically significant (*W*=9.0, *p*=0.786, *rank biserial correlation*=0.20).

Visual representation of these results is provided in Figure 14 below.

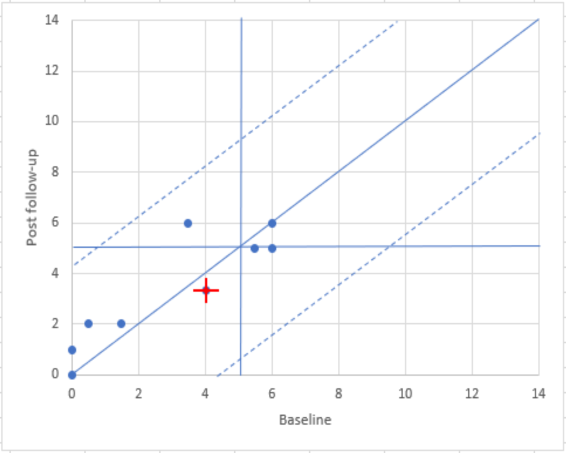
Figure 14

Brinley Plots for DASS-21 Depression Scale Comparisons: a. Baseline and Immediate Post-treatment and b. Baseline and Follow-up c. Immediate Post-Treatment and Follow-up

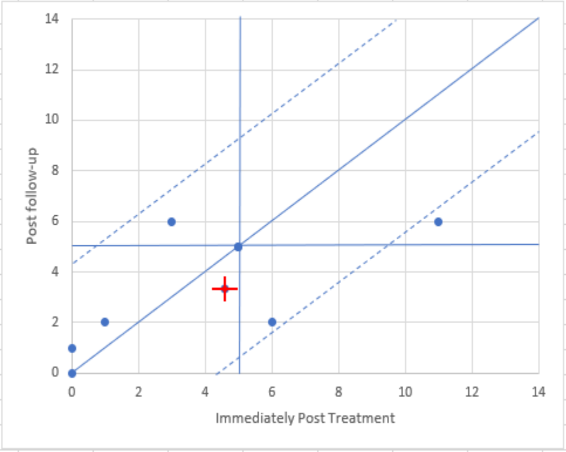
a.



b.



c.



DASS-21 Anxiety

A Wilcoxon Sign-Rank Test indicated a decrease in DASS-21 anxiety scale scores between baseline and post-intervention (*Meddiff* = 3.50) although the difference was not statistically significant (*W*=15.0, *p*=0.058, *rank biserial correlation*=1.00).

Baseline and follow-up comparison also indicates a decrease in DASS-21 anxiety scale scores between the two time points (*Meddiff* = 2.00) although the difference was again not statistically significant (*W*=13.5, *p*=0.136, *rank biserial correlation*=0.80).

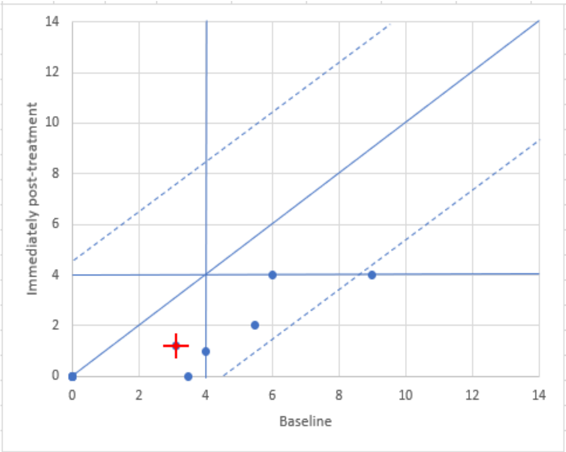
Immediate post-intervention and follow-up comparison of DASS-21 anxiety scale scores revealed a slight increase post follow-up (*Meddiff* = -1.41) although the significance of this was difficult to estimate given that 5 pairs of values were tied (*W*=0.0, *p*=0.174, *rank biserial correlation*=-1.00).

Visual representation of these results is provided in Figure 15 below.

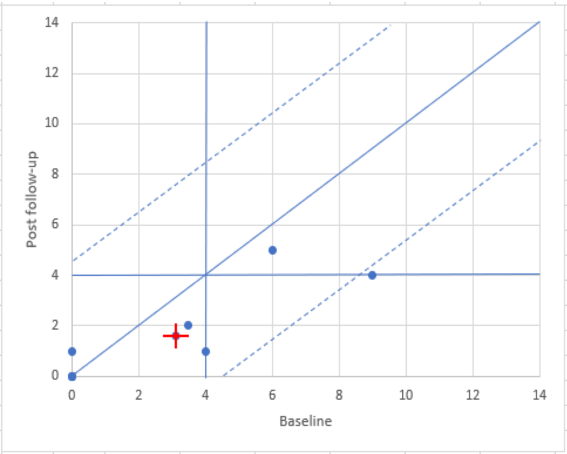
Figure 15

Brinley Plots for DASS-21 Anxiety Scale Comparisons: a. Baseline and Immediate Post-treatment and b. Baseline and Follow-up c. Immediate Post-Treatment and Follow-up

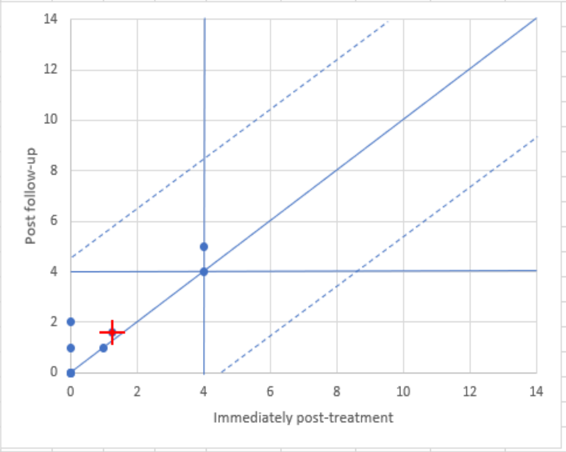
a.



b.



c.



DASS-21 Stress

A Wilcoxon Sign-Rank Test indicated a decrease in DASS-21 stress scale scores between baseline and post-intervention (*Meddiff* = 2.00) the difference was statistically significant (*W*=33.5, *p*=0.033, *rank biserial correlation*=0.86).

Baseline and follow-up comparison also indicates a decrease in DASS-21 stress scale scores between the two time points (*Meddiff* = 2.50) although the difference was not statistically significant (*W*=18.5, *p*=0.114, *rank biserial correlation*=0.76).

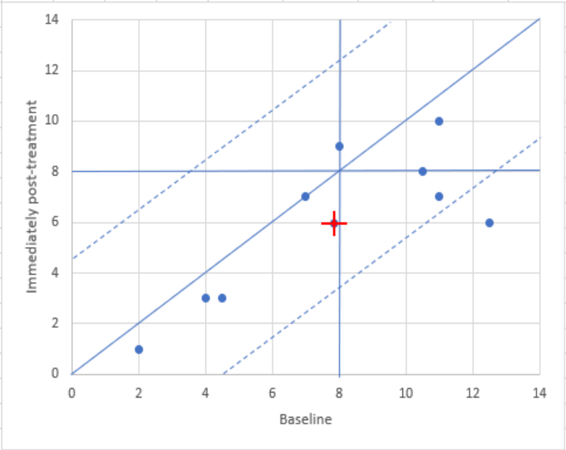
Immediate post-intervention and follow-up comparison of DASS-21 stress scale scores indicates a slight increase post follow-up (*Meddiff* = -0.35) although the significance of this was difficult to estimate given that 4 pairs of values were tied (*W*=4.0, *p*=0.850, *rank biserial correlation*=-0.20).

Visual representation of these results is provided in Figure 16 below.

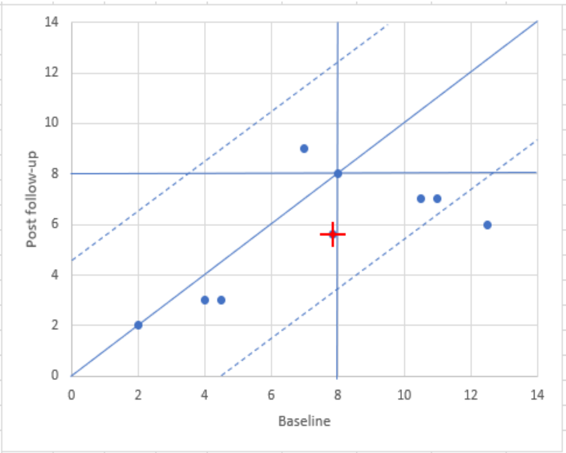
Figure 16

Brinley Plots for DASS-21 Stress Scale Comparisons: a. Baseline and Immediate Post-treatment and b. Baseline and Follow-up c. Immediate Post-Treatment and Follow-up

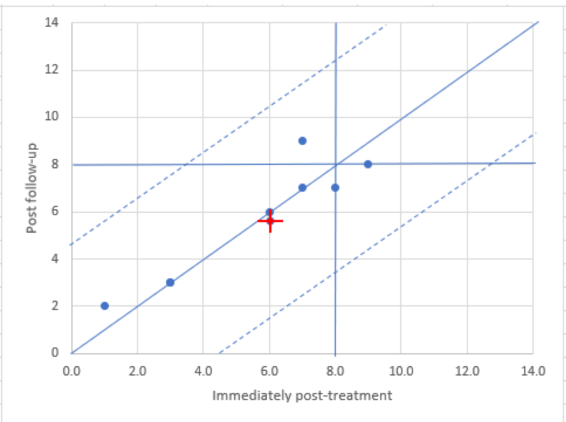
a.



b.



c.



7.2 Rest-activity Results

7.2.1 Limitations in Data Collection and Presentation

The current research aimed to investigate sleep-wake patterns and circadian rhythms using actigraphy data as a valuable tool for objective and continuous monitoring in real-world settings. However, it is important to acknowledge the study related and technical challenges, such as low quality batteries and lack of delivery due to COVID-related delivery stops, encountered during the data collection process, which resulted in the presentation of results for only one participant in the study.

More extensive discussions on the encountered limitations will be provided in the subsequent discussion section. This will include an in-depth exploration of the methodological challenges, potential sources of bias, and the implications of the restricted sample size on the study's overall findings. The data of one participant was visually inspected and only days, where the device was worn for at least 21 hours were included. The actigraphy data is presented in Table 10. The terms used for the time periods presented below differ from other measures already presented. This stems from the fact that the actigraphy data involves continuous data that has been averaged based on the stage at which it was collected during the intervention, as opposed to individual time points.

Table 10

Actigraphy Results for Participant P2 Averaged Across Each Study Phase

	Baseline Period	Light Intervention Period	Follow-up Period
Circadian parameters			
Intra-daily Variability (IV)	1.24	1.04	1.07
Inter-daily Stability (IS)	0.50	0.64	0.48
Relative Amplitude (RA)	0.97	0.97	0.95
Amplitude	21259	29477	25728
L5 onset	23:00	22:45	22:15
Sleep parameters			
Bed-time	21:33	21:16	21:36
Get-up time	7:04	6:23	6:53
Time in bed	9:31	9:06	9:16
Sleep duration	8:34	8:15	8:11
Sleep efficiency	90.13%	90.72%	88.51%
Mean wake bout time	0:02	0:02	0:02
Fragmentation index	24.97	23.73	23.90
Activity parameters			
M10 onset	7:00	7:45	6:00
M10 Average	21603	29912	26325

Note. IV measures the fragmentation of activity-rest periods within a 24-hour cycle; IS quantifies the regularity in the Activity-Rest pattern; RA is calculated by first finding the difference between the average activity levels during the M10 (ten most active hours) and L5 (five least active hours) periods - with higher values indicating a rhythm with a stronger amplitude; Sleep efficiency is actual sleep time expressed as a percentage of time in bed; The Fragmentation Index reflects the degree of sleep period fragmentation and serves as an indication of sleep quality. (Camntech, The MotionWatch User Guide 2023).

Looking at the change over time in the actigraphy data for participant P2 reveals several positive observations during the course of the study. Intra-daily variability values became lower during the treatment phase, suggesting a decrease in fragmentation within the activity-rest cycles. These scores remained relatively stable at follow-up, indicating sustained improvements in sleep pattern regularity. Inter-daily stability scores peaked during the treatment phase, implying a positive effect on stabilizing the regularity of the activity-rest pattern; however, these scores returned to baseline levels post-treatment. It is important to note that circadian amplitude remained relatively stable throughout all three phases of the study.

Regarding sleep-related outcomes, discernible changes were minimal, and sleep patterns exhibited limited fluctuations across the study phases. However, in the context of activity levels, participant P2 appeared to be more active during the treatment phase of the study, potentially indicating a positive impact of the light treatment on energy levels. Although activity levels experienced a slight decline during the follow-up phase, they did not regress to baseline levels.

7.3 Individual Data for Participants who Withdrew due to Adverse Effects

One participant, who had commenced light therapy in February 2021, completed just under two weeks of the intervention before deciding to discontinue participation. This decision was primarily attributed to the negative side effects experienced during the initial phase of treatment. Notably, the participant reported headaches, sore eyes, disrupted sleep patterns, and early morning awakenings without the ability to return to sleep. These adverse effects raised concerns and discomfort during the course of the intervention. It is important to note that, upon further discussion with the participant, they noted that the light therapy had a stimulating effect and it was revealed that they had therefore increased their work hours during the study period. The additional cognitive effort expended due to this increase in time at work was believed by the participant as potentially contributing to heightened fatigue and may have exacerbated the side effects. Despite these challenges, the adverse effects experienced by this individual were not deemed severe enough to warrant suspension of their participation in the study. It was revealed subsequent to their participation that they had tried a different form of light therapy in the past (red light) and they expressed a belief that the dosage of light in the current study may have been too high. Further adding to the complexity of understanding this individuals experience were his reported past experiences with self-described serotonin syndrome and norephedrine toxicity, which he felt may have influenced his reaction to the treatment.

In March 2022, a second participant chose to withdraw from the study, primarily due to the emergence of significant and distressing side effects. This participant experienced a substantial exacerbation of fatigue symptoms, which he reported had a profound and adverse impact on his mood and overall well-being. It is important to note that a direct causal link between the intensified symptoms and the light intervention couldn't be firmly established, but the participant personally believed that the intervention might have played a role in this exacerbation. Consequently, he was undergoing further evaluation and consultation with his medical team to explore potential connections and underlying causes. Given the severity of this participant's response, coupled with the previously reported adverse experiences of the participant mentioned above, it was decided to suspend further recruitment to the study from that point. Whilst this led to the study having fewer participants than originally planned, the decision was made to ensure the safety and well-being of participants. Subsequent follow-up with this client revealed that no medical reason was found for the increase in fatigue and that he has slowly improved, although still has significant fatigue.

7.4 Individual Data

This section presents the findings from the current research in the form of individual data presentation. While the group-level results provide valuable insights into the overall trends and effects of the intervention, as has been highlighted, it is important to interpret them with caution due to the small sample size in the current study. With caution in mind, considering the impact of the intervention within the context of each individual is deemed to be valuable in providing a broader understanding of the implications of the results, but this did not form part of the methodological process. Exploratory analyses were therefore conducted at the individual level to gain additional insights regarding the efficacy of light therapy and to provide a more comprehensive understanding of the data.

This section is structured to first offer a written contextual overview of each participant's involvement in the study. This is followed by a table that details individual results, capturing the trends and change observed through each time point. Daily fatigue ratings are represented graphically, affording a visual conduit for discerning shifts in fatigue levels over time. Additionally, where there are specific limitations or concerns in relation to an individual's participation in the study, these are discussed. Visual interpretation of these individual findings can be viewed as supplementary graphs in Appendix D.

7.4.1 Participant 1 (P1):

P1 was a 42-year-old male who sustained his injury in April 2019. The injury occurred after a high-speed fall, and resulted in symptoms that reportedly included cognitive deficit, noise sensitivity, a verbal stutter, and debilitating fatigue. P1 was subsequently diagnosed with mTBI and he reported that the slow pace of his recovery resulted in the loss of his business and income at that time. The cumulative effect of his physical injury and resulting cognitive and emotional consequences, coupled with the loss of his livelihood, reportedly contributed to his experience of increasing emotional and financial stress. P1 reported to have been focussed on making any (and all) recommended changes possible to improve his quality of life prior to his recruitment for the current study. At the time of recruitment, he met criteria in the sense that his cognitive difficulties had resolved, and his speech was intact. However, P1 still reported to be experiencing fatigue to a level that it was holding him back from resuming life as he had known it. P1 was very focussed on his wellbeing at this time. His goal was to reach a point where he had completely recovered from his injury, but he also hoped to be rehabilitated to a point where he felt he was both stronger and living a more positive and meaningful life than he had prior to April 2019. P1 expressed his frustration with the lack of support and evidence-based treatment for post mTBI fatigue. He felt that he was unable to be the person he aspired to be, and he expressed concerns with the impact his fatigue (and related irritability) had on his partner and children whanau. P1 agreed to take part in this research having recovered from the cognitive impact of his injury, stating that the residual fatigue he experienced was what was holding him back from resuming his normal day-to-day life:

> *"It's exciting to see some developments into the effects of "Mild" TBI. Since the accident it has been a lonely place in regards to recovery. No constants, no examples, no timelines, no cure. It is hard to process some days, but seeing the start of practical research is where changing the world all begins".*

It was clear that P1 was a very motivated individual throughout the recruitment process. Visiting him in his home, and meeting his partner provided further evidence that his fatigue was impacting both himself and his wider network in a negative way, and that he was willing to do whatever it took to recover from this and move forward with his life.

P1 was a participant who had a thirst for understanding the theory behind the light therapy intervention. From early on in his participation in this study he reported that he noticed the impact of the treatment, and at the conclusion of the intervention phase he reported:

"It has made a difference in respect to me being optimistic about my future beyond what I have been in the past. My CBF (Can't Be F@&ked) days have been few and far between. My energy levels seem constant rather than peaks and troughs. My fatigue levels were often unpredictable, but I seem to now have a balance from day to day which has helped increase my confidence…"

However, on objective testing, these subjectively noted benefits are less clear. P1's results, provided in Table 11, reveal intriguing patterns during the intervention and follow-up period. On the Fatigue Severity Scale, he displayed a slight decrease in scores between baseline and immediately following the intervention, further declining after the 4-week follow-up. His score at follow-up is still indicative of significant fatigue, but no longer would be considered severe.

While P1's objective assessments did not yield a significant positive shift, his subjective experience of fatigue appeared to be less severe following light therapy. He reported that his fatigue levels, which had often presented unpredictably in the past, had stabilised through the treatment process. Notably, P1 expressed a keen interest in acquiring a light therapy lamp to sustain the treatment benefits beyond the study's conclusion. This demonstrates not only the nuanced interplay between subjective experiences and objective measures, but also P1's strong motivation and proactive approach towards managing fatigue symptoms.

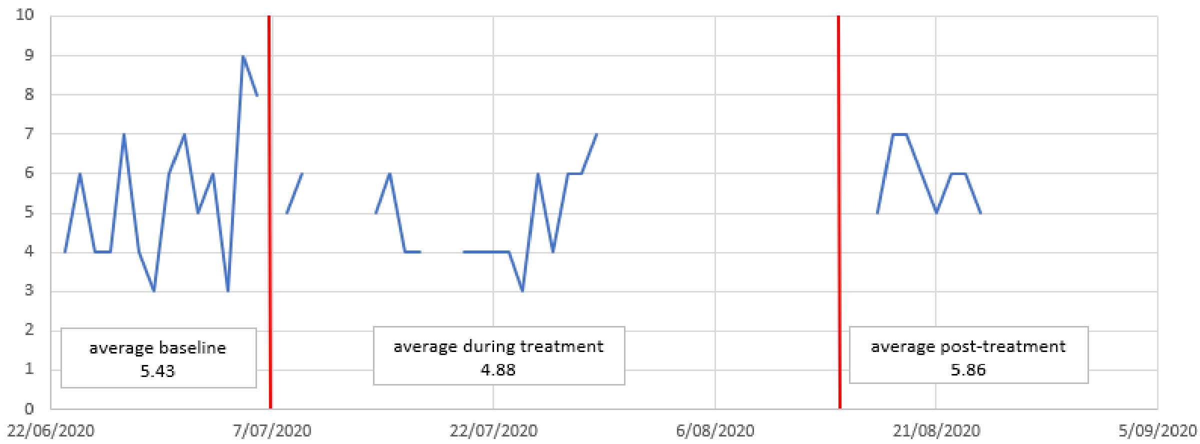
Table 11

P1's Individual Results

	Intake	Pre-Treatment	Post-Treatment	Post Follow-up
FSS	5.67	5.67	5.56	4.89
ESS	8	8	8	10
PSQI	6	8	9	8
DASS-D	6	6	5	5
DASS-A	6	6	4	5
DASS-S	7	7	7	9

Figure 17

P1's Daily Fatigue Ratings



NB: Red vertical lines indicate the start and finish of the light therapy intervention

Limitations for P1:

Casting a spotlight on P1's personal experience, it is important to note possible confounding circumstances, and/or possible explanations for the discrepancy between his subjective report, and his objective test results. Throughout our correspondence, P1 reported that the light therapy intervention was a catalyst for change in multiple aspects of his life. For example, he reported that he coincided this treatment with quitting smoking and improving his health through diet and exercise. He also joined a mentorship programme to work with youths from troubled homes. It is not possible to decipher through the data collected through the current research whether the therapy contributed to an increase in energy to pursue these positive goals, or whether it had more of a placebo effect in enabling P1 to achieve beyond what he felt capable of doing within the confines of his fatigue. It is possible that his experience of fatigue was not reliably measured through objective instruments due to the uplift in his energy which allowed him to embark on new ventures that he was mentally unable to tackle prior.

7.4.2 Participant 2 (P2):

P2 sustained her mTBI in September 2018. P2 reported taking 300mg of gabapentin each night before bed to alleviate racing thoughts and improve sleep. This was the only medication she used, and her routine with it was consistent over time. Despite her medication use, consultation with supervision deemed her eligible for inclusion in the study, considering its stability. P2 had an extended baseline period due to planned travel and perceiving it would be too difficult to routinely use light therapy while staying in hotels.

Subjectively, P2 expressed no noticeable relief from her fatigue during the study and experienced periods where she believed it worsened, leading her to resume daytime napping. She acknowledged that overexertion may have contributed to her fatigue as well.

Objective test results are presented in Table 12 and indicated that her scores on the Fatigue Severity Scale remained relatively consistent throughout the study, however, a review of her average daily fatigue ratings showed a slight improvement between baseline, treatment, and post-treatment. Consistent with her reporting an increase in daytime napping, on the ESS, her scores showed an increase baseline to post-treatment and follow-up, however, all ESS scores are considered in the normal range.

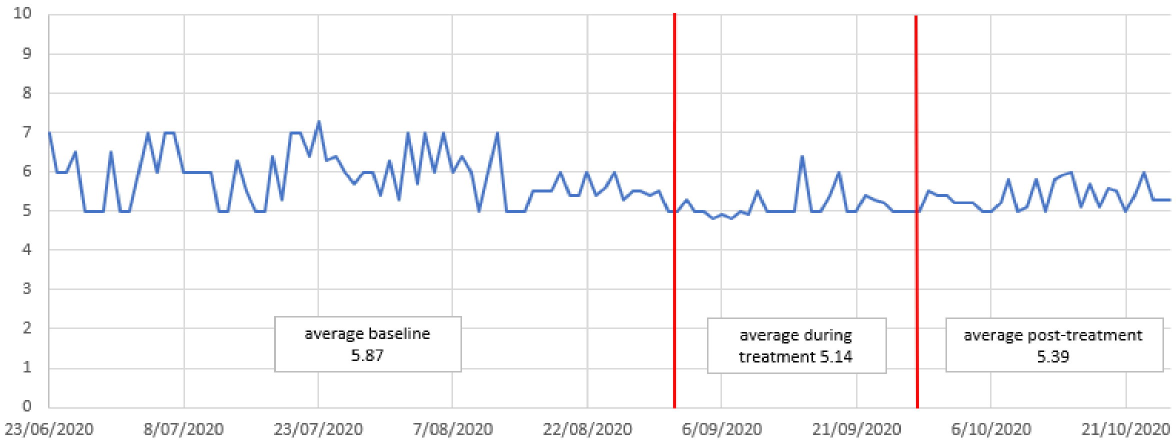
Table 12

P2's Individual Data

	Intake	Pre-Treatment	Post-Treatment	Post Follow-up
FSS	6.22	6	6.22	6.33
ESS	5	2	3	4
PSQI	7	10	9	8
DASS-D	0	1	6	2
DASS-A	0	0	0	0
DASS-S	5	4	3	3

Figure 18

P2's Daily Fatigue Ratings



7.4.3 Participant 3 (P3):

P3, a 52-year-old male sustained his mTBI in March 2015. This made him the participant with the greatest length of time between injury and light therapy (5 years, 4 months). He is a very active individual and disclosed that on days when he was snowboarding, surfing, or windsurfing, he often would exhaust himself, prioritising his love of those activities over his fatigue. P3 reported that he felt he was doing better than he had (in terms of fatigue) for a long time. He requested to buy the research lamp, signalling that he found it to be therapeutically beneficial.

Objectively, P3's computed FSS scores demonstrated a downward trend over the course of the study. His FSS score decreased from intake to the start of treatment. This was not due to the light intervention but is consistent with his self-report that he felt better than he had leading up to his participation. Notably, in terms of P3's psychological well-being, his stress levels decreased from the severe range at intake, to moderate at the start of treatment, and then reduced to being in the normal range post-treatment. He remained in the normal range after the follow-up phase. Unfortunately, P3 misplaced his daily records from the earlier phases of the study. Consequently, the missing data means we must interpret the results cautiously. However, it appears that he rated his fatigue significantly lower during the intervention phase of the study. While this trend is not as evident in his FSS scores, it may offer insight into why he sought to purchase the lamp.

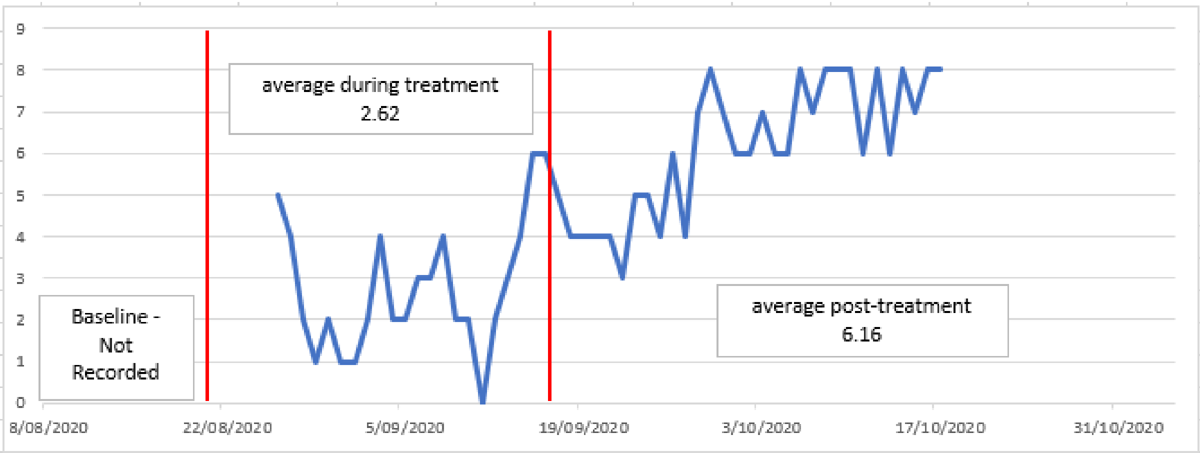
Table 13

P3's Individual Data

	Intake	Pre-Treatment	Post-Treatment	Post Follow-up
FSS	6.22	5.67	5.44	5.89
ESS	13	6	4	8
PSQI	12	12	11	11
DASS-D	2	1	1	2
DASS-A	4	3	0	2
DASS-S	14	11	6	6

Figure 19

P3's Daily Fatigue Ratings



7.4.4 Participant 4 (P4):

P4 sustained his mTBI during an assault in July 2019. At the time of his participation in the current study he was involved in legal proceedings to maintain ACC payments. He perceived that the impact of his post-mTBI fatigue limited his ability to work full-time. However, he also had a genetic health condition that caused him significant pain and which ACC attributed as the primary reason for his work limitations (rather than the head injury). This context is important as it sheds light on the stress and physical limitations P4 was experiencing during the study.

Despite his pain and physical limitations, P4 remained active while participating in the study and was engaged in rehabilitation at the gym and playing basketball. Notably, during the study, he was also transitioning through some major life events. These were positive for him, but he reported that they added additional stressors to his life.

Examining the objective measures, P4's FSS scores remained relatively stable. He did not complete the follow-up survey and measures, so it is unknown whether these remained stable beyond the point of therapy stopping. His daily fatigue scores showed fluctuations but demonstrated a downward trend across the course of the study. P4's individual results are presented in Table 14.

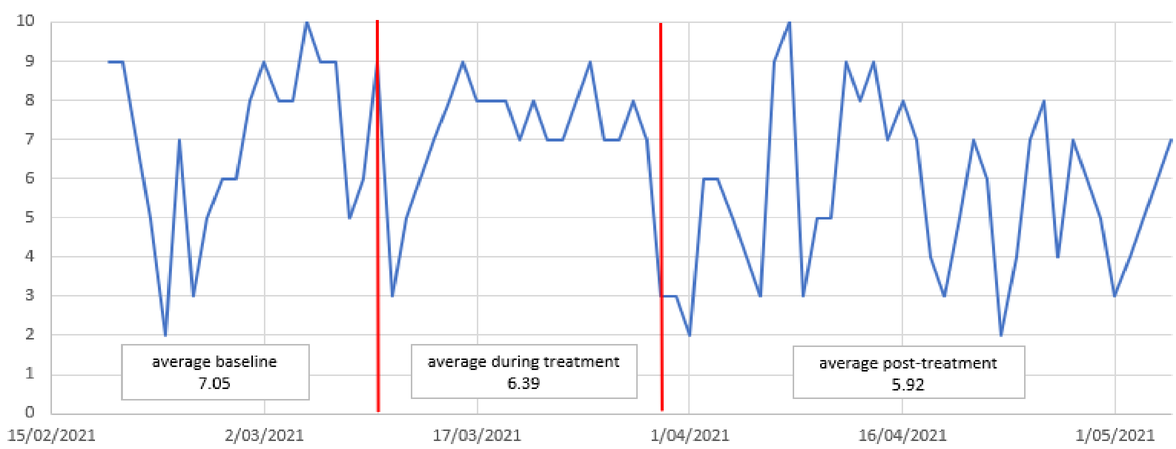
Table 14

P4's Individual Data

	Intake	Pre-Treatment	Post-Treatment
FSS	6.78	6.67	6.67
ESS	4	5	9
PSQI	12	12	12
DASS-D	14	12	10
DASS-A	7	4	2
DASS-S	11	11	10

Figure 20

P4's Daily Fatigue Ratings



Limitations for P4:

Concerns regarding his compliance and the potential motivations behind his participation should be considered when interpreting the results. Although cognitive impairment was not found during screening, and there was no evidence of incomplete effort, P4 reported to struggle with remembering to complete the required measures. He required frequent reminders, attributing his difficulty completing stages of the research to memory deficits post-mTBI. His daily logs were submitted in one email at the conclusion of his participation, raising concerns about the possible ad hoc nature of their completion, and their potential lack of scientific rigor.

7.4.5 Participant 5 (P5):

P5 a 46 year old male sustained his mTBI in November 2020 and self-referred after learning about it through the TBI Network newsletter. P5 had sustained multiple previous concussion injuries and was active in the brain injury community, volunteering at a local brain injury support group. P5 also had some prior knowledge about the relationship between light and circadian rhythms from his psychology study at university. He reported that he found the light to have a useful impact – stating that:

> *"My sleep patterns and duration of sleep have greatly improved which has been a very difficult issue for me to manage post injury. So, I am feeling more alert off the back of that which is good. However, when I hit the fatigue wall, I still do so in a manner that needs a complete shut down for an hour or so in the afternoon or after a cognitively demanding activity like studying, for example."*

Examining the objective measures shown in Table 15, P5's FSS scores remained consistent with scores indicating sever fatigue at all time points. As has been seen with most participants in the study, P5's daily fatigue scores demonstrated some fluctuations, but in his case indicated a slight upward trend or worsening of fatigue. As mentioned, P5 reported improved sleep quality and increased alertness when using the light. This indicates a positive subjective experience despite the limited changes observed in the objective measures.

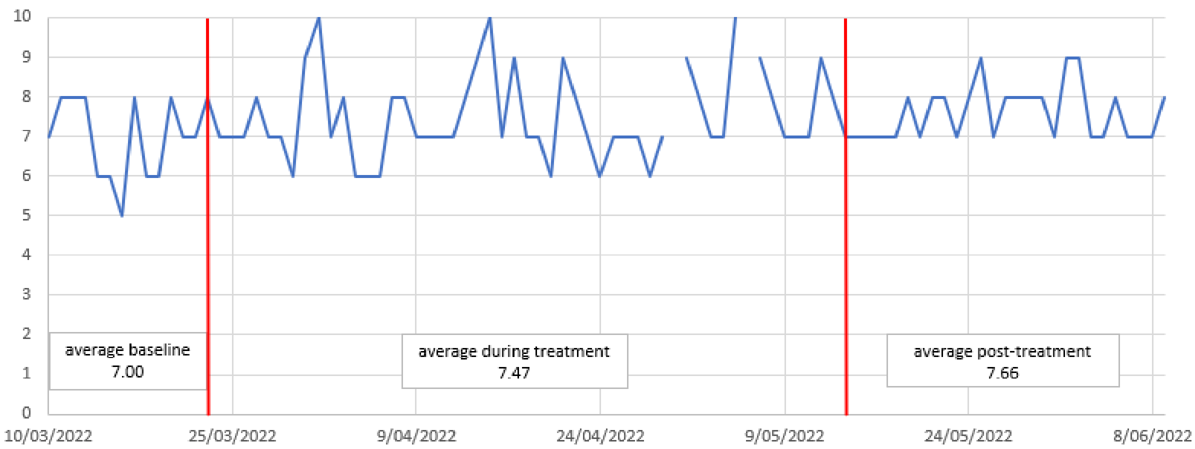
Table 15

P5's Individual Data

	Intake	Pre-Treatment	Post-Treatment	Post Follow-up
FSS	6.22	6.22	6.22	7
ESS	24	24	24	22
PSQI	11	11	11	11
DASS-D	0	0	0	1
DASS-A	0	0	0	1
DASS-S	4	4	3	3

Figure 21

P5's Daily Fatigue Ratings



7.4.6 Participant 6 (P6):

P6 was referred to the study through Assessment Providers Taranaki and was 34 years old when she completed her intake survey. She disclosed that she takes a natural (valerian root) sleep supplement which she had been using for a long period of time. She was aware that she needed to be consistent with any supplements she took for the duration of the study.

P6's injury date was October 2019, and she did not report having any prior TBI's. Subjectively, P6 said she continued to feel fatigue at similar levels throughout the study, however she also said she had increased her activity levels. After the study concluded she reported to be feeling better than she was, but that she found it hard to say whether the light was helpful or not.

P6’s individual results are presented in Table 16. These show that her initial FSS score at intake was in the severe range, and this dropped to a score well below the cut-off for fatigue being indicated at all following the intervention. Unfortunately, during the follow-up phase, her FSS score increased again, suggesting a partial return of fatigue symptoms. This aligns with her self-report that she had not noticed any major change in levels of fatigue. P6’s daily fatigue data did not capture the magnitude of change observed in the FSS scores, and may suggest some anomaly on the day she completed the FSS post-treatment. P6’s individual results are presented below in Table 16.

Regarding psychological well-being, P6's DASS-21 scores indicated depression symptoms in the mild or normal range prior to the intervention. However, her post-intervention score spiked to what is considered at the lower end of the severe range before dropping back to mild post follow-up. No significant anxiety was reported during the study period and initial stress scores in the moderate range reduced to mild post-intervention, remining mild after the follow-up phase.

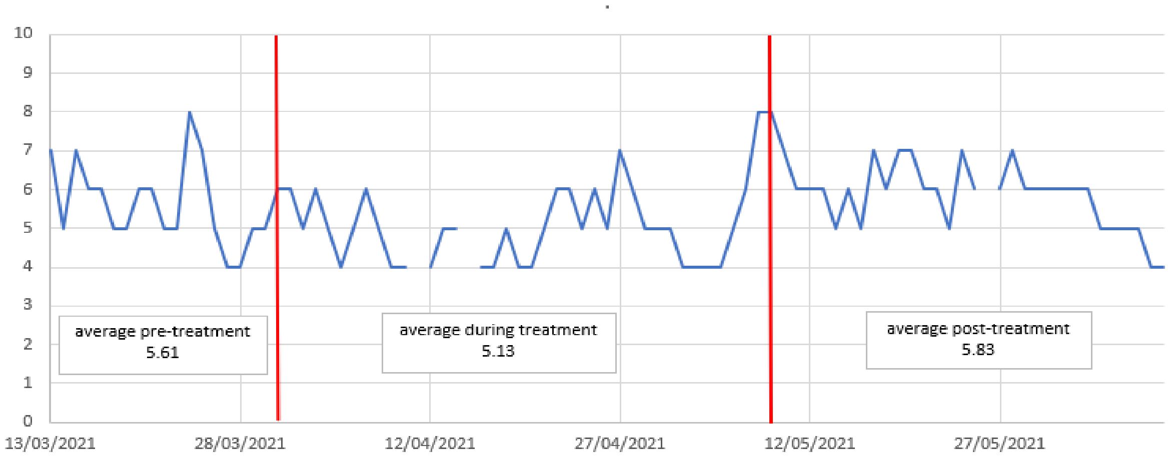
Table 16

P6’s Individual Data

	Intake	Pre-Treatment	Post-Treatment	Post Follow-up
FSS	6.33	5.22	1.56	5.11
ESS	3	4	3	2
PSQI	14	12	10	9
DASS-D	4	3	11	6
DASS-A	0	0	0	0
DASS-S	12	9	8	7

Figure 22

P6's Daily Fatigue Ratings



7.4.7 Participant 7 (P7):

P7 was referred to this study after working with another psychologist in the recovery process following a 2018 injury. He had tried red light therapy a year prior to participating in this study which was marketed through a consumer facing company Joovv. He has also tried a pharmaceutical approach to mitigating his fatigue, but not having found either of these to be sufficiently effective, he was eager to try something new. P7 missed a few days of light therapy due to competing demands on his time. He reported that he initially noticed an improvement in his energy levels, but wasn't sure that this continued.

P7's test results are presented in Table 17. Overall, P7's test results suggest relatively stable levels of fatigue, sleepiness, sleep quality, and psychological well-being throughout the study. The minimal changes observed in these measures indicate a consistent experience for P7 across different phases of the intervention and indicate that light therapy has not been helpful in alleviating his fatigue.

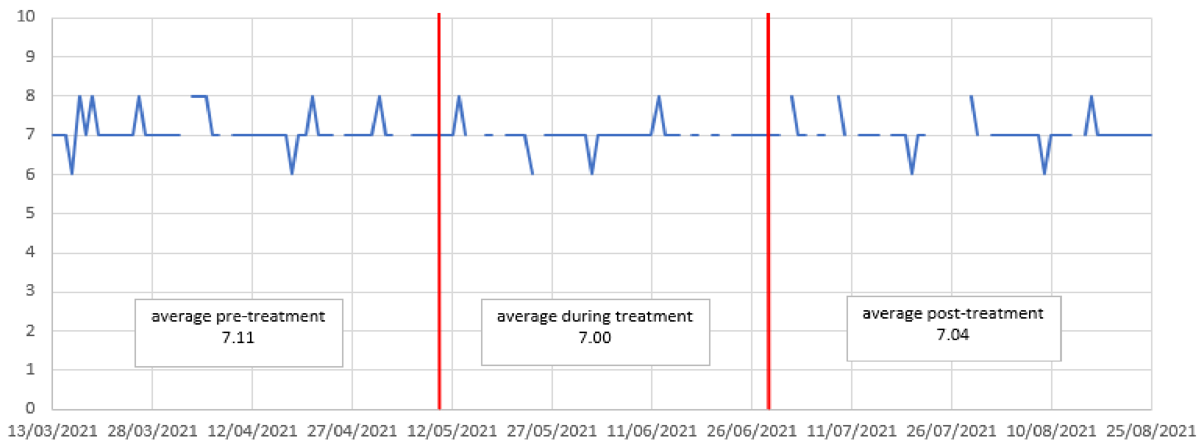
Table 17

P7's Individual Data

	Intake	Pre-Treatment	Post-Treatment	Post Follow-up
FSS	6.78	6.33	6.33	6.22
ESS	8	14	10	12
PSQI	11	10	9	10
DASS-D	5	6	5	5
DASS-A	4	4	1	1
DASS-S	6	10	9	8

Figure 23

P7's Daily Fatigue Ratings



7.4.8 Participant 8 (P8):

P8 was 36 years old at intake and her results should be interpreted with caution due to her involvement in shift work as a medical professional. However, she was included in the study as her shift work did not involve full night shifts that would significantly disrupt her sleep cycle. In her communication, P8 expressed uncertainty regarding the effectiveness of the light therapy. She mentioned feeling "slightly better" but acknowledged that the improvement could also be attributed to the natural course of time.

Regarding her fatigue, P8's FSS intake score was higher than what was measured post intervention and after the follow-up phase. Unfortunately, due to timing and communication issues, her survey was not completed just before starting the light therapy. Her scores on the PSQI indicated a positive trend in sleep quality across the course of the study, but remain at a level suggestive of moderate to severe sleep difficulties. Results are presented in Table 18.

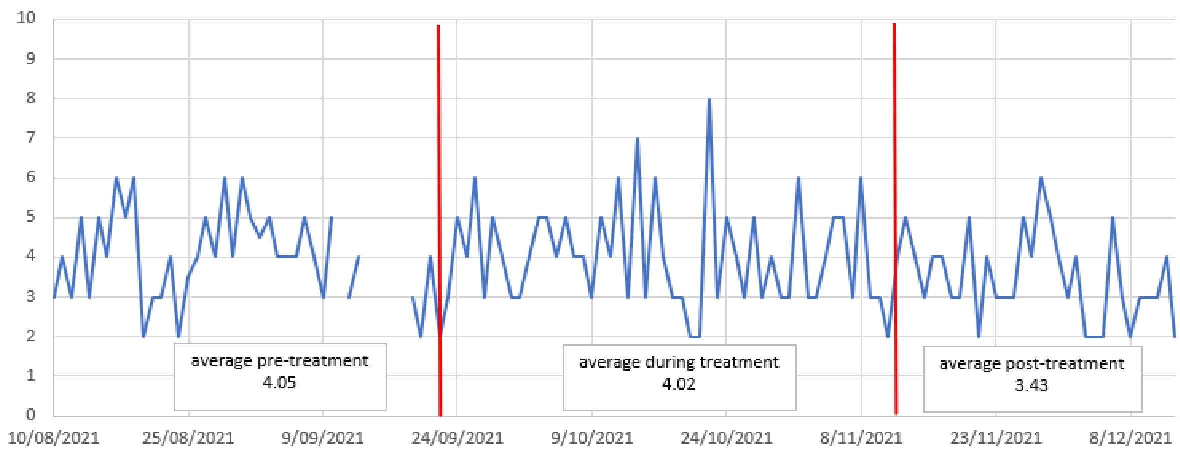
Table 18

P8'*s Individual Data*

	Intake	Post-Treatment	Post Follow-up
FSS	5.67	5.11	5.11
ESS	2	2	1
PSQI	10	9	7
DASS-D	0	0	0
DASS-A	0	0	0
DASS-S	2	1	2

Figure 24

P8'*s Daily Fatigue Ratings*



Limitations for P8:

It is important to note that P8's feedback regarding the effectiveness of the light therapy was mixed, and she acknowledged the potential influence of time on her perceived improvement. Additionally, her involvement in shift work introduces additional variables that may have impacted her results.

7.4.9 Participant 9 (P9):

P9, a 33-year-old male of NZ European/Maori background, participated in the study following a mTBI he sustained in a car accident in May 2020. While P9 also experienced unrelated physical pain, he did not notice his fatigue interfering with his day-to-day life until after his accident, and so attributed his fatigue to the mTBI. P9 disclosed occasional cannabis use (this disclosure was subsequent to his inclusion in the study), and he had the responsibility of caring for his one-year-old son while his partner was at work. P9 adhered to a strict routine for sleep, diet, and exercise, demonstrating his commitment to his health, and he reported that a focus on his health was the motivation to try the intervention.

P9's individual results are presented in Table 19. He had the lowest initial fatigue score at intake, and this fell to a level suggesting that fatigue was no longer significant for him post the follow-up phase. In terms of P9's psychological well-being, the DASS-21 data showed a decrease in depression from mild at intake to not significant at the post-treatment phase. This returned to the mild range post follow-up. His anxiety scores reduced from a score considered severe at intake, to mild post-treatment and post follow-up. Similarly, his stress scores reduced from moderate at intake, to mild post-treatment and post follow-up.

Overall, P9's results indicate some improvements in fatigue levels and psychological well-being, although challenges with sleep quality were observed. It is important to consider the confounding factors, including physical pain, distractions, cannabis use, and some motivational issues when interpreting P9's results.

Table 19

P9's Individual Data

	Intake	Post-Treatment	Post Follow-up
FSS	4.44	4.11	3.44
ESS	10	6	7
PSQI	9	12	13
DASS-D	6	3	6
DASS-A	9	4	4
DASS-S	11	7	7

Despite his reported best intentions, P9 faced challenges in consistently keeping his daily sleep/fatigue log, and he also missed the time two survey. He said he did complete his log most of the time, but that data was missing as he had lost the papers.

Limitations for P9:

Unfortunately, P9 also lost one of the actigraphy watches. Adherence during the light therapy phase was reportedly somewhat sporadic. P9 said he had used it most of the time for two weeks, took a short break, and then used it for another 10 days. P9 said it was hard for him to motivate himself to use the light on some days, and that sometimes even when he did, he would be interrupted. Despite these issues, P9 reported that on the days he used the light therapy, he experienced noticeably increased energy levels.

Chapter Eight: Discussion

8.1 Restatement of Rationale and Aims

The current study was prompted by the limited but promising existing literature reporting significant improvements in self-reported fatigue symptoms during the treatment phase of light therapy following TBI. In light of these findings, the present study aimed to extend this research to individuals with mTBI, an area that had not been extensively explored. Additionally, while previous studies focused primarily on the efficacy of blue light therapy, the current study centered on the potential benefits of polychromatic bright white light. This choice was informed by the recommendation of broad-spectrum white light as a therapeutically comparable alternative.

Despite the promising evidence supporting light therapy, there are gaps in understanding its underlying mechanisms and the specific effects on circadian rest-activity cycles that might benefit fatigue. Thus, the primary objective of the current research was to determine the effectiveness of daily exposure to polychromatic bright white light in reducing mTBI-related fatigue symptoms. Secondary objectives included assessing the impact of light therapy on daytime sleepiness, sleep quality, levels of depression, anxiety, and stress

Based on these objectives, hypotheses were formulated to test the anticipated outcomes following light therapy intervention. Hypotheses posited reductions in fatigue severity, daily fatigue ratings, daytime sleepiness, sleep quality, and psychological distress scores post-intervention compared to baseline measures. These hypotheses provided a framework for evaluating the efficacy of light therapy in addressing mTBI-related fatigue and associated symptoms, contributing to the growing body of knowledge in this area of research.

While not the primary objective of the study, a significant portion of the following discussion is dedicated to highlighting insights from individual-level data analysis. This examination focuses on the variability of treatment responses and potential factors influencing individual outcomes. Additionally, the discussion provides an opportunity to review the feasibility and repeatability of the current study shedding light on the practical considerations and challenges that might be encountered in conducting similar investigations in the future.

8.2 Exploration of Feasibility

The exploration of study feasibility emerged unexpectedly within this research endeavour, driven by the small sample size and acknowledged limitations, which will be detailed later in this chapter. However, what has been learned regarding the feasibility of conducting research of this nature is deemed pivotal to the findings. In terms of feasibility, this section illuminates the intricate landscape of implementing light therapy as an intervention for individuals with mTBI. It explores the demand for light therapy within the mTBI population, elucidates factors influencing participation willingness and eligibility, and navigates the complexities of recruitment within busy concussion services environments. Furthermore, logistical hurdles, adherence complications, and other challenges related to data collection are discussed. This section serves as a pragmatic contemplation regarding the feasibility of future research endeavours within this domain, aiming to offer suggestions for potential methodological alterations to improve replication efforts and begin to establish the groundwork for robust future investigations.

8.2.1 Demand for Light Therapy within the mTBI Population

Initial expectations of the demand for light therapy within the fatigued mTBI population were optimistic, given the anticipated benefits of this intervention for managing fatigue symptoms. However, as outlined in earlier chapters, various barriers to participation resulted in a lower-than-anticipated sample size. In considering the feasibility of future research endeavours, it is important to explore the underlying reasons for these challenges.

The stringent inclusion and exclusion criteria adopted in the current study aimed to ensure robust research outcomes. While this approach was intended to bolster confidence in study conclusions, it significantly limited the participant pool. Notably, while all potential participants met inclusion criteria, many were excluded due to factors such as current or historic sleep problems, the use of medications affecting sleep or sleepiness, and photophobia following mTBI, rendering light therapy unsuitable for them. Reflecting on this, it is apparent that while exclusion criteria were tailored to identify and remove individuals with fatigue symptoms more likely to be secondary to mTBI, disentangling these experiences from the injury process itself posed challenges. Thus, future research might benefit from a more nuanced exploration of individual circumstances and needs.

Another significant challenge was encountered in obtaining support for referrals through concussion clinics, which are typically busy environments with limited time for client appointments. Because this was an anticipated hurdle, efforts were made to establish working relationships with clinic staff and to streamline the dissemination of participant requirements and research information through detailed information sheets. Moving forward, continued efforts to build and expand relationships with service providers across the country could enhance awareness of research opportunities in this field.

While the sample size of the current study is insufficient to draw definitive conclusions, it is worth considering the potential impact of the “time since injury” as a barrier to motivation for seeking help. Many participants in the study had been grappling with fatigue for a prolonged period (average just under 2 years) and had already explored various management strategies without success. Therefore, without having an established evidence base of efficacy for light therapy, their motivation to enrol in a study of this nature would be understandably low. These individuals are likely to have made accommodations in their lives in order to live within the means of their fatigue symptoms, and with depleted reserves, asking them to adhere to what has already been described as a “burdensome” treatment protocol might be considered to be too demanding.

A final consideration pertains to the secondary financial benefits received by some injured individuals through the ACC system in New Zealand. While the ACC status of participants approached to take part in this research was not investigated, for a small minority, there may be a preference to manage their symptoms and avoid returning to work, as seeking treatment could potentially jeopardise these payments[13]. In summary, future research should consider these multifaceted barriers and design recruitment strategies accordingly to better serve the needs of individuals within the fatigued mTBI population.

[13] Data released under the Official Information Act shows that in 2022, of 1160 investigations done by ACC’s fraud protection team, 664 cases indicated misuse of the scheme by those receiving accident compensation. This data is not broken down by injury type (https://www.rnz.co.nz/)

8.2.2 Practicality of the Intervention

The practical implementation of light therapy for treating fatigue following mTBI encompasses several essential considerations. Foremost among these is the burden imposed by the requirement to sit sedentary for 30 minutes each morning. This demand places a significant strain on individuals' daily routines and may conflict with their professional or personal commitments. This burden is especially relevant in a cohort of individuals already navigating fatigue, as they may have limited energy reserves and may face heightened challenges in adhering to additional therapeutic interventions. New technology is emerging to administer light therapy via less restrictive means, such as the face-mounted devices used in the Quera Salva et al. (2020) study. It might be considered that a wearable device could enhance compliance, however, this was not able to be measured objectively, and as is the case in the current study, compliance relied on participants self-report. Recognising the onerous nature of more traditional light therapy protocols, Connolly et al. (2021) trialled an in-home intervention using dynamic light therapy. This involved using providing therapeutic lighting as part of the ambient environment, reducing compliance burden and potentially increasing treatment efficacy. The findings of that study reported the results to provide preliminary support for in-home light therapy as an effective, safe, low-demand, and long-term means for treating fatigue. However, it is important to note that these results did not achieve statistical significance, a point reflected in a later published meta-analysis that underscores the low confidence in such studies addressing sleep difficulties following mTBI (Srisurapanont et al., 2022).

The assessment of compliance with the light therapy protocol poses methodological challenges, as evidenced by the current study's reliance on participant-recorded daily diaries for this purpose. While these diaries potentially offer insight into adherence, their completion lacked substantive detail beyond documenting sleep times and fatigue levels. Several methodologies have been employed to gauge adherence to light therapy, encompassing techniques such as recorded telephone messages (Glickman et al., 2006), along with the utilisation of timers on light boxes to quantify duration of exposure (Michalak et al., 2002). Nevertheless, none of these approaches provide foolproof assurance. Actigraphy presents another avenue for assessing light exposure, albeit wrist-worn devices often encounter impediments like being obscured by clothing or positioned in environments where accurate detection of light emission from the therapy device may be compromised. While addressing non-compliance remains challenging, a fundamental recommendation involves the objective verification of whether individuals adhere to prescribed light therapy usage schedules. Enhancing compliance monitoring may necessitate a heightened level of engagement from research personnel, potentially requiring expanded team resources to facilitate more comprehensive oversight and real-time resolution of adherence barriers among study participants. In lieu of efficacious objective measures of compliance, psychoeducation has been found to be an important component in increasing treatment adherence (Danielsson et al., 2018). This educational approach encompasses providing participants with comprehensive information regarding the rationale behind the timing of light therapy, thereby fostering a deeper understanding and appreciation of the therapeutic process.

In summary, assessing the practical implementation of light therapy within the framework of mTBI treatment requires a thorough examination of multiple factors, such as its realistic integration into daily routines and the development of robust adherence monitoring mechanisms.

8.3 Core Findings of this Research

The results pertaining to the efficacy of the intervention provide valuable insights into the potential impact of bright light exposure for individuals experiencing these symptoms following a mTBI. However, it is important to interpret these insights cautiously, mindful of the limitations and nuances within the data, rather than solely focusing on statistical significance

Regarding the hypothesis related to fatigue symptoms measured using the Fatigue Severity Scale (FSS), the findings indicated a statistically significant decrease in FSS scores following the intervention. This suggests a potential positive effect of bright light exposure on reducing fatigue symptoms. This aligns with previous research highlighting the potential benefits of bright light therapy in mitigating fatigue in various populations (Srisurapanont et al., 2022). It is important to acknowledge the limitations of the small sample size of the current study, which may have influenced the statistical significance of the results. Nonetheless, the observed trends warrant further investigation with larger sample sizes to elucidate the potential effectiveness of bright light exposure in managing concussion-related fatigue symptoms.

In terms of daily fatigue ratings assessed using the visual analogue scale (VAS), the results indicated a non-significant decrease in daily fatigue scores between baseline and the treatment phase, as well as between baseline and the follow-up phase. Although the differences were not statistically significant, the trends suggest a potential positive impact of bright light exposure on reducing daily fatigue. However, it is worth noting that there was a non-significant increase in daily fatigue scores between the treatment phase and the follow-up phase, which could indicate a temporary or fluctuating effect of the intervention. This finding is consistent with prior research which has shown that fatigue levels trend back to baseline during the follow-up phase post light intervention (e.g., Sinclair et al., 2014). Future studies with extended follow-up periods and larger sample sizes are needed to better understand the long-term effects of bright light exposure on daily fatigue.

The secondary questions focused on the effects of bright light exposure on other aspects. In terms of daytime sleepiness measured by the Epworth Sleepiness Scale (ESS) and sleep quality measured by the Pittsburgh Sleep Quality Index (PSQI), in their most recent review, Srisurapanont et al. (2022) found that blue-wavelength light therapy was beneficial for both sleepiness and sleep disturbance, which was not noted in their earlier network meta-analysis (Srisurapanont et al., 2021). The results from the current study revealed mixed findings regarding daytime sleepiness. While there was a non-significant decrease in ESS scores between baseline and the follow-up phase, the analysis comparing post-intervention scores with post-follow-up scores showed an increase in ESS scores. These results suggest that bright light exposure may have a limited effect on reducing daytime sleepiness in individuals with fatigue symptoms, but that as is consistent with prior research (e.g. Sinclair et al., 2014), improvements do not persist post-treatment.

Similarly, the analysis of the PSQI scores did not yield statistically significant differences, indicating a minimal impact of bright light exposure on sleep quality. Connolly et al. (2021) propose that differences in sleep outcomes might be explained by variance in participant's exposure to both the illuminance and short-wavelength content of evening night-time lighting. Exposure to blue-enriched evening light has been demonstrated to enhance alertness during the evening while adversely affecting the quality of subsequent sleep (Campbell et al., 2023). Therefore, future research would benefit from a more controlled research protocol which might reduce exposure to blue light in the period before sleep onset.

The analysis of depression, anxiety, and stress levels, as measured by the Depression, Anxiety, and Stress Scale (DASS-21), provided valuable insights into the potential psychological effects of bright light exposure in individuals with mTBI. The results yielded a significant reduction in stress scores immediately post-treatment compared to baseline, while no significant differences were observed for depression and anxiety symptoms. This suggests that while bright light exposure may not significantly influence depression and anxiety symptoms, it may have a positive impact on reducing stress levels in this population. The lack of significant effects on depression and anxiety warrants further investigation, especially considering the established evidence supporting the efficacy of blue light therapy in alleviating depressive symptoms (Srisurapanont et al., 2022).

It is important to acknowledge the possibility of extraneous factors contributing to the observed reductions in stress scores. The mere act of participating in an intervention study aimed at addressing fatigue symptoms may have exerted a placebo effect or therapeutic influence, leading to decreased stress levels among participants. This phenomenon underscores the importance of considering the psychosocial context and participant expectations in interpreting treatment outcomes. However, the strong positive correlations between baseline and post-treatment stress scores suggest that individual differences in stress levels remained consistent throughout the intervention phase of the study period. This indicates that the observed reductions in stress scores following the intervention are not merely due to random fluctuations but may reflect meaningful changes in psychological well-being.

Moving forward, future research should delve deeper into the potential mechanisms underlying the effects of light therapy on stress reduction and explore its impact on broader mental health outcomes in individuals with mTBI. Additionally, considering the nuances of individual responses and the influence of study participation on psychological factors, incorporating qualitative methodologies may provide valuable insights into participants' experiences and perceptions of the intervention.

Overall, the results of this study contribute to the growing body of literature on the potential benefits of bright light exposure as an intervention for individuals with mTBI experiencing fatigue symptoms, daytime sleepiness, and psychological distress. While the findings did not consistently reach statistical significance, the observed trends suggest avenues for further research. It is crucial to acknowledge the limitations of current and prior studies, including the small sample size and the need for replication with larger and more diverse populations.

Caution is therefore encouraged in considering the results and credence should be given to the fact that the 2022 meta-analysis identified the absence of a dose-response relationship for treatment effect and the lack of evidence supporting the exclusion of all plausible residual confounding factors. Additionally, the risk of bias was observed to be high across all outcome measures. Inconsistency, imprecision, publication bias, and large effect sizes were found to vary among the outcomes from the included studies which lead to the final certainty levels of light therapy effects being determined as follows: moderate for depressive symptoms, low for sleep disturbance and dropout rates, and very low for sleepiness and fatigue (Srisurapanont et al., 2022).

8.3.1 Data Outlier

In examining the dataset, participant P6's response stood out, showcasing a dramatic decrease in fatigue alongside a substantial increase in depression scores. This pattern was unexpected, particularly given P6's self-report indicating a lack of noticeable change in fatigue levels during the intervention phase of the study. The magnitude of change in fatigue scores post-intervention was also not reflected in P6's daily fatigue data, suggestive of a potential anomaly in the data collection process on the day P6 completed the post-treatment questionnaire. The discrepancy between self-reported experiences and objective measures raises questions about the reliability of the data and the interpretation of P6's response to the intervention. Consequently, running the group data analysis through JAMOVI after excluding P6's data alters the overall group profile, resulting in a statistically non-significant outcome on the FSS measure. This underscores the importance of reviewing individual responses and their potential impact on group-level analyses to ensure the robustness and validity of study findings.

8.4 Individual Data Analysis and Additional Insights

Several themes emerge from the individual data concerning both the efficacy of light therapy and the feasibility of studies in this domain. Relating to the efficacy of the treatment, what is shown in the individual data is that for some participants, there are significant discrepancies between the FSS data and daily fatigue ratings. These raise questions about the sensitivity and specificity of these measures in capturing the true nuances of fatigue experiences in individuals with mTBI. While both measures are validated and commonly used in clinical and research settings, their differential response patterns observed in this study prompt further exploration.

One plausible interpretation is that the FSS, being a retrospective self-report measure, may not capture the day-to-day variability and nuances of fatigue experienced by participants. In contrast, daily fatigue ratings provide a more granular and real-time assessment, potentially reflecting fluctuations in fatigue levels more accurately. This finding underscores the importance of considering multiple assessment modalities to comprehensively capture the complexity of fatigue in mTBI populations. Additionally, it raises questions about the underlying constructs measured by these instruments and whether they capture distinct aspects of fatigue, such as chronicity versus episodic fluctuations. Further research exploring the convergent and discriminant validity of these measures in relation to other clinical outcomes could provide valuable insights into their utility and interpretability in assessing fatigue in individuals with mTBI.

Additionally, although qualitative research methods were not initially integrated into the methodology of the current study, insights gained from informal interactions with participants highlight their potential significance for understanding subjective experiences. Participant 1 serves as a prime example, with his reported experience showing how light therapy can positively influence subjective perceptions of fatigue, even when objective measures show limited changes. Participant 1's active involvement and reported perceived benefit from the intervention emphasises the importance of evaluating both subjective and objective outcomes and the potential value of including a qualitative element in future research to better capture the nuances of individual experiences.

Looking across the experiences of all nine research participants, it is evident that while some experienced an improvement in fatigue, others experienced minimal change, highlighting the variability in individual responses to light therapy. Furthermore, the challenges encountered by some participants with adherence to the therapy protocol serve as a tangible manifestation of the feasibility issues previously discussed in this chapter. The contrasting experiences seen from individual outcomes underscore the need for further research in this space and support the need for personalised approaches to treatment and comprehensive evaluation of both subjective and objective outcomes in future studies. The necessity for the development of personalised treatments is strongly corroborated from the extant literature emphasising the impact of individual variability on treatment outcomes for fatigue within the context of brain injury (e.g. Ezekiel et al., 2021).

8.5 Adverse Effects

It needs to be acknowledged that two participants withdrew from the current study citing a sense of being "worse off." Existing literature suggests that reported side effects following light therapy typically fall within the realm of minor discomforts, including headache, eyestrain, nausea, insomnia, and hyperactivity. While prior research using light therapy with the TBI population has documented such discomforts, they have not escalated to a degree where participants opted to discontinue treatment. This highlights the significance of the experiences reported by the two participants who withdrew from this research study, as they were unexpected and not aligned with typical outcomes observed in previous research. As detailed in earlier chapters, fatigue in the mTBI population presents as a complex symptom influenced by various factors. The exacerbation of fatigue observed in these participants may be attributable to external factors beyond the scope of the study. It is essential to recognise the multifaceted nature of fatigue in mTBI and to consider the potential impact of external variables on participant experiences.

Although the current study did not establish a priori procedures for reporting or assessing adverse effects of the intervention, Anderson et al. (2009) provided an example of incorporating such measures in their research on light therapy for seasonal affective disorder. In their study, participants were tasked with rating the severity (ranging from none to severe) of 16 listed 'current discomforts' over three weeks of daily treatment. Notable discomforts reported at the conclusion of treatment included fatigue, headache, eye irritation, increased appetite, sleep disorder, drowsiness, anxiety, and irritability. However, it is noteworthy that the severity of these discomforts decreased significantly over the treatment period and was strongly associated with the severity of depressive illness.

Ensuring the safety and well-being of participants is paramount in research endeavours. While the decision to halt recruitment in the current study was prompted by the negative experiences reported by these individuals, existing research literature underscores the safety of light therapy protocols. Therefore, it would be premature to discount light therapy as a therapeutic approach solely based on the experiences of two participants in the current study. Moving forward, future research should continue to prioritise participant safety and explore strategies to minimise adverse experiences while maximising the potential benefits of light therapy interventions. By addressing safety concerns and refining study protocols, researchers can uphold ethical standards and contribute to the advancement of evidence-based interventions for individuals with mTBI.

8.6 Discussion of Fatigue Return to Baseline

Similar to what has been published in prior studies, the current study has indicated that fatigue deteriorates once the light therapy stopped. This introduces the possibility of a placebo effect driving treatment gains, or improvement in fatigue. The placebo effect refers to the phenomenon where an individual experiences improvement in symptoms solely due to their belief in the efficacy of a treatment, regardless of whether the treatment itself has any inherent therapeutic properties (Benedetti, 2021). In the context of light therapy for fatigue reduction, individuals may experience subjective improvements in fatigue levels simply because they believe the intervention to be effective. This could manifest as a temporary alleviation of fatigue symptoms during the intervention period, with subsequent return to baseline levels once the intervention is discontinued. Several studies have attempted to address the potential influence of placebo effects in assessing the efficacy of light therapy for fatigue reduction, particularly in individuals TBI (Sinclair et al., 2014; Raikes et al., 2020; Killgore et al., 2020). These studies used amber light therapy as a placebo control relative to blue light therapy, and demonstrated improvements in various outcomes related to fatigue, sleepiness, and cognitive function among participants receiving blue light therapy, compared to those receiving amber light therapy. Their findings suggested that the observed effects were not solely attributable to placebo responses. However, blinding participants to their assigned treatment group (blue or amber light) presents a considerable challenge, as participants can visually discern the colour of the light they are exposed to, potentially influencing their subjective perceptions and expectations of treatment efficacy.

While the placebo effect is a pertinent consideration when making sense of the pattern of results in the current study, with fatigue returning to baseline levels four weeks following treatment cessation. Solely attributing the observed effects to a placebo effect might oversimplify the findings. The transient nature of the observed improvements certainly raises questions about the sustained effectiveness of light therapy interventions for fatigue management. Nevertheless, past studies as well as the current one tentatively suggest that there may be potential benefits of light therapy in ameliorating fatigue, sleepiness, and cognitive dysfunction following TBI, during the active phase of the intervention. Therefore, even if the effects diminish post-treatment cessation, the short-term relief provided may still be valuable for individuals managing fatigue. Individuals may opt to incorporate light therapy into their daily routines, akin to other long-term treatment approaches such as pharmacotherapy and physical exercise. Thus, even if the effects are not enduring after cessation, the relief provided by light therapy can still hold value for individuals managing fatigue.

Given the considerations highlighted in the above discussion, it appears crucial for future research in this field to be transparent with participants regarding the anticipated outcomes beyond the intervention period. Researchers should openly acknowledge the likelihood of fatigue levels reverting to baseline once the treatment is discontinued. Additionally, if the continued use of light therapy over the long-term is considered to be overly burdensome, it could be considered that its benefit lies more in the short-term improvement in fatigue levels, which could serve as a valuable tool for introducing adjunct therapies. By acknowledging the transient nature of intervention effects, clinicians may be able to tailor support strategies to address fatigue management comprehensively. This approach may ultimately lead to more successful outcomes by incorporating interventions that have both short-term benefits and the potential to support longer-lasting effects in managing fatigue. Later in this chapter, further discussion is introduced relating to the implications of positive short-term intervention effects on the development and implementation of more comprehensive and long-lasting support strategies for fatigue management following mTBI.

8.7 Implications for Practice

The findings of this study, although not reaching statistical significance, suggest a promising trend toward fatigue reduction following bright light exposure as an intervention for individuals with mTBI. Clinicians could consider the potential benefits of bright light exposure in mitigating fatigue symptoms, even in the absence of statistically significant findings. However, due to the limited empirical support for its efficacy, a judicious approach would involve integrating light therapy as an element within a comprehensive treatment protocol, pending the emergence of additional confirmatory evidence substantiating its autonomous therapeutic benefits. The ease of implementation, cost-effectiveness, and non-invasiveness of this intervention make it an appealing option for fatigued individuals seeking non-pharmacological approaches or those concerned about medication-related side effects. While the specific results did not show a significant decrease in fatigue, it is worth noting that the observed reductions in stress levels imply potential psychological benefits of this intervention. These findings highlight the multifaceted nature of fatigue and the need for comprehensive approaches in its management.

Considering the non-invasive and non-pharmaceutical nature of the treatment, the use of bright light exposure can be cautiously recommended as part of a holistic treatment approach for mTBI-related fatigue. The observed reductions in stress, coupled with anecdotal reports of improved well-being and increased energy levels, provide valuable clinical insights. Incorporating bright light exposure into the therapeutic repertoire for mTBI-related fatigue may serve as a complementary approach that addresses not only fatigue but also the psychological well-being of individuals.

8.8 Limitations

Despite efforts to conduct a rigorous study, several limitations were identified that may impact the interpretation of the findings.

8.8.1 Sample size limitations

The sample size aimed to be comparable to previous studies investigating and treating fatigue in patients with TBI. However, due to the negative side effects experienced by two participants during the course of the study, data collection was only completed for nine individuals. This small sample size limits the generalizability of the findings and the ability to detect statistically significant effects. Additionally, a small sample size is considered to have restricted the ability to control for other confounding factors. For example, symptom severity appeared to be influenced by or sensitive to extraneous lifestyle factors for some participants (such as travel, varying levels of physical activity, busy work schedules, variable daytime napping, moving house, general stress). These extraneous factors may have introduced variability in symptom outcomes, which could have impacted the reliability of the results. A larger sample size may help reduce the influence of these extraneous factors on symptom variation and improve the internal validity of the study. The small sample size is also considered to be relevant when considering the self-report nature of the measures used in this study. Self-report measures may be subject to biases and may not always accurately reflect the true nature and severity of symptoms. Again, a larger sample size would have helped to control for this.

The limitations imposed by the small sample size also restricted the exploration of potentially significant demographic factors that could influence the efficacy of light therapy on individuals experiencing fatigue post-mTBI. For instance, it is well-established that individuals with a history of multiple recurrent mTBIs tend to exhibit poorer outcomes. Although data on TBI history was collected and flagged through demographic questionnaires, the sample size proved insufficient to effectively utilise this information. Among the nine participants enrolled in the study, six had experienced a prior injury. However, with such a limited number of cases, it was challenging to draw meaningful conclusions regarding the impact of TBI history on treatment outcomes.

8.8.2 Participant recruitment

Study participants were referred and enrolled on the basis of their suitability for engaging in research and fulfilment of inclusion criteria. It has been considered that for some participants, there may have been an underlying financial motivation to participate as a means to legitimise their ACC payments. This was moderated through discussions with the referral source, and while many of the participants who completed the study were receiving payments from ACC to account for loss of income, their motivation to lessen their experienced fatigue appeared genuine.

8.8.3 Testing environment

Outcomes should be considered in the context of the timing of testing and the testing environment. The literature suggests that the time of day tested could influence outcomes, for example due to the additional amount of natural light (Terman & Terman, 2005). Although attempts were made to control for the time of day during testing, it is unclear how strictly participants adhered to these guidelines, which may have introduced variability in the results.

There is also suggestion that the time of year may impact the outcomes of light therapy. For example, interventions during summer months are likely to differ from interventions during winter months due to variability in participants exposure to natural light. It is important to acknowledge that the current research was underpowered to make definitive claims on this matter. However, considering the potential impact of seasonal variability, such as differences in participants' exposure to natural light during summer versus winter months, it is a factor that warrants careful consideration in future studies with more robust sample sizes. Additionally, the home-based testing environment limited the ability to control for outside distractions during light intervention and to maintain consistency between testing environments. For example, participants with young children at home may have been more susceptible to being pulled away from the light source at times in order to attend to the needs of those children. Similarly, participants with higher demands in their work or social life may have found setting aside 30 minutes each morning to be more challenging the others. This lack of control over the testing environment may have introduced additional variability in the results.

8.8.4 Medication use

Although participants who were taking sleep medications were excluded from the study, some participants used other medications that may affect sleep architecture. Given the high prevalence of medication use following TBI, these participants were not excluded from the study. The inclusion of a larger sample size in future research may allow for more insightful comparison of patients with TBI and investigation of treatment effects, controlling for or even excluding medication factors.

8.8.5 Treatment expectancy effects

A limitation in most light intervention studies is the lack of a plausible placebo. Although this study attempted to address this limitation by using a methodology that did not require controls, it was not strictly adhered to, due to the life circumstances of participants. Allocation to treatment groups could not be masked, as participants knew how long they would be in the baseline period, which may have influenced treatment expectancy and potentially biased the results.

8.8.6 Compliance with intervention

An additional limitation that has been reported in other light intervention trials and considered relevant to the current study, is the risk of non-compliance with the intervention. Observationally, some participants appeared to be more dedicated than others. For example, the frequency of contact during the light therapy phase of participation was greater for some than it was for others. Attempts were made to monitor compliance using actigraphy data, but due to clothing often covering the sensor, as well as the fragmented recordings able to be analysed, this was not possible. Compliance was therefore determined based on self-report, which may not always be accurate. Another proxy indicator for compliance was the completion of, and quality of, daily sleep/wake and fatigue logs. For some participants, these were completed with detailed comments, for others it appeared to be a very rushed approach with detail limited to only fatigue ratings in one case. The use of more advanced technology, such as an electronic diary which could be set up to prompt daily recording, may ameliorate this limitation in future research.

8.8.7 Research Equipment

As discussed earlier in this thesis, due to changing circumstances of one of the supervision team members overseeing the current study, a change was required in the make and model of the actigraphy watches. Both watches were validated for clinical research, however, the second type had a much lower performing battery. While these devices are successfully used in shorter term research projects, they needed to be employed in a prolonged manner for this study. Similar to the original devices, the watches suggested a battery life of approximately four weeks, however there was a great deal of variation in the performance of the watches despite purchasing high end batteries. The watches would sometimes last two weeks, but on occasion they would be flashing a low battery alert within two days of participants receiving them. This inconsistency posed challenges for participants who had to return the watches via pre-paid courier bags, and it also introduced logistical complexities for the researcher in managing the hardware while ensuring the integrity and quality of data collection.

8.8.8 COVID-19

The COVID-19 pandemic has introduced a number of limitations that researchers have had to contend with. Relevant to the current study, social distancing measures, lockdowns, and travel restrictions created barriers to meeting with participants face-to-face. This reduced contact is likely to have contributed to their adherence to the study protocols, which may have implications for the validity and reliability of findings. From the researcher's perspective, these restrictions also created barriers to accessing the University equipment required for programming, distributing, and downloading and analysing data from the actigraphy devices.

More broadly, COVID-19 had a significant impact on the social context within which the research was conducted. The pandemic has resulted in widespread changes to individuals' daily lives, including increased stress, anxiety, depression, and changes in social, economic, and environmental factors. These contextual changes may impact the psychological processes and behaviours under investigation, making it challenging to disentangle the effects of the pandemic from the research variables of interest. Most pertinent to the current study is that the prolonged cognitive efforts to maintain safety behaviours, as well as the hypervigilance fuelled by a constant flow of negative and threatening information during this time, is likely to have contributed to increased fatigue. Indeed, research has shown that mental fatigue is positively correlated with lockdown restrictions (Torrente et al., 2022). The scope of the current study did not allow for any specific analysis on the impact of the COVID-19, however, it should be considered when interpreting and drawing conclusions from research conducted during and in the aftermath of the pandemic.

8.9 Future Directions

It is worth noting that the nonsignificant findings regarding the reduction of fatigue symptoms were unexpected, considering prior research indicating the potential effectiveness of bright light exposure in this domain. These findings underscore the need for further investigation and replication in larger-scale studies to establish a robust evidence base for the use of bright light exposure as an intervention for reducing fatigue in individuals with mTBI. Larger sample sizes will enhance statistical power and open up the possibility to explore potential moderating factors, ultimately providing a more comprehensive understanding of the effects of this intervention.

It was hoped that the inclusion of actigraphy data could provide an avenue for exploring the underlying mechanisms through which bright light exposure influences fatigue. However, the limited data available does not allow for any robust findings in this space and therefore, focus on the mechanisms by which light can reduce fatigue would be a valuable area for future research. Investigating physiological markers, neurobiological changes, or biomarkers associated with the effects of bright light therapy could enhance our understanding of the underlying processes and potentially identify individuals who are more likely to benefit from this intervention.

Further studies could explore different parameters of bright light exposure, such as intensity, duration, and timing, to identify the most effective and feasible intervention protocols. Additionally, the impact of contextual factors such as the variation in natural light levels across different seasons should be considered due to its influence on circadian rhythms, sleep patterns, and overall well-being. While our current dataset does not provide sufficient evidence to draw definitive conclusions regarding the effects of these contextual factors, it would be important for future research to account for variations in natural light and individual circumstances when designing and interpreting studies in this field. To undertake research of this nature, much larger sample sizes would be required in order to allocate participants to various subgroups.

If the number and quality of research studies in this domain grows sufficiently, it will allow for more robust investigation and comparison of bright light therapies for fatigue following mTBI alongside other interventions, such as cognitive-behavioural therapy or physical exercise. Additionally, the potential synergistic effects of combining bright light exposure with other therapeutic interventions, could yield more comprehensive and enhanced treatment approaches for this population.

8.9.1 Broad Spectrum White Light versus Blue Wave-Length Light

Previous published research in the context of light therapy for individuals post mTBI has predominantly focused on the use of blue light rather than broad-spectrum bright light. Whilst not anticipated, it is worth noting that this may have implications for the current study. Therefore, an avenue for future investigation lies in conducting a comparative study to discern potential differences in how individuals post mTBI respond to each of these light sources. As mentioned earlier in this thesis, a study examining the effectiveness of various polychromatic lights in shifting human circadian rhythms discovered that the use of a blue-enriched light did not yield significantly greater advancements of the circadian clock when compared to a broad spectrum bright white light (Smith et al., 2009). Additionally, in the treatment of seasonal affective disorder, blue-enriched light has been found to be no more effective than broad-spectrum bright white light (Meesters et al., 2011).

8.9.2 Consideration of the Nocebo Hypothesis

While efforts were made in the current study to consider symptom exaggeration due to external consequences or financial gain (e.g., ACC payments), it is important to acknowledge that illness beliefs may be an additional mechanism by which fatigue is maintained following mTBI. The "nocebo" effect, defined by Colloca and Miller (2011) as expectancy-induced functional symptoms, arguably warrants consideration when researching effective treatments for fatigue in this population. Public awareness campaigns and media coverage surrounding conditions like concussion and chronic traumatic encephalopathy have contributed to the perception that even minor concussions can result in severe and lasting consequences, potentially leading to symptom amplification (Silver, 2015). This phenomenon involves an attributional bias towards explaining symptoms as disease-related, fostering an excessive focus on somatic signals (Rief & Barsky 2005).

Future research in this field could benefit from including an assessment of participants' illness beliefs, as expectation has been shown to significantly influence the recovery process, where those who expect to do well after a mTBI have a better prognosis (Hou et al., 2011; Snell et al., 2011; Whittaker et al. 2007). Work is underway in developing therapeutic approaches targeting the nocebo effect. For example, Nocebo-Hypothesis Cognitive Behavioural Therapy

(NH-CBT) has been tested in populations impacted by functional neurological symptom disorder. This combines cognitive-behavioural therapy with movement retraining and video feedback, embedded within a comprehensive explanatory model of the etiology of functional neurological symptoms (Richardson et al., 2018; Richardson et al., 2020). This interdisciplinary rehabilitation approach, whilst not yet explored within mTBI populations, may be a relevant adjunct in understanding and further exploring the efficacy of light therapy for mTBI fatigue.

8.9.3 Wearable Devices

Exploring avenues to enhance accessibility to light exposure could potentially pave the way for obtaining larger sample sizes in research endeavours. By increasing the accessibility of light exposure interventions, such as through innovative delivery methods or broader implementation strategies, researchers may have the opportunity to reach a more diverse and representative participant pool. This approach not only has the potential to bolster the statistical power of studies but also fosters inclusivity and ensures that findings are applicable across a broader spectrum of individuals affected by mild Traumatic Brain Injury (mTBI).

8.9.4 Combined Approaches

Exploring the potential combined effects of light therapy with other therapeutic modalities represents a promising avenue in the field of mTBI research. By investigating the synergistic interactions between light therapy and complementary interventions, such as cognitive rehabilitation or pharmacotherapy, researchers aim to uncover novel treatment approaches that may offer higher efficacy than standalone therapies. This exploration acknowledges the multifaceted nature of mTBI and recognises the potential benefits of a holistic treatment approach that addresses various aspects of symptomatology. By combining modalities, researchers seek to optimize treatment outcomes and provide individuals with mTBI access to comprehensive and tailored interventions that better address their diverse needs.

8.7 Concluding Statement

In conclusion, this study has provided valuable insights into the potential benefits of bright light exposure as an intervention for individuals with mTBI experiencing fatigue symptoms, daytime sleepiness, and psychological distress. While the findings did not consistently reach statistical significance, the observed trends suggest promising avenues for further research. The multifaceted nature of fatigue and the complex interplay of factors in individuals with mTBI highlight the need for comprehensive approaches in its management.

Despite the limitations discussed, the trends toward fatigue reduction, coupled with reductions in anxiety and stress levels, imply potential benefits of bright light exposure. Clinicians could therefore consider incorporating bright light exposure as part of a holistic treatment approach for mTBI-related fatigue, especially given its non-invasive and non-pharmaceutical nature. However, further research with larger sample sizes, exploration of underlying mechanisms, and comparison with other interventions is warranted to establish a more robust evidence base for the use of bright light therapy in this context.

In reflecting on the researchers own journey through to completion of this thesis, it certainly has not been devoid of challenges. Throughout the course of this research project, I've been pushed to grow both as a researcher and as a practitioner in the clinical field. The difficulties discussed, while at times frustrating, have ultimately been transformative in shaping my approach to research and my ability to incorporate nuanced findings into my clinical practice. The complexities of managing a long-term study have allowed me to develop a keen problem-solving mindset, learning to troubleshoot and adapt on the fly.

Furthermore, the process of recruiting and working with individuals who have experienced mTBI has deepened my understanding of individual perspectives and their unique struggles. Motivating and engaging participants in the study required a delicate balance of empathy, clear communication, and ethical considerations.

Research findings, as I've come to appreciate, are seldom straightforward and often subject to various limitations. The complexities and intricacies inherent in the field of mTBI research have taught me to approach the literature with a critical eye, recognizing the need to weigh evidence carefully and consider the broader clinical implications.

In summary, the challenges I've encountered in this research journey have shaped me into a more resilient and adaptable researcher and a more empathetic clinician. These lessons have reinforced my commitment to evidence-based practice and the importance of considering the details and limitations of research findings when translating them into clinical work. As I move forward in my career, I am grateful for the growth and insights gained through this research, confident in my ability to contribute meaningfully to both the research and clinical domains.

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Appendix A: Summary of Published Research

Table. Research relating fatigue in adults after TBI to brain imaging techniques. Summary of study characteristics, including details on study sample, methods, and results.
Sourced from Johansson et al., 2021

Reference	Number of Participants Injury Severity	Time Since Injury	Age Year (sd)	Sex (Males/ Females)	Brain Imaging Fatigue Measure	Results
Berginström et al., 2018 [25]	57; TBI 40 mild 10 moderate 7 severe 27 HC	9 (7) years	TBI 42 (13) HC 38 (12)	TBI 31/26 HC 14/13	fMRI, modified SDMT FSS MFS VAS-fatigue	Lower brain activity (fMRI) in basal ganglia, primarily the caudate nucleus, thalamus, and anterior insula for the TBI group compared to controls (all $p < 0.05$). The brain activity decreased across the 27-min test session for the controls, whereas the TBI group remained on a similar lower activity level. Increased state-fatigue after the session compared to controls was reported ($p < 0.01$).
Berginström, Nordström, Nyberg, & Nordström, 2020 [76]	59 TBI; 40 mild 11 moderate 8 severe 27 HC	TBI 42 (9) HC 38 (12)	9 (7) years	TBI 32/27 HC 14/13	WM hyperintensity lesions FSS MFS	WMH lesions were more common in TBI compared to controls. WMH lesions were not related to cognitive tests. Increased WMH lesions correlated with reduced fatigue ($p = 0.026$).
Clark et al., 2017 [78]	59 TBI mild-moderate HC 25	64 (34) months	TBI 33 (6) HC 34 (8)	88% males 72% males	DTI MFIS	Decreased white matter microstructural integrity of left anterior internal capsule ($p = 0.02$) involved in basal ganglia circuitry in mTBI compared to HC, and this was associated with greater level of fatigue ($p = 0.01$).
Clark et al., 2018 [79]	63 mTBI	64 (43) months	32 (6)	87% males	MRI Thalamic volume MFIS	Greater levels of fatigue were associated with decreased right ($p = 0.026$) and left ($p = 0.046$) thalamic volumes. Regional morphometry analysis showed that fatigue was associated with reduction in the anterior and dorsomedial right thalamic body ($p < 0.05$).
Engström Nordin et al., 2016 [29]	10 mTBI 10 HC	At least 6 months Median 5 years	mTBI 37.5 (11) HC 36.9 (11)	mTBI 5/5 HC 5/5	Psychomotor vigilance task (PVT) adapted to MRI FSS VAS-fatigue	Functional connectivity was influenced by PVT task with a significant difference between mTBI and HC ($p < 0.05$) in thalamus and middle frontal cortex, indicating that HC have more extensive functional connectivity network in thalamus and stronger functional connectivity in

Reference	Number of Participants Injury Severity	Time Since Injury	Age Year (sd)	Sex (Males/ Females)	Brain Imaging Fatigue Measure	Results
						medial frontal cortex both before and after the PVT task.
Hattori et al., 2009 [74]	15 mTBI 15 HC	At least 6 moths	mTBI 45 (11) HC 43 (9)	mTBI 3/12 HC 3/12	rCBF SPECT PASAT (information processing and sustained and divided attention) Persistent cognitive complaints, specifically the complaint of cognitive fatigue	In all 4 trials, mild TBI had lower PASAT scores ($p < 0.05$). A different pattern of rCBF between mTBI and HC ($p < 0.05$). Less activation for mTBI in the cerebellum and more activation in the prefrontal cortex. mTBI showed dynamic changes in supratentorial rCBF during PASAT, with larger areas of activation bilaterally in the dorsolateral prefrontal cortex and larger areas of suppression in the occipital and parietal cortices.
Kohl, Wylie, Genova, Hillary, & DeLuca, 2009 [27]	11 moderate to sever TBI 11 HC	9 (9) years	TBI 39 (14) HC 38 (9)	More men in TBI compared to HC	fMRI modified SDMT No fatigue scale	TBI group increased activity in the middle frontal gyrus, superior parietal cortex, basal ganglia, and anterior cingulate. Controls decreased activity over time ($p < 0.005$) TBI had slower reaction during all 3 times ($p < 0.05$).
Liu et al., 2016 [72]	25 mTBI acute phase 21 mTBI chronic phase 20 HC	acute; within 2 weeks chronic; more than 12 months	mTBI acute 36 (10) mTBI chronic 36 (13) HC 32 (8)	Acute 15/10 Chronic 12/9 HC 12(8	ASL-fMRI Psychomotor vigilance task (PVT) MFS	PVT was related to arterial spin labeling–fMRI. Sustained attention was impaired in mTBI patients both in acute and in chronic phases comapred to controls, and with worse performance in the acute phase.
Möller et al., 2017 [26]	10 mTBI 10 HC	At least 6 months after	mTBI 38 (11) HC 37 (11)	mTBI 5/5 HC 5/5	rCBF SPEC Psychomotor vigilance task (PVT) FSS	A significant interaction effect between mTBI and HC in several brain regions ($p < 0.05$). In mTBI, at the end of the PVT, fatigability was related to increased rCBF in the right middle frontal gyrus. Self-rated fatigue was related to increased rCBF in left medial frontal and anterior cingulate gyri and decreases of rCBF in a frontal/thalamic network.
Pardini et al., 2010 [80]	97 penetrating brain injuries Divided into; 17 ventromedial prefrontal cortex (vmPFC), 51 dorso/lateral prefrontal cortex (d/lPFC), 29	unknown	vmPFC 59 (1) d/lPFC 58 (0.3) Nonfrontal 58 (0.5) HC 59 (0.6)	All males	CT scan Krupp fatigue scale	Individuals with PBI with vmPFC lesion were significantly more fatigued than the other groups as well as the healthy controls ($p = 0.013$). VmPFC volume correlated with fatigue scores ($p = 0.0053$), the

Reference	Number of Participants Injury Severity	Time Since Injury	Age Year (sd)	Sex (Males/ Females)	Brain Imaging Fatigue Measure	Results
	nonfrontal lesion 37 HC					larger the lesion volume, the higher the fatigue scores.
						Brain activation associated with effort and fatigue did not differentiate the mTBI and controls, while functional connectivity did. FSS correlated with functional connectivity between the left insula and the dorsal anterior cingulate cortex ($p < 0.01$), the left insula and the right inferior frontal gyrus ($p < 0.05$), and the dorsal anterior cingulate cortex and the right inferior frontal gyrus ($p < 0.05$) medial frontal gyrus correlated with FSS, all during the first half of the 75% effort level.
Schönberger et al., 2017 [75]	53 TBI mild to severe, most moderate or severe 36 subgroup vigilance test	2 (1) years	38 (14)	77% male	MRI total brain volume, and lesions; GM and WM separately as well as combined. Vigilance task FSS	MRI revealed GM and WM brain lesions but fatigue was not related to brain lesions.
Skau, Bunketorp-Käll, Kuhn, & Johansson, 2019 [24]	20 mTBI 20 HC	28 (21) months	mTBI 42 (10) HC 39 (11)	mTBI 7/13 HC 8/12	fNIRS, modified Stroop-Simon, one repetition MFS VAS- energy	Lower event-related oxygenated hemoglobin (oxy-Hb) concentration in the frontal cortex for the mTBI group, compared to controls ($p < 0.05$). No time effect. An interaction ($p < 0.05$) was found, with the mTBI group having a similar lower oxy-Hb concentration for both congruent and incongruent trials, whereas the controls had a higher concentration of oxy-Hb in the more demanding incongruent trial compared to the congruent trial. Higher MFS correlated with lower oxy-HB ($p < 0.05$).
Wylie et al., 2017 [28]	22; 20 TBI moderate to severe, 2 complicated mTBI 20 HC	80 (51) months	TBI 41 (13) HC 38 (11)	TBI 14/8 HC 8/14	fMRI Four blocks of working memory, 2-back task (difficult), and 0-back speed VAS-fatigue	TBI group was slower in response time ($p < 0.001$). Fatigue interacted with task in several areas. Negative correlation between reaction time and fatigue ($p = 0.08$) TBI; correlation between fatigue and activation for 2-back and 0-back were weak (coefficient = 0.0003). HC; there was a positive correlation between fatigue

Reference	Number of Participants Injury Severity	Time Since Injury	Age Year (sd)	Sex (Males/ Females)	Brain Imaging Fatigue Measure	Results
						and brain activation for difficult 2-back task (coefficient = 0.0035), and negative for the 0-back task (coefficient = −0.0013). Fatigue in relation to brain activation was related to caudate nucleus.
Wäljas et al., 2014 [77]	48 mTBI 24 HC	27 (9) days	mTBI 36 (12) HC 37 (10)	mTBI 60% females HC 67% females	DTI Post-concussion symptoms (including fatigue but not specifically measured).	mTBI reported more post-concussion symptoms, did not differ on cognitive tests, and had a larger number of low DTI measures (fractional anisotropy values, p = 0.003) compared to controls.

Abbreviations: sd (standard deviation), mTBI (mild Traumatic Brain Injury), HC (healthy controls), OC (orthopedic controls), fMRI (functional Magnetic Resonance Imaging), rCBF SPECT (regional Cerebral Blood Flow Single-Photon emission computed tomography), ALS (arterial spin labeling), fNIRS (functional Near-Infrared Spectroscopy), DTI (Diffusion Tensor Imaging), GM (grey matter), WM (white matter), SDMT (Symbol Digit Modality Test), MFI (Multidimensional Fatigue Inventory), FSS (Fatigue Severity Scale), MFS (Mental Fatigue Scale), VAS (Visual Analogue Scale).

Appendix B: Online Intake Survey

Block 1

This research is being conducted by Kate Connolly as part of the requirements for a Doctor of Clinical Psychology degree. Her supervisors are Professor Janet Leathem, Associate Professor Mirjam Munch, and Dr Stephen Hill.

The following survey is designed to assess your suitability for participation in an intervention trial to reduce fatigue following a mild traumatic brain injury/concussion. If you have any difficulty understanding or responding to the questions, or if you have any general queries you wish to discuss before proceeding, please contact Kate Connolly at kathryn.connolly.1@uni.massey.ac.nz

Before proceeding, please make sure you have carefully read and understood the information sheet, including the inclusion and exclusion criteria noted.

This project has been approved by both the Central Health and Disability Ethics Committee (ref: 20/CEN/49) and the ACC Ethics Committee.

Please answer yes or no to the following statements.

	Yes	No
I have read the Information Sheet and understand the details of this study. I have sought explanation about any details of the study that I do not understand.	O	O
I have had time to consider my participation and my questions have been answered to my satisfaction. I understand that I may ask further questions at any time.	O	O
I agree to participate in this study under the conditions set out in the Information Sheet. I understand that my participation is voluntary and that I can withdraw myself and any data that has been collected from the study at any time.	O	O
I understand that my participation in this study is confidential and that no material which could identify me personally will be used in any reports on this study.	O	O
I know who to contact if I have any questions about the study in general.	O	O
I wish to receive a summary of the research when it is completed.	O	O

Default Question Block

Please enter your 3 digit participant ID

What is your age in years?

What gender do you identify with?

- Male
- Female
- Nonbinary / Gender fluid / Other

Which ethnic group(s) do you belong to?
(mark as many as are applicable)

- NZ European
- Māori
- Pacific Peoples
- Asian
- Middle Eastern Latin American African
- Other Ethnicity (please add in the text box below)

What is your highest qualification?

- No formal school qualification
- NCEA Level 1 (School Certificate or equivalent)
- NCEA Level 2 (6th Form Certificate or equivalent)
- NCEA Level 3 (Bursary or equivalent)
- Trade Certificate or Diploma
- Undergraduate Degree
- Postgraduate Degree
- Doctoral Degree

What was the date that you sustained the concussion injury that you believe has caused your current experience of fatigue (dd/mm/yyyy)

Have you sustained any previous head injuries?

- Yes
- No

If your response to the above question was yes, please describe in the box below how many prior injuries you have had and how severe each of those was.

On average, I spend the following amount of time outdoors in daylight (without a roof above my head).

Please write times in hours and minutes.

On workdays:

Hours

Minutes

On free days:

Hours

Minutes

Please type approximate amounts of stimulant use per day/week/month in the boxes below. If you don't use a particular stimulant, please indicate this by typing 0 in the box provided.

	Per day	Per week	Per month
Cigarettes (tobacco)			
Glasses of beer			
Glasses of wine			
Glasses of liquor/whiskey/gin etc.			
Cups of coffee			
Cups of black tea			
Cans of caffeinated drinks			

I have been a shift or night worker in the past three months.

- Yes
- No

Please select a number between 1 and 7 which you feel best fits the following statements. This refers to your usual way of life within the last week.

1 indicates "strongly disagree" and 7 indicates "strongly agree".

	1	2	3	4	5	6	7
1. My motivation is lower when I am fatigued.	O	O	O	O	O	O	O
2. Exercise brings on my fatigue.	O	O	O	O	O	O	O
3. I am easily fatigued.	O	O	O	O	O	O	O
4. Fatigue interferes with my physical functioning.	O	O	O	O	O	O	O

	1 indicates "strongly disagree" and 7 indicates "strongly agree".						
	1	2	3	4	5	6	7
5. Fatigue causes frequent problems for me.	O	O	O	O	O	O	O
	1	2	3	4	5	6	7
6. My fatigue prevents sustained physical functioning.	O	O	O	O	O	O	O
7. Fatigue interferes with carrying out certain duties and responsibilities.	O	O	O	O	O	O	O
8. Fatigue is among my most disabling symptoms.	O	O	O	O	O	O	O
9. Fatigue interferes with my work, family, or social life.	O	O	O	O	O	O	O

Please select the number on the number line which describes your global fatigue with 10 being the worst and 0 being normal.

	0	1	2	3	4	5	6	7	8	9	10	
Normal	O	O	O	O	O	O	O	O	O	O	O	Worst

During the past month, what time have you usually gone to bed at night?

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

During the past month, what time have you usually gotten up in the morning?

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

For each of the statements in the question below, check the one best response. Please do so for all statements.

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

	Not during the past month (0)	Less than once a week (1)	Once or twice a week (2)	Three or more times a week (3)
a. Cannot get to sleep within 30 minutes	O	O	O	O
b. Wake up in the middle of the night or early morning	O	O	O	O
c. Have to get up to use the bathroom	O	O	O	O
d. Cannot breathe comfortably	O	O	O	O
e. Cough or snore loudly	O	O	O	O
	Not during the past month (0)	Less than once a week (1)	Once or twice a week (2)	Three or more times a week (3)
f. Feel too cold	O	O	O	O
g. Feel too hot	O	O	O	O
h. Have bad dreams	O	O	O	O
i. Have pain	O	O	O	O
j. Other reason(s), please describe, including how often you have had trouble sleeping because of this reason(s):	O	O	O	O

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

- O Very good
- O Fairly good
- O Fairly bad
- O Very bad

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

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

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

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

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

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

Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ: Psychiatry Research, 28:193-213, 1989.

How likely are you to doze off or fall asleep in the following situations, in contrast to feeling just tired?

This refers to your usual way of life in recent times.

Even if you haven't done some of these things recently, try to work out how they would have affected you.

Use the following scale to choose the **most appropriate number** for each situation:

0 = would **never** doze off
1 = **slight chance** of dozing
2 = **moderate chance** of dozing
3 = **high chance** of dozing

It is important that you answer each question as best you can.

	0	1	2	3
Sitting and reading	O	O	O	O
Watching TV	O	O	O	O
Sitting, inactive in a public place (e.g. a theatre or a meeting)	O	O	O	O
As a passenger in a car for an hour without a break	O	O	O	O
Lying down to rest in the afternoon when circumstances permit	O	O	O	O
Sitting and talking to someone	O	O	O	O
Sitting quietly after a lunch without alcohol	O	O	O	O
In a car, while stopped for a few minutes in the traffic	O	O	O	O

Depression, Anxiety and Stress Scale

Please read each statement and indicate how much the statement applied to you over the past week. There are no right or wrong answers. Do not spend too much time on any statement.

	Did not apply to me at all	Applied to me to some degree, or some of the time	Applied to me to a considerable degree, or a good part of time	Applied to me very much, or most of the time
1. I found it hard to wind down	O	O	O	O
2. I was aware of dryness of my mouth	O	O	O	O
3. I couldn't seem to experience any positive feeling at all	O	O	O	O
4. I experienced breathing difficulty (eg., excessively rapid breathing, breathlessness in the absence of physical exertion)	O	O	O	O
5. I found it difficult to work up the initiative to do things	O	O	O	O
6. I tended to over-react to situations	O	O	O	O

	Did not apply to me at all	Applied to me to some degree, or some of the time	Applied to me to a considerable degree, or a good part of time	Applied to me very much, or most of the time
7. I experienced trembling (eg., in the hands)	O	O	O	O
8. I felt that I was using a lot of nervous energy	O	O	O	O
9. I was worried about situations in which I might panic and make a fool of myself	O	O	O	O
10. I felt that I had nothing to look forward to	O	O	O	O
11. I found myself getting agitated	O	O	O	O
12. I found it difficult to relax	O	O	O	O

	Did not apply to me at all	Applied to me to some degree, or some of the time	Applied to me to a considerable degree, or a good part of time	Applied to me very much, or most of the time
13. I felt down-hearted and blue	O	O	O	O
14. I was intolerant of anything that kept me from getting on with what I was doing	O	O	O	O
15. I felt I was close to panic	O	O	O	O
16. I was unable to become enthusiastic about anything	O	O	O	O

	Did not apply to me at all	Applied to me to some degree, or some of the time	Applied to me to a considerable degree, or a good part of time	Applied to me very much, or most of the time
17. I felt I wasn't worth much as a person	O	O	O	O
18. I felt that I was rather touchy	O	O	O	O

	Did not apply to me at all	Applied to me to some degree, or some of the time	Applied to me to a considerable degree, or a good part of time	Applied to me very much, or most of the time
19. I was aware of the action of my heart in the absence of physical exertion (eg., sense of heart rate increase, heart missing a beat)	O	O	O	O
20. I felt scared without any good reason	O	O	O	O
21. I felt that life was meaningless	O	O	O	O

Appendix C: Online Repeated Time Point Survey

Demographic Questions

Please enter your 3 digit participant registration number.

What is your age in years?

Stimulants

On average, I spend the following amount of time outdoors in daylight (without a roof above my head).

Please write times in hours and minutes.

On workdays:

Hours

Minutes

On free days:

Hours

Minutes

Please type approximate amounts of stimulant use per day/week/month in the boxes below. If you don't use a particular stimulant, please indicate this by typing 0 in the box provided.

	Per day	Per week	Per month
Cigarettes (tobacco)			
Glasses of beer			
Glasses of wine			
Glasses of liquor/whiskey/gin etc.			
Cups of coffee			
Cups of black tea			
Cans of caffeinated drinks			

The following section will ask you questions in regards to your sleep and wake behaviour on work and work-free days. Please estimate an average of your 'normal' sleep behaviour over the past 6 weeks.

I have been a shift or night worker in the past three months.

- Yes
- No

How many days a week do you normally work?

Please answer all the following questions even if you do not work or work 7 days/week. Please don't forget to indicate times with AM or PM.

On WORK days I normally fall asleep at (this is NOT when you get into bed, but rather when you fall asleep)

Time

On WORK days I wake up at (this is NOT when you get out of bed, but rather when you wake up)

Time

On WORK-FREE days I normally fall asleep at (this is NOT when you get into bed, but rather when you fall asleep)

Time

On WORK-FREE days I wake up at (this is NOT when you get out of bed, but rather when you wake up)

Time

Fatigue Questions

Please select a number between 1 and 7 which you feel best fits the following statements. This refers to your usual way of life within the last week.

1 indicates "strongly disagree" and 7 indicates "strongly agree".

	1	2	3	4	5	6	7
1. My motivation is lower when I am fatigued.	O	O	O	O	O	O	O
2. Exercise brings on my fatigue.	O	O	O	O	O	O	O
3. I am easily fatigued.	O	O	O	O	O	O	O
4. Fatigue interferes with my physical functioning.	O	O	O	O	O	O	O
5. Fatigue causes frequent problems for me.	O	O	O	O	O	O	O
	1	2	3	4	5	6	7
6. My fatigue prevents sustained physical functioning.	O	O	O	O	O	O	O

1 indicates "strongly disagree" and 7 indicates "strongly agree".

	1	2	3	4	5	6	7
7. Fatigue interferes with carrying out certain duties and responsibilities.	O	O	O	O	O	O	O
8. Fatigue is among my most disabling symptoms.	O	O	O	O	O	O	O
9. Fatigue interferes with my work, family, or social life.	O	O	O	O	O	O	O

Please select the number on the number line which describes your global fatigue with 10 being the worst and 0 being normal.

	0	1	2	3	4	5	6	7	8	9	10	
Normal	O	O	O	O	O	O	O	O	O	O	O	Worst

Morningness-Eveningness Questionnaire

For each question, please select the answer that best describes you. You should select the point value that best indicates how you have felt in recent weeks.

Approximately what time would you get up if you were entirely free to plan your day?

- 5:00 AM - 6:30 AM *(05:00 - 06:30 h)*
- 6:30 AM - 7:45 AM *(06:30 - 07:45 h)*
- 7:45 AM - 9:45 AM *(07:45 - 09:45 h)*
- 9:45 AM - 11:00 AM *(09:45 - 11:00 h)*
- 11:00 AM - 12 noon *(11:00 - 12:00 h)*

Approximately what time would you go to bed if you were entirely free to plan your evening?

- 8:00 PM - 9:00 PM *(20:00 - 21:00 h)*
- 9:00 PM - 10:15 PM *(21:00 - 22:15 h)*
- 10:15 PM - 12:30 AM *(22:15 - 00:30 h)*
- 12:30 AM - 1:45 AM *(00:30 - 01:45 h)*
- 1:45 AM - 3:00 AM *(01:45 - 03:00 h)*

If you usually have to get up at a specific time in the morning, how much do you depend on an alarm clock?

- Not at all
- Slightly
- Somewhat
- Very much

How easy do you find it to get up in the morning (when you are not awakened unexpectedly)?

- Very difficult
- Somewhat difficult
- Fairly easy
- Very easy

How alert do you feel during the first half hour after you wake up in the morning?

- Not at all alert
- Slightly alert
- Fairly alert
- Very alert

How hungry do you feel during the first half hour after you wake up?

- Not at all hungry
- Slightly hungry
- Fairly hungry
- Very hungry

During the first half hour after you wake up in the morning, how do you feel?

- Very tired
- Fairly tired
- Fairly refreshed
- Very refreshed

If you had no commitments the next day, what time would you go to bed compared to your usual bedtime?

- Seldom or never later
- Less than 1 hour later
- 1-2 hours later
- More than 2 hours later

You have decided to do physical exercise. A friend suggests that you do this for one hour twice a week, and the best time for him is between 7-8 AM. Bearing in mind nothing but your own internal "clock", how do you think you would perform?

- Would be in good form
- Would be in reasonable form
- Would find it difficult
- Would find it very difficult

At *approximately* what time in the evening do you feel tired, and, as a result, in need of sleep?

- 8:00 PM - 9:00 PM *(20:00 - 21:00 h)*
- 9:00 PM - 10:15 PM *(21:00 - 22:15 h)*
- 10:15 PM - 12:45 AM *(22:15 - 00:45 h)*
- 12:45 AM - 2:00 AM *(00:45 - 02:00 h)*
- 2:00 AM - 3:00 AM *(02:00 - 03:00 h)*

You want to be at your peak performance for a test that you know is going to be mentally exhausting and will last two hours. You are entirely free to plan your day. Considering only your "internal clock", which one of the four testing times would you choose?

- 8 AM - 10 AM *(08-10 h)*
- 11 AM - 1 PM *(11-13 h)*
- 3 PM - 5 PM *(15-17 h)*
- 7 PM - 9PM *(19-21 h)*

If you got to bed at 11 PM, how tired would you be?

- Not tired at all
- A little tired
- Fairly tired
- Very tired

For some reason you have gone to bed several hours later than usual, but there is no need to get up at any particular time the next morning. Which one of the following are you most likely to do?

- Will wake up at usual time, but will not fall back asleep
- Will wake up at usual time and will doze thereafter
- Will wake up at usual time, but will fall asleep again
- Will not wake up until later than usual

One night you have to remain awake between 4-6 AM (04-06 h) in order to carry out a night watch. You have no time commitments the next day. Which one of the alternatives would suit you best?

- Would not go to bed until the watch is over
- Would take a nap before and sleep after
- Would take a good sleep before and nap after
- Would sleep only before the watch

You have two hours of hard physical work. You are entirely free to plan your day. Considering only your internal "clock," which of the following times would you choose?

- 8 AM - 10 AM
- 11 AM - 1 PM
- 3 PM - 5 PM
- 7 PM - 9PM

You have decided to do physical exercise. A friend suggests that you do this for one hour twice a week. The best time for her is between 10-11 PM (22-23 h). Bearing in mind only your internal "clock," how well do you think you would perform?

- Would be in good form
- Would be in reasonable form
- Would find it difficult
- Would find it very difficult

Suppose you can choose your own work hours. Assume that you work a five-hour day (including breaks), your job is interesting, and you are paid based on your performance. At *approximately* what time would you choose to begin?

- 5 hours starting between 4-8 AM
- 5 hours starting between 8-9 AM
- 5 hours starting between 9 AM - 2 PM
- 5 hours starting between 2-5 PM
- 5 hours starting between 5 PM - 4 AM

At *approximately* what time of day do you usually feel your best?

- 5-8 AM
- 8-10 AM
- 10 AM - 5 PM
- 5-10 PM
- 10 PM - 5 AM

One hears about "morning types" and "evening types." Which one of these types do you consider yourself to be?

- Definitely a morning type
- Rather more a morning type than an evening type
- Rather more an evening type than a morning type
- Definitely an evening type

Sleep

During the past month, what time have you usually gone to bed at night?

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

During the past month, what time have you usually gotten up in the morning?

During the past month, how many hours of <u>actual sleep</u> did you get at night? (This may be different than the number of hours you spent in bed.)

For each of the statements in the question below, check the one best response. Please do so for all statements.

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

	Not during the past month (0)	Less than once a week (1)	Once or twice a week (2)	Three or more times a week (3)
a. Cannot get to sleep within 30 minutes	○	○	○	○
b. Wake up in the middle of the night or early morning	○	○	○	○
c. Have to get up to use the bathroom	○	○	○	○
d. Cannot breathe comfortably	○	○	○	○
e. Cough or snore loudly	○	○	○	○
	Not during the past month (0)	Less than once a week (1)	Once or twice a week (2)	Three or more times a week (3)
f. Feel too cold	○	○	○	○
g. Feel too hot	○	○	○	○
h. Have bad dreams	○	○	○	○
i. Have pain	○	○	○	○
j. Other reason(s), please describe, including how often you have had trouble sleeping because of this reason(s):	○	○	○	○

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

- ○ Very good
- ○ Fairly good
- ○ Fairly bad
- ○ Very bad

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

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

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

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

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

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

Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ: Psychiatry Research, 28:193-213, 1989.

How likely are you to doze off or fall asleep in the following situations, in contrast to feeling just tired?

This refers to your usual way of life in recent times.

Even if you haven't done some of these things recently, try to work out how they would have affected you.

Use the following scale to choose the **most appropriate number** for each situation:

0 = would **never** doze off
1 = **slight chance** of dozing
2 = **moderate chance** of dozing
3 = **high chance** of dozing

It is important that you answer each question as best you can.

	0	1	2	3
Sitting and reading	○	○	○	○
Watching TV	○	○	○	○
Sitting, inactive in a public place (e.g. a theatre or a meeting)	○	○	○	○
As a passenger in a car for an hour without a break	○	○	○	○
Lying down to rest in the afternoon when circumstances permit	○	○	○	○
Sitting and talking to someone	○	○	○	○
Sitting quietly after a lunch without alcohol	○	○	○	○
In a car, while stopped for a few minutes in the traffic	○	○	○	○

DASS-21

Depression, Anxiety and Stress Scale

Please read each statement and indicate how much the statement applied to you over the past week. There are no right or wrong answers. Do not spend too much time on any statement.

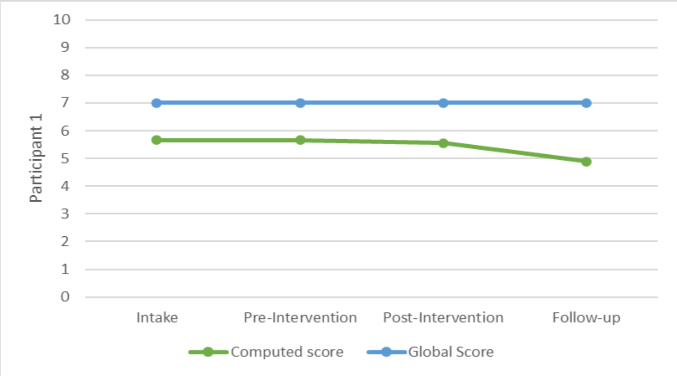
	Did not apply to me at all	Applied to me to some degree, or some of the time	Applied to me to a considerable degree, or a good part of time	Applied to me very much, or most of the time
1. I found it hard to wind down	○	○	○	○
2. I was aware of dryness of my mouth	○	○	○	○
3. I couldn't seem to experience any positive feeling at all	○	○	○	○
4. I experienced breathing difficulty (eg., excessively rapid breathing, breathlessness in the absence of physical exertion)	○	○	○	○
5. I found it difficult to work up the initiative to do things	○	○	○	○
6. I tended to over-react to situations	○	○	○	○
	Did not apply to me at all	Applied to me to some degree, or some of the time	Applied to me to a considerable degree, or a good part of time	Applied to me very much, or most of the time
7. I experienced trembling (eg., in the hands)	○	○	○	○
8. I felt that I was using a lot of nervous energy	○	○	○	○
9. I was worried about situations in which I might panic and make a fool of myself	○	○	○	○
10. I felt that I had nothing to look forward to	○	○	○	○
11. I found myself getting agitated	○	○	○	○
12. I found it difficult to relax	○	○	○	○
	Did not apply to me at all	Applied to me to some degree, or some of the time	Applied to me to a considerable degree, or a good part of time	Applied to me very much, or most of the time
13. I felt down-hearted and blue	○	○	○	○
14. I was intolerant of anything that kept me from getting on with what I was doing	○	○	○	○
15. I felt I was close to panic	○	○	○	○
16. I was unable to become enthusiastic about anything	○	○	○	○
17. I felt I wasn't worth much as a person	○	○	○	○
18. I felt that I was rather touchy	○	○	○	○
	Did not apply to me at all	Applied to me to some degree, or	Applied to me to a considerable degree, or a	Applied to me very much, or most of the time

	Did not apply to me at all	Applied to me to some degree, or some of the time some of the time	Applied to me to a considerable degree, or a good part of time good part of time	Applied to me very much, or most of the time
19. I was aware of the action of my heart in the absence of physical exertion (eg., sense of heart rate increase, heart missing a beat)	○	○	○	○
20. I felt scared without any good reason	○	○	○	○
21. I felt that life was meaningless	○	○	○	○

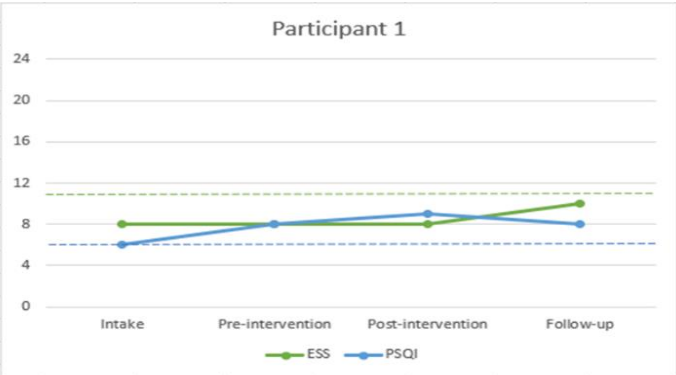
Appendix D: Individual Participant Graphs

Participant 1:

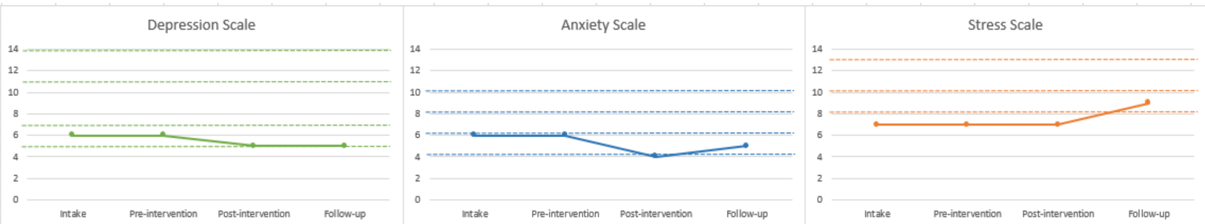
P1's FSS Scores



P1's ESS and PSQI Scores

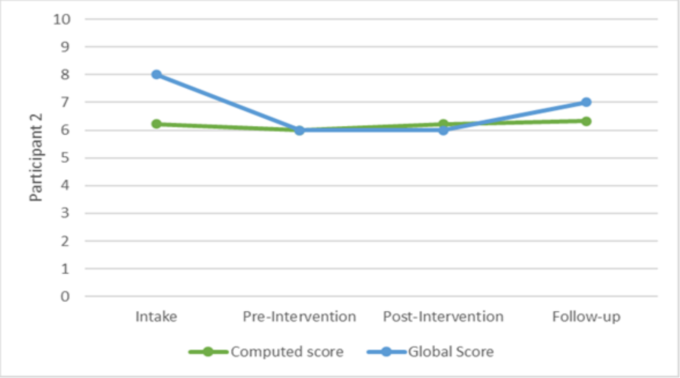


P1's DASS-21 Scores

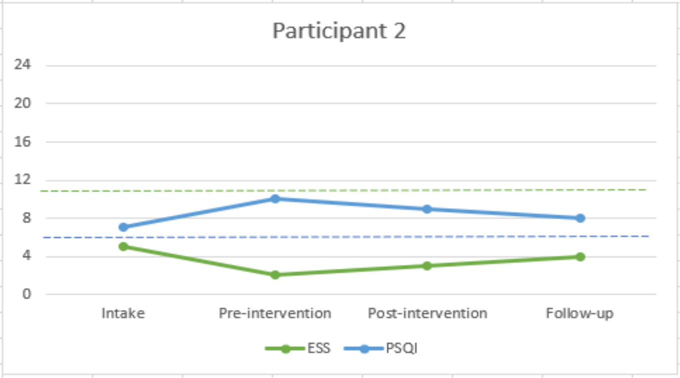


Participant 2:

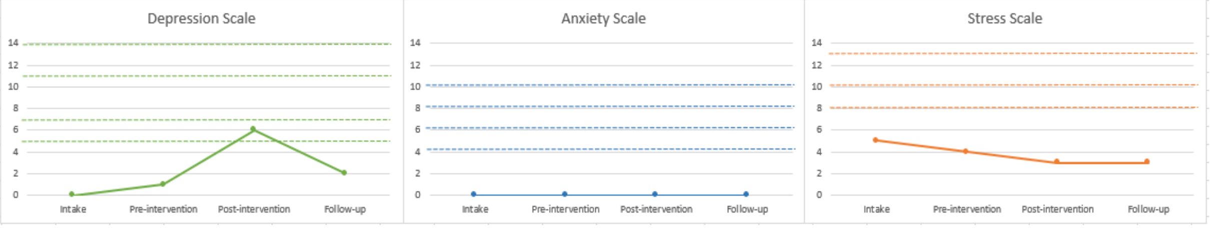
P2's FSS Scores



P2's ESS and PSQI Scores

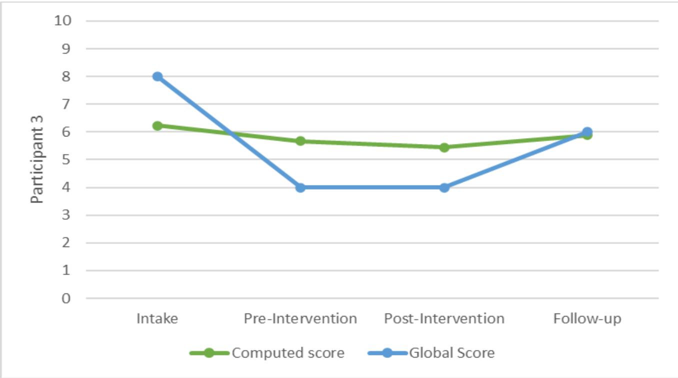


P2's DASS-21 Scores

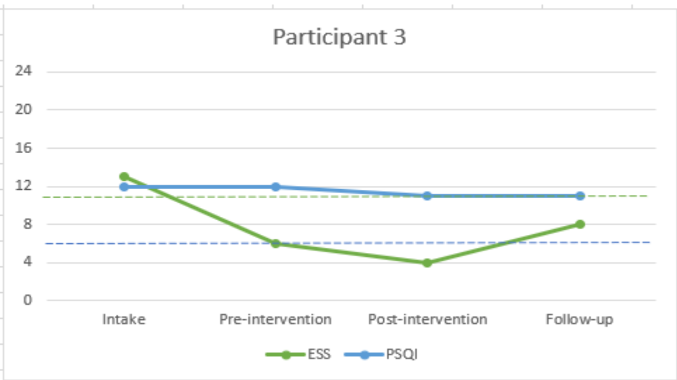


Participant 3:

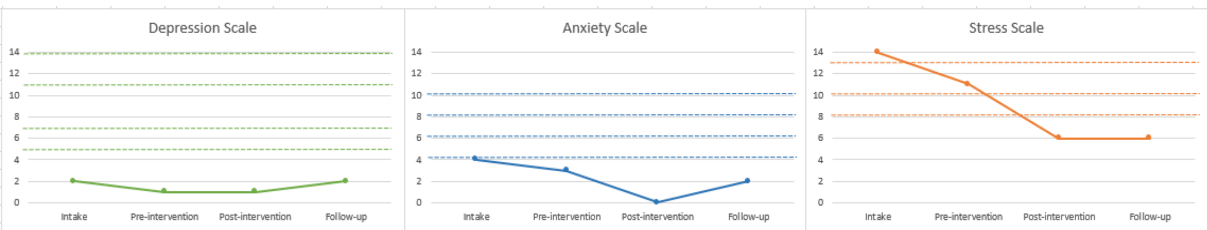
P3's Fatigue Severity Scale Scores



P3's ESS and PSQI Scores

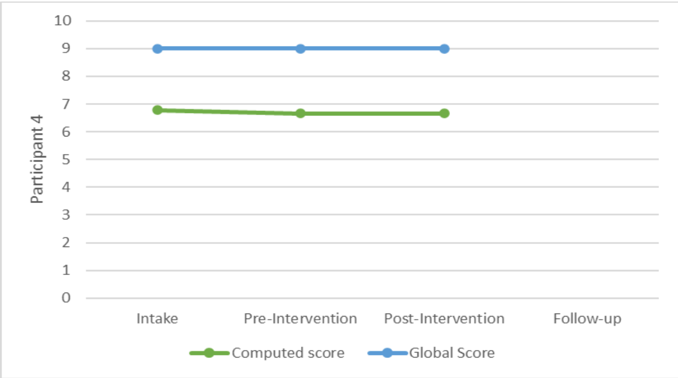


P3's DASS-21 Scores

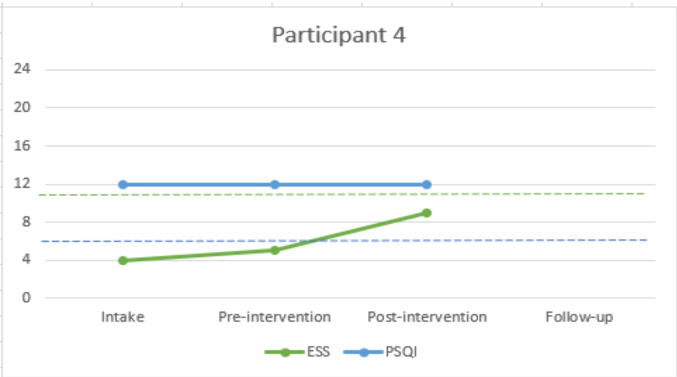


Participant 4:

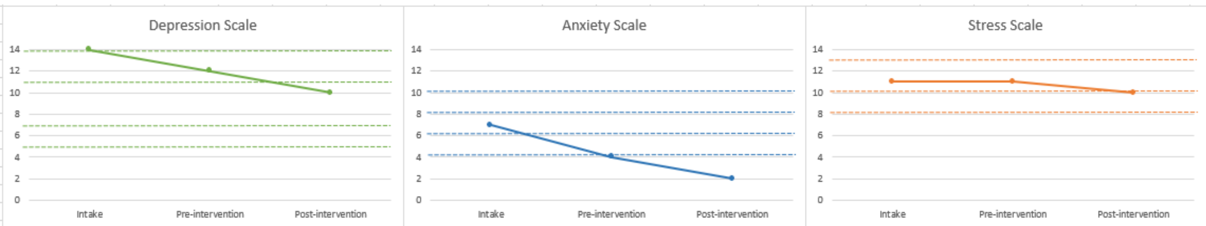
P4's Fatigue Severity Scale Scores



P4's ESS and PSQI Scores

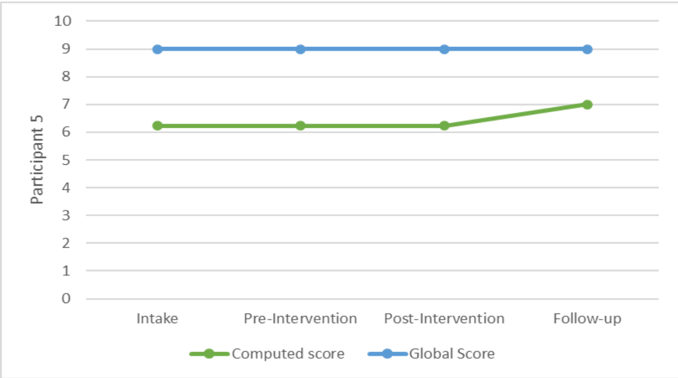


P4's Depression, Anxiety and Stress Scale Scores (DASS-21)

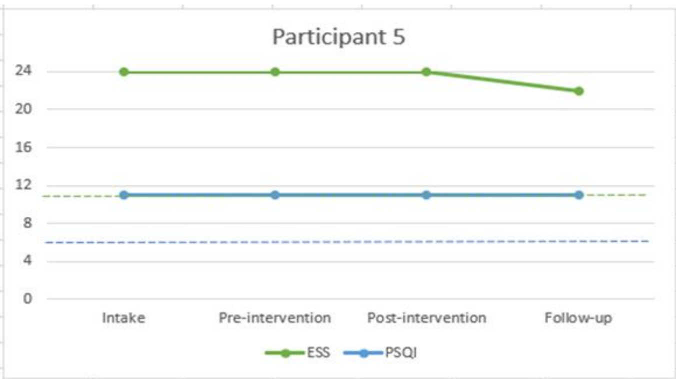


Participant 5:

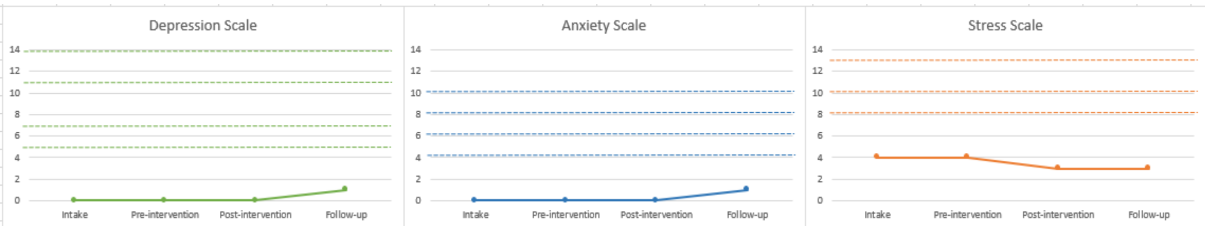
P5's FSS Scores



P5's ESS and PSQI Scores

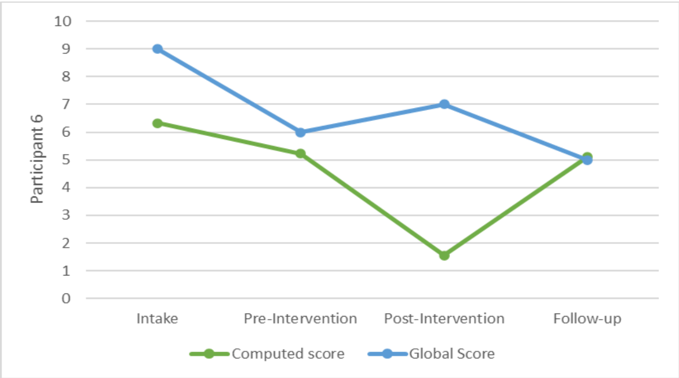


P5's Depression, Anxiety and Stress Scale Scores (DASS-21)

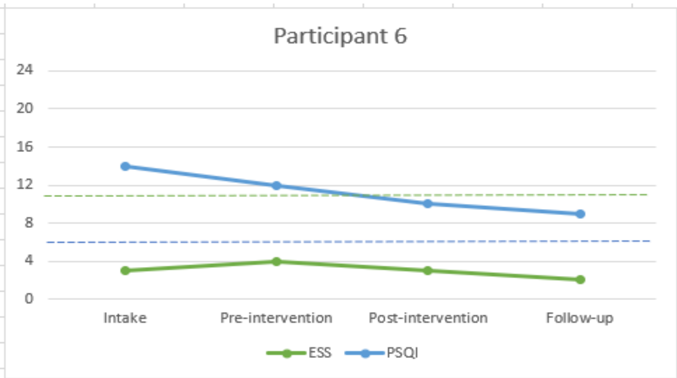


Participant 6:

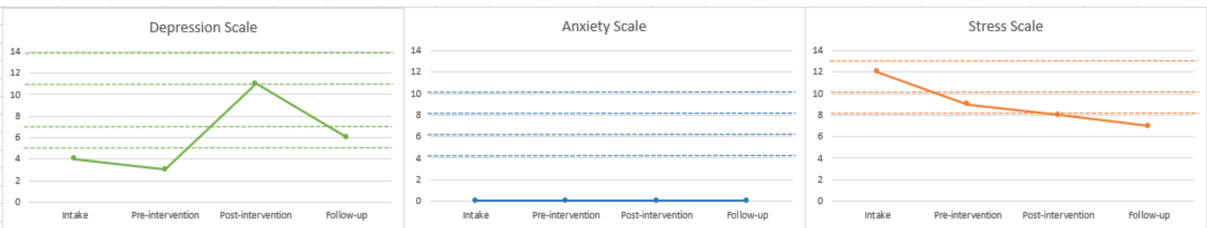
P6's FSS Scores



P6's ESS and PSQI Scores

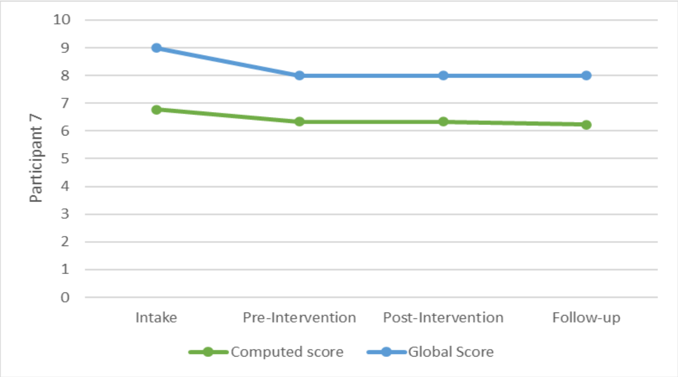


P6's DASS-21 Scores

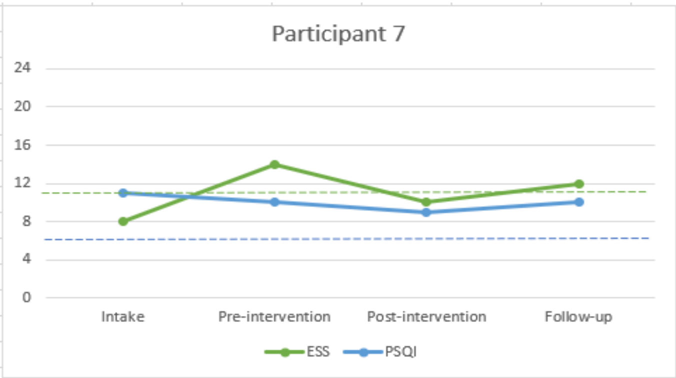


Participant 7:

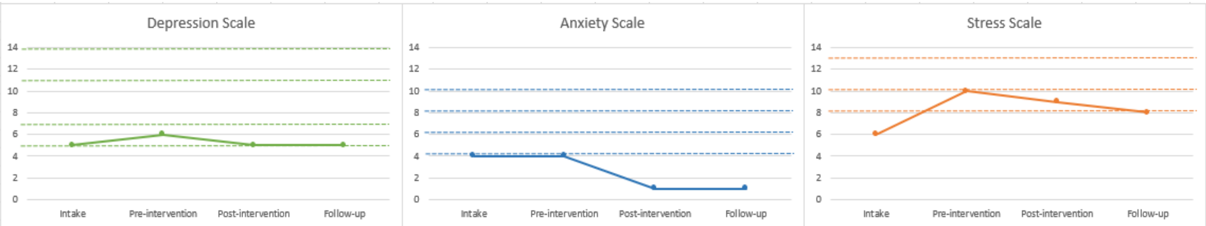
P7's FSS Scores



P7's ESS and PSQI Scores

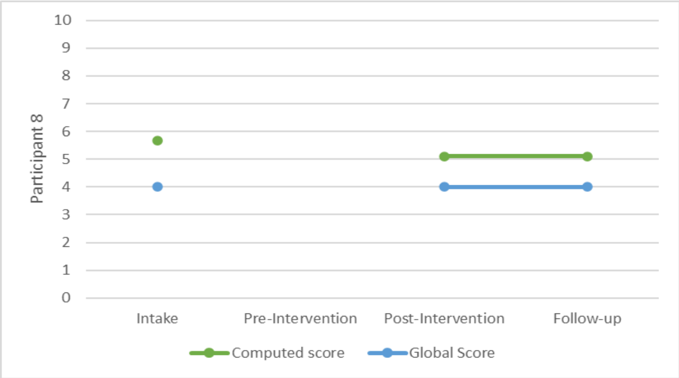


P7's DASS-21 Scores

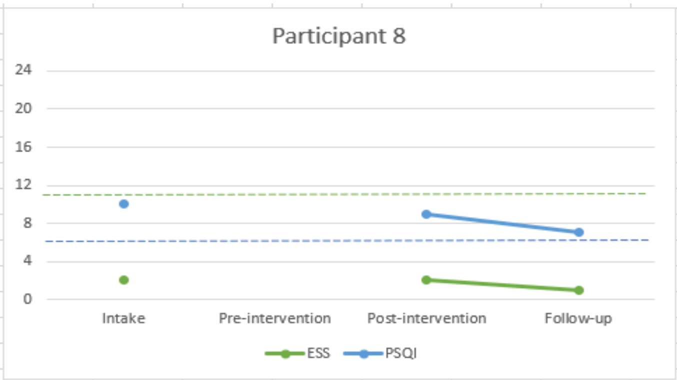


Participant 8:

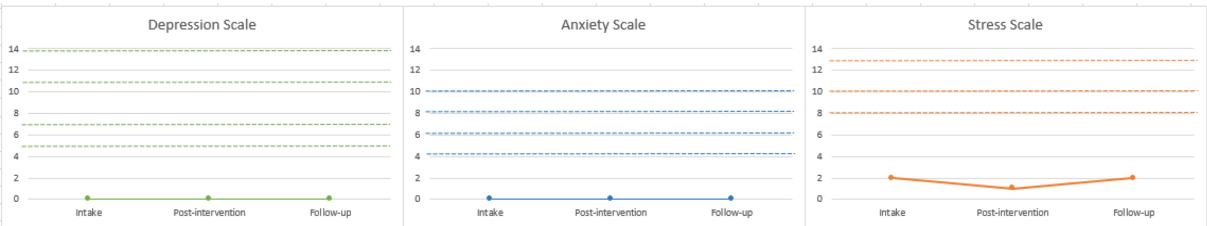
P8's *FSS Scores*



P8's ESS and PSQI Scores

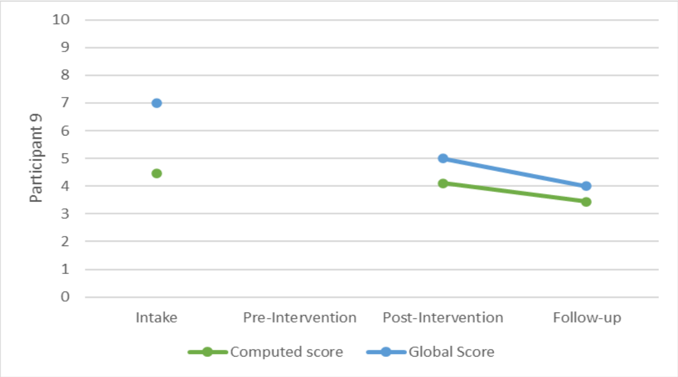


P8's DASS-21 Scores

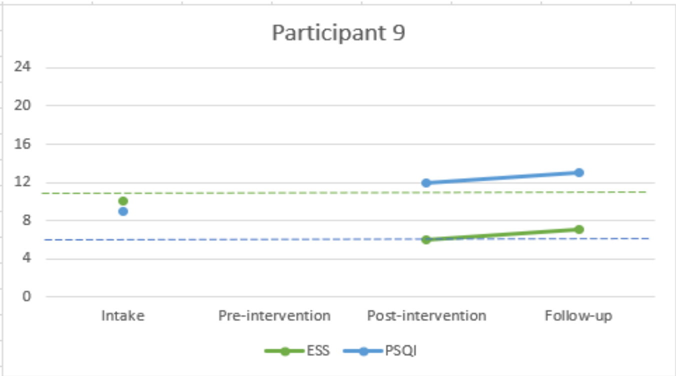


Participant 9:

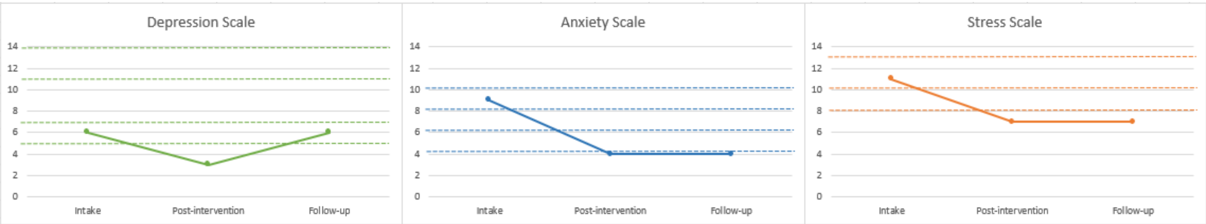
P9's FSS Scores



P9's ESS and PSQI Scores



P9's DASS-21 Scores



Appendix E: Information Sheet and Consent Form

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

PARTICIPANT INFORMATION SHEET

Title of Project: Evaluation of the efficacy of broad-spectrum light therapy in treating fatigue following mild traumatic brain injury.

An invitation

My name is Kate Connolly and I am a doctoral student in the School of Psychology at Massey University. I am inviting you to participate in a research project that I am leading to investigate whether broad-spectrum light therapy is effective in reducing fatigue symptoms experienced as a result of a mild traumatic brain injury (mTBI). This participant information sheet will help you decide if you would like to take part. If you agree to take part in this study, you will be asked to sign a consent form on the last page of this document.

This document is four pages long, including the consent form. Please make sure you have read and understood all the pages.

Overview of this research?

The proposed study leverages off recent evidence that has found light therapy to be helpful in reducing fatigue following brain injuries. However, research to date has focussed more on individuals who have sustained severe TBI and so the question of whether these positive effects will translate to individuals who have incurred minor injuries has not yet been answered.

The purpose of this study is to investigate the relationship between exposure to broad-spectrum light therapy and consequent experiences of fatigue symptoms. To facilitate this investigation, participants will be assigned to one of two groups. The first group will begin light therapy two weeks following baseline fatigue monitoring and introductory questionnaire completion. The second will undergo fatigue monitoring for a further four weeks prior to beginning therapy. It is hoped that splitting participants into these two groups, will allow for a better understanding of any placebo effects relating to entry into the trial. Results from participants in the second group will also aid the understanding of fatigue reduction that might be better accounted for due to the natural passing of time.

Your participation in the study will allow us to gain an understanding of whether the positive outcomes reported in prior research translate to individuals who have incurred a mTBI.

Who is eligible to take part?

We are looking for adult women and men between 19 and 65 years old who have sustained a mTBI (or concussion injury) at least three months prior to recruitment. Additionally, potential participants should have recovered from any obvious cognitive difficulties but will have ongoing symptoms of fatigue that were not present prior to the injury. You should not have performed shift work or travelled more than 3 time zones within the last month.

We will need to recruit a range of volunteers who represent the diversity of people in New Zealand. In other words, we are hoping to recruit participants who range in age, gender and ethnicity.

Exclusion criteria:

Due to the risk of jeopardising our understanding of how light might aid in the reduction of fatigue, we are unable to include participants in this study who are experiencing any other chronic or acute medical or psychiatric illness that might account for fatigue. We are also unable to include participants who perform shift work, have very recently travelled across multiple times zones (i.e. within the last month), or who have current or historic sleep problems such as sleep apnea or restless legs syndrome. We can not consider participants taking any medications which impact on their sleep or waking state or who have a recent history of drug or alcohol abuse. Exclusion criteria are particularly focussed on identification of those individuals whose reported fatigue symptoms might be better understood as having causes secondary to the mTBI itself. You are very welcome to enquire, using the contact details below, to best understand your suitability for this study.

If you participate, what will you need to do?

If you agree to participate then in the first instance you will be invited to meet with a researcher for a screening interview at a location that is most convenient for you. This may be done over the phone or via Zoom to adhere to social distancing requirements. The meeting will not exceed 60 minutes and will involve answering a series of brief questionnaires which will take around 30 minutes. The questionnaires are about your habitual sleep quality, your fatigue symptoms, your daytime sleepiness, your mood and determining whether you are an evening or morning type. You will then receive all study information and instructions for the upcoming weeks. At the end of this initial meeting you will also provide written informed consent. It might be that we cannot include you in further study participation due to our study inclusion criteria. In this case, your personal information will be safely destroyed. Once we can confirm your registration, you will be asked to wear an actigraphy device on your wrist for the duration of the study. This is much like a modern exercise device and will collect detailed information about your sleep and activity during the time you are enrolled in the study.

During the intervention phase itself, you will be asked to use a light therapy lamp daily. This will involve sitting approximately 30 cm from the lamp for 30 minutes within the first two hours of waking. You will need to do this every day for 4 weeks, ideally always at the same time. You will not be required to be looking directly into the light source, but rather have it at a distance at which you can, for example, comfortably read or have breakfast.

Each day you will be asked to very briefly rate how fatigued you are feeling. Additionally, at three time points (which will occur during the intervention phase, and then four weeks after) you will be asked to fill in some further questionnaires which will help to determine whether the treatment has contributed to any positive changes in your experience of mTBI related fatigue. These can be done on a computer, or be paper based if you prefer.

We invite you to request a summary of the research findings by indicating so on the consent form. The summary will be posted or emailed to you at the conclusion of the project.

If you participate, what are the benefits?

Importantly, there will be no cost to you associated with participating in this study. The rest-activity monitor and light therapy devices will be provided to you by the research team to use while enrolled in the study. If you find that the light therapy device has been useful for you, we can provide guidance in how you can obtain your own device at the conclusion of the study.

Additionally, we will offer you a token of our appreciation (koha) at the conclusion of your involvement in this study. This will be a $20 voucher of your choice from either New World or Countdown.

An added benefit of your participation is likely to be the knowledge that you have contributed to our understanding of an intervention for fatigue following mTBI.

If you participate, what are the risks of being involved?

The use of these light therapy devices is deemed to be safe and non-invasive for participants. Previous studies have found a small number of participants reporting mild headaches which may or may not have been experienced as a result of the intervention. We are always available to talk through any concerns with you throughout your enrolment in this study, and if you were to suffer any discomfort using the device, there would be no expectation that you continue in the study.

Your rights

You are under no obligation to participate in this research, and if you decide to participate, you have the right to:

- Decline to answer any particular question;
- Withdraw from the study at any time;
- Ask any questions about the study at any time during participation;
- Provide information on the understanding that your name will not be used;
- Access to information collected about yourself, and the ability to correct this if necessary;
- Be given access to a summary of the project findings when it is concluded with all participants.

If you participate, how will your data be managed and stored?

Data will be stored securely in password protected electronic files or locked filing cabinets until such a time that it is destroyed. We will only use deidentified data for analysis, reporting and publication of the results. Each participant will be given a non-identifiable participant number. Only the research team (see below) will have access to the key which attributes personal data to the participant number. Your personal health information will be kept but access to this will be restricted to the study team (please see below), approved representatives of the Health and Disability Ethics Committee and other regulatory bodies for audit purposes.

Who else is involved in this research?

My research is being conducted under the supervision of Professor Janet Leathem, Associate Professor Mirjam Munch and Dr Stephen Hill at Massey University.

Who should you contact if you have concerns or require further information about the research?

If you have any questions or concerns please contact Project Leader, Kate Connolly via phone, email or text:

Phone:	027 201 3455
Email:	kathryn.connolly.1@uni.massey.ac.nz

If you want to talk to someone who isn't involved with the study, you can contact an independent health and disability advocate on:

Phone:	0800 555 050
Fax:	0800 2 SUPPORT (0800 2787 7678)
Email:	advocacy@advocacy.org.nz
Website:	https://www.advocacy.org.nz/

You can also contact the health and disability ethics committee (HDEC) that approved this study on:

Phone:	0800 4 ETHICS
Email:	hdecs@moh.govt.nz

Yours sincerely, Kate Connolly

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UNIVERSITY OF NEW ZEALAND

PARTICIPANT CONSENT FORM

Title of Project: Evaluation of the efficacy of broad-spectrum light therapy in treating fatigue following mild traumatic brain injury.

This consent form will be held for a period of ten years

I have read the Information Sheet and understand the details of these studies. I have sought explanation about any details of the studies that I do not understand.

I have had time to consider my participation and my questions have been answered to my satisfaction. I understand that I may ask further questions at any time.

I agree to participate in this study under the conditions set out in the Information Sheet. I understand that my participation is voluntary and that I can withdraw myself and any data that has been collected from the study at any time.

I understand that my participation in this study is confidential and that no material, which could identify me personally, will be used in any reports on this study.

I know who to contact if I have any questions about the study in general.

YES NO

I wish to receive a summary of the research when it is completed

YES NO

Postal Address for Summary:

....

.... Postal Code...................

Email address for research summary: ....

Contact phone number: ....

Signature: .... Date: ....

Full Name Printed ....

Appendix F: New Zealand COVID-19 Alert Levels Summary

New Zealand COVID-19 **Alert Levels Summary**

Unite against COVID-19

- The Alert Levels are determined by the Government and specify the public health and social measures to be taken in the fight against COVID-19. Further guidance is available on **Covid19.govt.nz**.
- Different parts of the country may be at different Alert Levels. We can move up and down Alert Levels.
- Services including supermarkets, health services, emergency services, utilities and goods transport will continue to operate at any level. Employers in those sectors must continue to meet health and safety obligations.
- Restrictions are cumulative (for example, at Alert Level 4, all restrictions from Alert Levels 1, 2 and 3 apply).

Updated 27 October 2021

Elimination Strategy — New Zealand is working together to eliminate COVID-19

Alert Level	Risk assessment	**Measures** that can be applied locally or nationally	
4 Lockdown Likely the disease is not contained	• There is sustained and intensive community transmission. • Outbreaks are widespread.	• Stay home in your bubble. • No travel is allowed except for necessities or to undertake safe recreational activities. You must work and learn from home. • No gatherings are allowed. All public and education facilities close. • If you work for an Alert Level 4 business or service and you have no available options for childcare, you can extend your household bubble to include a carer for your children. • Businesses must close except for necessities (e.g. supermarkets, pharmacies, petrol stations) and lifeline utilities. Green grocers, butchers, bakeries, and fishmongers can sell uncooked food items online and must deliver all orders.	• As in Alert Level 2, you legally must wear a face covering in some settings. Refer to the detailed table for more information. It's recommended you wear a face covering whenever you leave the house. • Rationing of supplies and requisitioning of facilities as well as reprioritisation of healthcare services is possible. • Members of a household or shared bubble may view or accompany the deceased in a funeral home, cemetery or faith-based institution subject to strict conditions.
3 Restrict Medium risk of community transmission – active but managed clusters	• There are multiple cases of community transmission. • There are multiple active clusters in multiple regions.	• Stay home and keep your bubble small. You can expand to reconnect with close family/whānau, enable caregiving, or support isolated people. This extended bubble legally must remain exclusive. • Travel is still restricted, so stay local. Inter-regional travel is highly limited with limited permissions. You can travel for work, school, to pick up necessities and good purchased in a contactless way or undertake low-risk recreational activities. Work and learn from home if you can. • Only people who can't work from home should return to businesses that can safely open under Alert Level 3. • You legally must wear a face covering in some settings. Refer to the detailed table for more information. It's recommended you wear a face covering whenever you leave the house. • Gatherings of up to 10 people are allowed for weddings and civil union ceremonies, funerals and tangihanga (exclusive of staff). Up to 5 staff may be present. Physical distancing and record keeping are legally required.	• When you leave home, keep a 2-metre distance from others when in public or 1-metre in controlld environments like workplaces, where practical. • Customers are only allowed inside specific businesses: supermarkets, banks, primary produce retailers, pharmacies, petrol stations or hardware stores providing goods to trade customers, or if it is an emergency or critical situation. • Other businesses can open if they trade in a contactless way. • Public facilities remain closed. Early childhood centres and schools will open for students up to Year 10 for those who can't learn from home. • Healthcare services should use virtual, non-contact consultations where possible. • People at high risk of severe illness, such as older people and those with existing medical conditions, are encouraged to stay at home where possible, and take additional precautions when leaving home. You may choose to work.
2 Reduce Low risk of community transmission within applied area	• There could be limited community transmission. • There are active clusters in more than one region.	• You can connect with friends and whānau in person, socialise in groups and go shopping and travel domestically, if following public health guidance. • You can return to the place where you work or learn but alternative ways of working are still encouraged • Businesses, schools, early learning services, tertiary education providers and public facilities, such as museums, libraries and pools can now all open with additional health measures in place. • Gatherings of up to 100 people in a defined space are allowed including weddings, funerals and tangihanga. Mandatory record keeping (as in Alert Level 1) and physical distancing are legally required. • Hospitality businesses legally must keep groups of customers separated and seated. Physical distancing of 1 metre must be applied – this will determine the maximum capacity of the business. • Event facilities, including cinemas, stadiums, concert venues and casinos can open. Physical distancing of 1 metre must be applied – this will determine the maximum capacity of the event. • You legally must wear a face covering if you are aged 12 and over when: - using public transport, airplanes (including in departure points such as train/bus stations) and in a taxi or ride-share vehicle - visiting a healthcare or aged care facility (other than for a patient) - inside retail businesses, such as supermarkets, pharmacies, shopping malls, indoor marketplaces, takeaway food - stores and public venues – such as museums and libraries - visiting the public areas within courts and tribunals, local and central Government agencies, and social service - providers with customer service counters - providing services while on site in a home or place of residence (except for providing childcare).	• You legally must wear a face covering if you work: - as a driver of a taxi or ride-share vehicle - at close contact businesses, for example barbers, beauticians and hairdressers - in a public facing role at a hospitality venue, for example a cafe, restaurant, bar or nightclub - at retail businesses, such as supermarkets, shopping malls, indoor marketplaces, takeaway food stores - in the public areas of courts and tribunals, local and central Government agencies, and social service providers with customer service counters - at indoor public facilities, for example libraries and museums (but not swimming pools) • Health and disability care services can operate as normally as possible. • Keep 2 metres apart from people you do not know in public and places like retail stores, libraries, gyms, and museums. • Keep 1 metres apart from people in other places like office buildings and factories, and in places where there is a cap on numbers, like cinemas and hospitality. • People at higher risk of severe illness from COVID-19 (for example, those with underlying medical conditions, especially if not well-controlled, and older people) are encouraged to take additional precautions when leaving home, unless fully vaccinated. You may work, if you agree with your employer that you can do so safely. • Sport and recreation activities are allowed, subject to conditions on gatherings, record keeping, and – where practical– physical distancing. Gyms – 2m physical distancing, outdoor teams sport – no physical distancing.
1 Prepare The disease is contained in New Zealand	• COVID-19 is uncontrolled overseas. • There could be sporadic imported cases. • There could be isolated local transmission in New Zealand.	• All businesses, facilities, schools, education providers and workplaces can open. • NZ COVID Tracer QR codes issued by the NZ Government legally must be displayed in workplaces and on public transport. • The following places legally must have systems and processes to ensure visitors keep a record of where they have been (whether via the NZ COVID Tracer app or otherwise), including healthcare facilities, aged care facilities, close-contact businesses, hospitality venues, public facilities, exercise facilities and social gatherings such as weddings, funerals and tangihanga. • In all other places, we encourage you to keep track of everywhere you have been, as this helps contact tracing to identify any potential spread of COVID-19.	• There are no restrictions on personal movement or gatherings. • In all other settings you are encouraged to maintain a record of where you have been. • You legally must wear a face covering if you are aged 12 and over when: - using public transport and airplanes (excluding inter-island ferries and school buses) - exclusions apply for people with disabilities or mental health conditions.

New Zealand COVID-19 Alert Levels Summary Updated 27 October 2021

Appendix G: Research Case Study

Abstract

The current case study opens with a summary of my doctoral research – an intervention trial evaluating the efficacy of light therapy in treating cognitive fatigue following mild traumatic brain injury (mTBI). This includes an overview of the research topic, method and methodology, and evidence that bright light interventions have also shown efficacy in reducing fatigue in more broad clinical populations. Reflections then follow on how my research experience contributed to my clinical practice as an intern psychologist, particularly in my work with clients experiencing fatigue. These reflections include the learned value of prioritising the development of a sound understanding of how fatigue impacts clients during assessment, and also the value of considering the ongoing impacts of fatigue during treatment.

Doctoral Research Overview

The topic of my doctoral research focuses on trialling bright light therapy as an intervention to alleviate or reduce fatigue following mTBI. There are no current evidence-based treatments for fatigue following mTBI, despite this being one of the most commonly reported, enduring, and debilitating symptoms. Fatigue in this population contributes to a decline in quality of life, interference with the ability to work, and exacerbation of problems with social functioning.

The study leverages off recent evidence that found blue light therapy helpful in reducing fatigue following TBIs of varying severities. It is hoped that the intervention trial will bolster the evidence base for light therapy as a treatment for fatigue by testing its efficacy with individuals who have specifically suffered a mTBI, a group largely neglected in prior studies. The study also seeks to trial a more naturally appearing form of light therapy using broad-spectrum polychromatic white light in place of more commonly used blue-enriched light. Participants have been (and continue to be) recruited through concussion clinics in Wellington and New Plymouth, as well as through concussion networks in Waikato. Prior studies have used control groups who are either exposed to a dim light source, or who receive no treatment at all. The current study uses a multiple base line design where participants are allocated either to Group 1, who undertake treatment right away, or Group 2, who undertake treatment after a six week wait. This design allows the measurement of the overall efficacy of light therapy while also providing data to assist our understanding of whether light therapy generates longer lasting benefits in fatigue reduction for participants and whether there are placebo effects accounting for some of the benefit of light therapy during the waitlist phase.

The intention of this study is to add knowledge for non-pharmaceutical approaches to mitigate the symptoms of fatigue following a mTBI. It has the potential to make a tangible difference to people suffering from the debilitating effects of fatigue. If the treatment is found to be effective, this could positively impact many thousands of individuals globally.

Research Questions:

1. The primary objective of the current research is to determine whether daily exposure to bright light is effective in reducing concussion related fatigue symptoms.

Independent variable: Time (baseline, treatment, no treatment)

Dependent variable: Fatigue symptoms (as measured by the Fatigue Severity Scale)

If we can confirm that daily polychromatic bright light exposure is effective in reducing fatigue, this research will also provide further insight into the mechanisms that underlie efficacy. Specifically, secondary objectives aim to answer the following questions:

2. Does bright light exposure reduce daytime sleepiness and/or improve sleep quality in patients with fatigue symptoms?

Independent variable: Time (baseline, treatment, no treatment)

Dependent variables: Sleep Quality (as measured by the Pittsburgh Sleep Quality Index)

3. Does bright light exposure reduce depression, anxiety, and stress?

Independent variable: Time (baseline, treatment, no treatment)

Dependent variables: Anxiety, Depression and Stress (as measured by the DASS-21)

4. Does bright light exposure alter circadian rest-activity cycles?

Independent variable: Time (baseline, treatment, no treatment)

Dependent variables: Objective sleep and activity data (as measured by wrist actigraphy)

Method and Methodology:

The research uses a multiple baseline design. It has been conducted with participants recruited through concussion clinics in Wellington and New Plymouth, as well as participants recruited through the TBI Network in Hamilton. Previous research in this area has used randomised controlled trials (RCT), however RCTs have limitations in their practicality, ethical appropriateness, and cost when evaluating population-based interventions (Hawkins et al, 2007). Like RCTs, the multiple baseline design used in this study can demonstrate whether a measurable change has occurred in the relevant outcome measures, whether the change is a result of the light therapy intervention, and whether the change is statistically significant. The strength of using a multiple baseline controlled trial is that because participants may act as their own controls, fewer participants are required to detect significant differences.

Participants are allocated to either Group 1, who undertake treatment right away, or Group 2, who undertake treatment after a six week wait. Monitoring occurs at three crucial time periods:
Time 1: Baseline measures are recorded for both groups. Group 1 then commences daily light therapy for four weeks. Group 2 receives no therapy during this time.
Time 2: Both groups are retested on all measures at the conclusion of that four weeks and therapy ceases for Group 1 and commences for Group 2.
Time 3: Both groups are retested on all measures. Group 1 will have had four of weeks without light therapy and Group 2 will have just concluded four weeks of light therapy.

This design allows for the measurement of the overall efficacy of light therapy. Data from Group 1 participants will aid the understanding of whether light therapy generates lasting benefits in fatigue reduction and data from Group 2 will pick up the possible waitlist placebo effects - where part of the benefit of light therapy might relate to anticipation of the intervention, or by the natural passing of time.

Participants:

Participants in this study will be adult women and men between 19 and 65 years of age. They must have sustained a mTBI (or concussion injury) at least three months prior to recruitment. They must have cognitively recovered, but will meet the threshold for significant fatigue symptoms based on scores of 4 or more on the Fatigue Severity Scale (FSS). Consistent with the inclusion criteria used in prior studies, scores of 10 or more on the Epworth Sleepiness Scale (ESS) and/or 5 or more on the Pittsburgh Sleep Quality Index (PSQI) will also be considered as inclusion criteria.

Exclusion criteria: Participants are excluded if they report any other chronic or acute medical or psychiatric illness that might account for fatigue; if they have a DASS-21 depression score higher than 14; if they performed recent shift work or travelled across multiple times zones; if they have current or historic of sleep problems such as sleep apnea or restless legs syndrome; if they are currently using sleep or sleepiness affecting medications.[14] Further exclusion criteria are cataracts, glaucoma and other eye diseases as well as known pregnancy in women, migraine and photophobia (hypersensitivity to light). Exclusion criteria are particularly focussed on identification of those individuals whose reported fatigue symptoms are likely better understood as having causes secondary to the mTBI itself. Participants are also excluded if pre-assessment scores indicate that *malingering*, factitious disorder, or somatic disorder is a possible cause of fatigue.

Recruitment strategy:

Participants are recruited through concussion clinics in Wellington and New Plymouth, and the TBI Network in Hamilton. There is a possibility that catchment areas could be extended depending on availability of sufficient numbers of participants.

Sample Size and Statistical Analysis:

In order to balance what is feasibly achievable within the time and resource constraints of the current study with the need to obtain sufficient participant data to conduct meaningful statistical analyses, 20 participants will be recruited. Both the Sinclair et al. (2014) and

[14] Sleepiness affecting medications are considered on a case-by-case basis due to their common use in this population. If the dosage is stable and the effects are not deemed significant to the integrity of the study, participants have been able to continue with the intervention.

Quera Salva et al. (2019) studies were conducted using randomized controlled trial study designs with sample sizes of 10 in the light therapy group, and 10 the no treatment control group (Sinclair et al. also had an additional 10 participants in a placebo light control group). Because multiple-baseline research allows for evaluation of data obtained from a small number of participants who act as their own controls (Hawkins et al., 2007), the reported limitations due to small sample sizes in prior studies provide rationale for adopting a multiple-baseline design for the current study.

The data analysis strategy will involve visual inspection of time-series graphs, modified Brinley plots, and complementary statistical analyses. Visual analysis has traditionally been the primary method of multiple-baseline data analysis (Wolfe et al., 2019). One of the advantages of using this form of analysis is that data points can be plotted to show not only whether change is statistically significant, but also whether outcomes have clinical significance. In other words, would we expect the reduction in FSS scores to be noticed by participants and to reflect a positive outcome in terms of their quality of life?

Efficacy of Light Therapy for Fatigue Reduction in Other Populations:

The first use of light therapy in psychology was shown to have a significant antidepressant effect on individuals with seasonal affective disorder (James, Wehr, Sack, Parry & Rosenthal, 1985). More recently, evidence has also been found for its efficacy in treating non-seasonal depression (Lam et al. 2016). Relevant to the current study, light therapy devices have long been commercially marketed as being useful in alleviating fatigue resulting from shift work and jet lag. Research has shown that timed exposure to light can help resetting circadian rhythms in individuals and alleviate symptoms of fatigue due to shift work (Griepentrog, Labiner, Gunn & Rosengart, 2018) and jet lag (Bin, Postnova & Cistulli, 2019).

Perhaps more pertinent to my research, light therapy has been trialled in other clinical populations such as with individuals who have Parkinson's disease (PD) and varying types of cancer. Alterations to the circadian system are increasingly recognised in the manifestations of PD and this determines the rationale underlying the use of light therapy to improve symptoms such as insomnia, fatigue, motor function and mood (Fifel & Videnovic, 2019). The outcome of some studies suggests that there are significant reductions of PD-related excessive daytime sleepiness (Videnovic et al., 2017; Willis & Freelance, 2018). An interesting finding from these studies was that there was a greater benefit for participants with more extreme difficulties with excessive daytime sleepiness (Raymackers et al., 2019) and highlights the importance of considering the severity of fatigue in the analysis of my current study – which may yield similar results.

Light therapy has also shown preliminary efficacy in reducing cancer-related fatigue (CRF), a prevalent symptom that is reported to occur with up to one third of survivors of cancer treatments (Johnson et al., 2018). Specific to CRF, light therapy has been shown to be beneficial both in preventing the worsening of fatigue during chemotherapy (Ancoli-Israel, 2012) and in reducing fatigue symptoms post-treatment (Redd et al, 2014; Johnson et al., 2018). As is the case with mTBI, there are no current evidence-based standard treatments for CRF and whilst other non-pharmacological interventions such as exercise and cognitive behavioural therapy (CBT) show promise for some individuals, they are not without limitation. A recent study evaluating the impact of physical exercise to reduce fatigue post-TBI reported a high drop out rate (30%) of participants in their study, indicating that this type of intervention may not be realistically achievable for all individuals (Kolakowsky-Hayner et al., 2017). For example, if motivation is reduced by the experience of fatigue, one advantage of using light therapy is its low behavioural demand relative to exercise and CBT (Johnson et al., 2018).

Reflections

The experience of embarking on my research has provided me with the opportunity to gain focussed knowledge across all aspects of fatigue. Additionally, my interactions with participants over extended periods of time has allowed me to gain valuable insight into the experiences and impacts of fatigue on an individual's quality of life. This knowledge, alongside the insights and practical experience gained through working alongside research participants, has enhanced my ability to work with clients during my internship. While it is expected that intern psychologists would be aware of, and attuned to, the co-occurrence of fatigue within varied clinical presentations, I believe that the depth of my understanding in this area has been beneficial to my clients. Where I have felt it is clinically appropriate, I have been able to share some of the knowledge I have gained relating to the impact of light on the presence and severity of fatigue with clients. This has been helpful in many respects, and I will expand on two of those that I think are particularly relevant.

Firstly, many clients I have worked with who experience difficulties with low mood and/or anxiety report difficulties with their sleep. This may be difficulty with sleep onset, difficulty maintaining sleep, or early morning waking. Whatever the specifics of their presentation may be, knowing what I do about the effects of light on the sleep/wake cycle has attuned me to focus on a functional analysis of sleep during initial assessments. This includes gaining an understanding of what they do prior to attempting to sleep and also what they do when they wake. Many of my clients reported experiencing frustration when they are not able to sleep, and this leads to the negative rumination that we know maintains their difficulties. However, I have also found that in an attempt to distract themselves from these frustrations and negative thoughts, many clients will pick up their phone and scroll social media, watch video content, or read news/blog articles. Many clients also report using their phones, tablets, or computers just prior to attempting to sleep. While I believe it is commonly understood that blue light emissions from screens are disruptive to sleep, I have found it helpful to be able to formulate sleep problems using my evidence-based knowledge to better understand the impact of screen use. I have found that this approach is helpful to build the required motivation with clients to change some of these behaviours. I can think of two clients in particular who had previously understood screen use to be beneficial in helping reduce stress and frustration relating to sleep difficulty (both thought it was helpful in allowing them to eventually resume sleep) but were able to shift their understanding and acknowledge that it may be (at least in part) maintaining their difficulties over the longer term. Knowledge and understanding provided these particular clients with the motivation to experiment with reducing screen use and I believe that this positively contributed to significant improvement with sleep.

Secondly, while light is known to negatively impact sleep when used in the later part of the day or through the night, my research has also allowed me to develop a sound understanding of the positive impact of light in the earlier stages of the day. For clients presenting with fatigue, I therefore will query how much light exposure they get day-to-day. For some clients who may work long hours in an enclosed office, or who may be homebound due to other presenting difficulties (such as low mood or social anxiety for example), I have found it useful to share the research-based evidence to emphasise the benefit of ensuring some daily exposure to natural light. In the case of clients who do not get frequent light exposure due to social withdrawal, motivation to prioritise getting outside can have additional benefits. For example, providing them with the opportunity to reconnect with nature and/or to make positive connections with others which positively correlates with improvements in mood. In the case of clients who have restricted natural light exposure due to working long hours, motivating them to take some time in the day to get outside can have the additional benefit of reducing stress and the related risk of burnout.

As well as informing my assessment processes, the knowledge that my research has provided me with has also informed my treatment approach with clients. I have developed a sound understanding of the impact fatigue has across many domains of a person's life. Regardless of whether the precipitant to fatigue relates to mTBI, persistent sleep difficulties, mood, anxiety, or other causes, the impact of it requires consideration during treatment. For example, it has been useful to acknowledge and empathise with a client's experience of fatigue and the related likelihood that it can produce additional barriers to engaging in homework outside of scheduled appointments. Knowing that a reduction in fatigue can positively impact other domains such as mood and cognition has also been useful in helping develop motivation with clients to make positive changes. Working from a CBT framework, we know that positive change in thoughts and perceptions positively influences the way we feel and behave, and by reducing fatigue it is often a natural consequence that distorted or unhelpful thinking tendencies also reduce.

In summary, I believe that the experiences and knowledge I have gained through my research have enhanced my clinical practice. Writing this case study required me to spend time focussing on the lessons I learned (and continue to learn) in my research and internship. In doing so, I have been able to better appreciate just how much the two overlap. In many respects they positively benefit each other; my clinical work is strengthened by my knowledge of the mechanisms and impacts of fatigue, and my research is strengthened by my client work in the sense that I can now better appreciate varying presentations of fatigue and the impact that is has on a person's wellbeing more generally.

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Appendix G: Descriptive statistics

Descriptive Statistics: Correlations between Measures at Timepoints 1-4, from Spearman's correlations (rho).

Time 1 :

	FSS	*FSS Global*	*PSQI*	*ESS*	*DASS_D*	*DASS_A*	*DASS_S*
FSS	1.000						
FSS Global	0.575	1.000					
PSQI	0.446	0.403	1.000				
ESS	-0.053	0.338	0.028	1.000			
DASS_D	0.150	0.326	0.162	-0.306	1.000		
DASS_A	-0.383	0.058	-0.192	-0.035	0.738	1.000	
DASS_S	-0.019	0.425	0.454	-0.067	0.487	0.502	1.000

Time 2: Pre-intervention

	FSS	*FSS Global*	*PSQI*	*ESS*	*DASS_D*	*DASS_A*	*DASS_S*
FSS	1.000						
FSS Global	0.728	1.000					
PSQI	0.036	-0.122	1.000				
ESS	0.338	0.574	-0.102	1.000			
DASS_D	0.507	0.498	-0.019	-0.253	1.000		
DASS_A	0.216	0.112	-0.463	-0.098	0.657	1.000	
DASS_S	0.037	-0.179	0.438	-0.336	0.569	0.514	1.000

Time 3: Immediately post-intervention

	FSS	*FSS Global*	*PSQI*	*ESS*	*DASS_D*	*DASS_A*	*DASS_S*
FSS	1.000						
FSS Global	0.283	1.000					
PSQI	-0.030	0.143	1.000				
ESS	0.408	0.700	0.279	1.000			
DASS_D	-0.328	0.450	0.045	-0.281	1.000		
DASS_A	0.028	0.071	0.255	-0.004	0.124	1.000	
DASS_S	-0.115	0.444	0.347	-0.030	0.683	0.455	1.000

Time 4: Post follow-up

	FSS	*FSS Global*	*PSQI*	*ESS*	*DASS_D*	*DASS_A*	*DASS_S*
FSS	1.000						
FSS Global	0.809	1.000					
PSQI	-0.206	0.029	1.000				
ESS	0.508	0.805	0.454	1.000			
DASS_D	-0.552	-0.155	0.334	-0.113	1.000		
DASS_A	-0.558	-0.051	0.368	0.229	0.471	1.000	
DASS_S	-0.410	0.022	0.270	0.047	0.873	0.650	1.000

All

	FSS	*FSS Global*	*PSQI*	*ESS*	*DASS_D*	*DASS_A*	*DASS_S*
FSS	1.000						
FSS Global	0.519	1.000					
PSQI	0.074	0.170	1.000				
ESS	0.311	0.583	0.157	1.000			
DASS_D	-0.135	0.313	0.138	-0.252	1.000		
DASS_A	-0.057	0.145	-0.039	0.023	0.511	1.000	
DASS_S	-0.015	0.297	0.408	-0.068	0.569	0.554	1.000