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Thesis, COLLÉGIALITÉ

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Faculté : Faculté de Médecine
Diplôme : Master en sciences biomédicales, à finalité approfondie
Année académique : 2023-2024
URI/URL : http://hdl.handle.net/2268.2/19816

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The impact of mental fatigue on cognitive performance in young healthy adults.

Thesis conducted under the direction of Madame Fabienne Collette and presented for the purpose of obtaining the master's degree in biomedical sciences, with a specialization in advanced studies.

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Academic years 2023-2024

Acknowledgements

I would like to thank Professor Fabienne Collette for allowing me to undertake this dissertation and explore the theme of mental fatigue within the Cyclotron.

I also want to express my gratitude to Maëlle Charonitis for her supervision throughout this dissertation. Her availability and explanations have been very helpful in the completion of this work.

My thanks also go to the interns who were there during my journey at the Cyclotron, especially Elisa Balthasart and Anais Gillet for their support and encouragement.

I am deeply grateful to my friends from the biomedical field, Alexandra Pirnay, Tatiana Rouschop, and Emilie Laverdeur, for their guidance, support, and invaluable advice throughout this process.

Finally, I would not have been able to accomplish this work without my friends, my boyfriend, and my family, who have supported me throughout this journey.

Abbreviation

ACC - Anterior Cingulate Cortex
ASP - Average Sleep Propensity
AX-CPT - A-X Continuous Performance Test
C - Criterion
CNS - Central Nervous System
DA - Dopamine
d' - Perceptual Sensitivity
EEG - Electroencephalography
ESS - Epworth Sleepiness Scale
FA - False Alarms
fMRI - Functional Magnetic Resonance Imaging
FSS - Fatigue Severity Scale
GABA - Gamma-Aminobutyric Acid
HCL - High Cognitive Load
HR - Hit Rate
LCL - Low Cognitive Load
MEG - Magnetoencephalography
mPFC - Medial Prefrontal Cortex
MSLT - Multiple Sleep Latency Test
MWT - Maintenance of Wakefulness Test
PET - Positron Emission Tomography
PSQI - Pittsburgh Sleep Quality Index
RT - Reaction Time
STD - Stimulus Time Duration
TLDB - Time Load Dual Back
ToT - Time-on-Task
VAS-f - Visual Analogue Scale for Fatigue
5-HT - Serotonin (5-Hydroxytryptamine)

Abstract

Introduction : La fatigue mentale est un problème omniprésent affectant la performance cognitive, mais ses mécanismes sous-jacents et les méthodes de mesures efficaces restent insuffisamment compris. Cette étude vise à examiner les effets de la charge cognitive (élevée vs faible) et de la durée de la tâche (16 minutes vs 32 minutes) sur la fatigue mentale chez de jeunes adultes en bonne santé avec la tâche Time Load Dual Back (TLDB).

Méthodes : Les participants ont été divisés en trois groupes en fonction de la modalité de la tâche : Groupe 1 (faible charge cognitive, tâche de 16 minutes), Groupe 2 (faible charge cognitive, tâche de 32 minutes) et Groupe 3 (charge cognitive élevée, tâche de 32 minutes). Les mesures objectives de performance (précision, temps de réaction, métriques de la théorie de la détection du signal) et les niveaux subjectifs de fatigue (mesurés via l'Échelle Analogique Visuelle de la fatigue, VAS-f) ont été enregistrés avant et après la tâche. L'impact de la durée de la tâche et de la charge cognitive sur ces mesures ont été analysés à travers les groupes à l'aide de méthodes statistiques. Dans le but d'évaluer l'impact d'une période entre le début et la fin des tâches, les deltas des scores des mesures ont été calculés. L'évaluation de la durée et de la charge de travail ont été effectuées par des tests t pour échantillons indépendants. Les analyses pour les mesures subjectives (VAS-f) ont été réalisées avec une ANOVA à mesures répétées suivies de test post-hoc pour analyser les différences entre les groupes. Pour la corrélation des mesures objectives et subjectives, les corrélations de Pearson ont été utilisées.

Résultats : Concernant l'analyse sur l'effet de la modulation de la durée de la tâche sur la performance, l'évolution des temps de réaction lors de la tâche était significativement différente entre les groupes. Une durée de tâche plus courte était associée à un temps de réaction plus rapide. Pour l'évolution de la performance établie à partir de la charge de travail, des différences significatives ont été observées entre la haute charge de travail et la basse. Une précision diminuée, ainsi qu'une moins grande sensibilité et réponse libérale ont été associées avec la charge de travail basse. De plus, le temps de réaction était plus conséquent avec la charge de travail basse. Les mesures utilisant le VAS-f ont montré une hausse significative des scores entre avant et après la tâche pour la durée et les analyses de charge de travail, avec une interaction significative entre le temps et le groupe pour la haute charge de travail. Cependant, il n'y avait aucun résultat significatif concernant les conditions des groupes. Les analyses de corrélation pour la durée de la tâche n'ont montré aucune corrélation significative entre la performance cognitive et le VAS. Pour la haute charge de travail, une corrélation négative significative a été trouvée entre l'évolution de la précision et le VAS.

Conclusion : L'étude confirme que la charge cognitive est un déterminant clé de la fatigue mentale. Des charges plus élevées entraînant des déclins plus prononcés de la performance cognitive et une corrélation avec la précision de la tâche et la sensation de fatigue. La durée de la tâche n'a pas montré de différences significatives entre une courte et une longue durée. La tâche TLDB est validée comme un outil efficace pour induire et mesurer la fatigue mentale chez les jeunes adultes en bonne santé, à l'exception du temps de réaction qui a montré des résultats contradictoires. Les recherches futures devraient explorer davantage de mesures physiologiques et subjectives pour élucider les mécanismes sous-jacents de la fatigue cognitive.

Abstract

Introduction: Mental fatigue is a pervasive problem affecting cognitive performance, but its underlying mechanisms and effective measurement methods remain insufficiently understood. This study aims to examine the effects of cognitive load (high vs. low) and task duration (16 minutes vs. 32 minutes) on mental fatigue in healthy young adults using the Time Load Dual Back (TLDB) task.

Methods: Participants were divided into three groups based on task modality: Group 1 (low cognitive load, 16-minute task), Group 2 (low cognitive load, 32-minute task), and Group 3 (high cognitive load, 32-minute task). Objective performance measures (accuracy, reaction time, signal detection theory metrics) and subjective fatigue levels (measured via the Visual Analogue Scale of fatigue, VAS-f) were recorded before and after the task. The impact of task duration and cognitive load on these measures were analysed across groups using statistical methods. The deltas of the measurement scores were calculated to evaluate the impact of the time between the start and end of the task. Evaluation of task duration and workload were performed using t-tests for independent samples. Analyses for subjective measures (VAS-f) were performed using repeated measures ANOVA followed by post-hoc tests to analyse the differences between the groups. Pearson correlations were used to correlate objective and subjective measures.

Results: Regarding the analysis of the effect of task duration modulation on performance, changes in reaction times during the task were significantly different between groups. The shorter task duration was associated with faster reaction times. For performance changes based on workload, significant differences were observed between the high and low workload. Lower accuracy, as well as lower sensitivity and liberal response, were associated with the high workload. Reaction time was more significant in the long-duration, low-workload group. Measurements using the VAS-f showed a significant increase in scores between before and after the task for duration and workload analyses, with a significant interaction between time and group for the high workload. However, there were no significant results regarding group conditions. Correlation analyses for task duration showed no significant correlation between cognitive performance and VAS-f. Significant negative correlations were found for high workload between changes in accuracy and VAS-f.

Conclusion: The study confirms that cognitive load is a key determinant of mental fatigue, with a higher workload leading to more pronounced declines in cognitive performance and a correlation with task accuracy and fatigue sensation. Task duration did not show significant differences between short and long durations. The TLDB task is validated as an effective tool for inducing and measuring mental fatigue in healthy young adults, except for reaction time, which showed contradictory results. Future research should explore more physiological and subjective measures to elucidate the underlying mechanisms of cognitive fatigue.

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I. Introduction

A. Definition of fatigue

Fatigue has been recognized for decades, the first mentions of it appeared in patients' reports late 19th century in medical literature (Penner & Paul, 2017). Everyone knows what fatigue is. However, when you ask to describe fatigue, it can widely be different from one another. It can range from tiredness to exhaustion. Fatigue has many concepts, depending on the individual and the background. It is a symptom quite difficult to define, evaluate, and treat. The issue is that fatigue is one of the most present symptoms in all the medicine, such as infectious disorders, cancer, and autoimmune conditions like multiple sclerosis (Krupp, 2003).

Fatigue, regardless of the underlying disorder, significantly impacts patient functioning, daily activities, quality of life, employment, and psychological well-being. The effects extend beyond the patient to their family members as well (Krupp, 2003). Fatigue can have consequences such as road accidents, a decrease in motivation and productivity in daily life or at work, in addition to depression or burnout (Jacquet et al., 2021). Roughly 20 to 30 percent of fatal crashes in the general population are believed to be influenced by fatigue, according to estimates (Saxby et al., 2008). There is a high prevalence rate of fatigue in the population, with research demonstrating a prevalence rate of 18% in a United-Kingdom sample (Pigeon et al., 2003). Despite the high prevalence and significant impact of fatigue, both healthcare providers and patients often do not give it sufficient attention. In a study involving over 1,300 cancer patients, 58% reported feeling "somewhat fatigued" or "very much fatigued," yet only 52% of those had discussed it with their hospital physician, and a mere 14% had received treatment or advice for their fatigue (Krupp, 2003).

The difficulty is also in distinguishing the "normal" or "pathological" level of fatigue. Normal fatigue could be described as a natural response to challenges and can be characterized as predictable and that could be resolved by resting. On the other side, unhealthy fatigue, also mentioned as chronic fatigue can be marked by prolonged duration, with severe impact on daily life, and can be associated with other symptoms. Thus, unhealthy fatigue could be described as a maladaptive and exaggerated expression of the same physiological response as "normal" fatigue (Raizen et al., 2023).

Healthcare providers face the challenge of identifying and appropriately treating fatigue. As said before, this is particularly difficult because many healthy individuals also experience fatigue at various times. Research indicates that about 20% of the general population experiences fatigue. The terminology used to describe fatigue varies widely, adding to the challenge of proper identification and treatment (Krupp, 2003).

Fatigue can be defined as an overwhelming feeling of exhaustion and tiredness (Penner & Paul, 2017). Fatigue can take the form of two distinct constructs: (a) physical fatigue and (b) mental fatigue. Physical fatigue is characterized by the depletion of the body, as perceived or measured in a physical sense, such as a decrease in voluntary muscle activation (Dotan et al., 2021). Mental fatigue can be a psychobiological state that follows intense and/or prolonged periods of demanding cognitive tasks and can be described by a subjective sensation of lack of energy and tiredness (Jacquet et al., 2021). There are multiple definitions for mental fatigue and fatigue in general, but the definition cited just before is more suitable to explain the fatigue involved in our study.

It is crucial to differentiate the two domains, since they might depend on different mechanisms or relate to different symptoms (Penner et al., 2009). However, the two domains could interact with each other but the effect of one another is still debated (Macaron et al., 2020). In this present thesis, we will mainly focus on the mental fatigue concept, for which literature lacks clarity. Before going deeper into mental fatigue, the origins, and causes of fatigue should be discussed.

B. Neurobiological origins of fatigue

While there isn't a single, universally agreed-upon definition or conceptual framework for fatigue, recent studies differentiate between peripheral and central fatigue. Peripheral fatigue is linked to identifiable causes like neuromuscular transmission issues, metabolic problems, muscle membrane defects, or failures in peripheral circulation. On the other hand, central fatigue is described as a decline in the ability to maintain attention, necessitating self-motivation to enhance performance (Holtzer et al., 2010).

To go deeper into central fatigue, more about the central nervous system fatigue should be discussed.

Central Nervous System (CNS) fatigue is a complex phenomenon influenced by various biochemical changes within the brain, notably involving neurotransmitters such as serotonin, dopamine, glutamate, and Gamma-aminobutyric acid (GABA) (Tornero-Aguilera et al., 2022).

Serotonin

This neurotransmitter's accumulation in the extracellular space during exercise is linked to feelings of lethargy and a decrease in neural drive, contributing significantly to the sensation of central fatigue. The serotonin/dopamine balance is crucial; increased serotonergic activity, particularly during intense exercise, can lead to diminished motor unit recruitment and performance decline (Tornero-Aguilera et al., 2022).

Dopamine

Dopamine plays a pivotal role in motivation and reward systems. Its secretion during physical activity is associated with delaying fatigue and exhaustion. Exercise can enhance dopamine transmission, which may mitigate central fatigue by promoting continued motor cortex stimulation. However, a reduction in dopamine secretion, particularly from areas like the substantia nigra, could impair basal ganglia activation, contributing to central fatigue onset (Tornero-Aguilera et al., 2022).

Glutamate

As the primary excitatory neurotransmitter, glutamate is involved in maintaining action potential velocity in neurons and muscle fibre activation. Changes in glutamate levels, particularly a decline in its clearance from the extracellular space, can affect the CNS's ability to sustain prolonged motor tasks. Glutamate homeostasis disruption is linked to alterations in neural excitability and may contribute to central fatigue (Tornero-Aguilera et al., 2022).

Gamma-aminobutyric acid (GABA)

GABA, the main inhibitory neurotransmitter in the brain, plays a role in modulating exercise-induced fatigue. Increased GABA concentration, particularly after high-intensity training, correlates with elevated blood lactate levels. This suggests a metabolic link between exercise, lactate accumulation, and GABAergic activity, influencing the perception and development of CNS fatigue (Tornero-Aguilera et al., 2022).

Central fatigue results from a combination of decreased voluntary muscle activation, reduced motor neuron frequency and synchronization, and a lower motor drive from the cortex. These factors are intricately linked to the biochemical changes in neurotransmitter levels and activity. The dynamic interplay between excitatory and inhibitory signals, influenced by serotonin, dopamine, glutamate, and GABA, forms the basis of central fatigue, impacting both physical performance and cognitive function (Tornero-Aguilera et al., 2022).

C. Neural mechanisms

The neural mechanisms are still not fully comprehended, as mental fatigue is a very complex phenomenon. It has been suggested that mental fatigue involves variation in the brain area including the anterior cingulate cortex (ACC) which is at the interface between emotion, cognition, and motor control (Jacquet et al., 2021).

Studies suggest that continuous exposure to tasks requiring significant mental effort would correspond with an increase in brain activity over time to maintain consistent performance. This trend of increasing brain activity over time underscores the role of the frontal areas in sustaining performance under heavy cognitive demands, potentially leading to cognitive fatigue. The frontal areas are known for their crucial role in using information to guide behaviour and in integrating signals related to reward anticipation (Borragán et al., 2019).

In the context of cognitive neuroscience, understanding the intricate mechanisms of mental fatigue, reward anticipation, cost-benefit analysis, and the role of dopamine in the brain provides a comprehensive insight into how our cognitive and motivational systems interact during decision-making processes. Central to the discussion is the Motivated Control Model, which integrates cognitive resources and compensatory effort to maintain performance under demanding conditions (Kok, 2022). This model underscores the significance of reward-based decision-making, as supported by neuroscience studies, in understanding fatigue. A distributed hierarchical neural network involving the frontal lobes, amygdala, basal ganglia, and dopamine (DA) system mediates effort-based decision processes, elucidating the complex interplay between cognitive demands and motivational drivers. Significantly, dopamine pathways emerge as crucial mediators in this framework, with DA's role extending even beyond neurotransmission to influencing cognitive and motivational dynamics. Dopamine levels in the brain modulate the balance between cost (effort) and benefit (reward), directly impacting our willingness to endure fatigue to achieve goals. The frontal cortex, particularly the medial prefrontal cortex (mPFC), integrates these considerations, calculating the net motivation value of stimuli and determining the course of action. These networks' functionality are crucial for understanding how mental fatigue impacts and is influenced by the cognitive processes governing decision-making (Kok, 2022).

More research has been done on the neural mechanism underlying mental fatigue using neuroimaging, behavioural, and electrophysiological techniques. Three systems have been described regarding mental fatigue, including the facilitation system, the inhibition system, and the dual regulation system (Ishii et al., 2014).

Facilitation System

The facilitation system refers to a neural network that responds to the mental workload by trying to maintain cognitive task performance when we experience mental fatigue. This network includes the thalamus, frontal cortex, and other regions. It gets activated by motivational inputs and compensates for the effects of mental fatigue, although its excessive activation may lead to further fatigue (Ishii et al., 2014).

Inhibition System

On the other side, the inhibition system can impair cognitive performance, and it's thought to be activated during low-demand tasks that are not engaging. This system includes areas like the insular cortex and the posterior cingulate cortex. It functions to limit task performance, possibly as a way to conserve resources or to signal a need for rest (Ishii et al., 2014).

Dual Regulation System

The dual regulation system combines both the facilitation and inhibition systems. It proposes that cognitive task performance is managed by a balance between these two systems. Mental workload triggers both systems: the facilitation system tries to maintain or enhance performance, while the inhibition system works to impair it. Chronic mental fatigue may result from the dysfunction of the facilitation system due to energy metabolism issues or from an overactive inhibition system (Ishii et al., 2014).

In essence, our brains have these two systems to regulate how we perform tasks when tired: one that tries to keep us going and another that holds us back to prevent overexertion. Understanding how they work together gives us a clearer picture of why we experience mental fatigue and how it affects our cognitive functions (Ishii et al., 2014).

D. Effects and causes of fatigue

As mentioned, overusing and utilizing the brain's resources results partly in mental fatigue. This fatigue can be followed by a diminishing of the ability of the brain to perform cognitive workloads efficiently. Fatigue can mostly be followed by a feeling of discomfort, a decline in motivation, and a need to rest (Ishii et al., 2014). Therefore, because of mental fatigue, both cognitive performance and physical can be reduced with accumulative decreases in productivity and increases in errors (O'Keeffe et al., 2020). There are few theories explaining the causes of fatigue in healthy subjects.

Central Governor Theory

This theory suggests that fatigue is a regulatory mechanism settled by the brain to protect the body from damage and avoid over-exertion. Therefore, the brain could be considered as the central governor, limiting physical performance through the subjective feeling of fatigue, thus preventing any harm. The Integrative Governor theory posits that central and peripheral fatigue function together, governed by both psychological and physiological needs that adhere to principles of homeostasis. This theory suggests that the activity level of each aspect is controlled by a dynamic negative feedback mechanism, serving as the primary operational regulator (Tornero-Aguilera et al., 2022). The central governor model is mainly based on the physiological aspect to examine the exercise performance regulation and the limits to what humans can do. However, the psychological aspect is neglected in this model (Smirmaul et al., 2013).

Psychobiological Theory

This theory integrates psychological and biological factors to explain fatigue. It suggests that fatigue is influenced by both physiological signals from the body (like muscle pH, temperature, and energy levels) and psychological factors (such as motivation, perception of effort, and mental stress). The Psychobiological model, based on Brehm's Motivational Intensity Theory, explores how potential motivation and motivation intensity influence exercise engagement and disengagement (Smirmaul et al., 2013). Potential motivation represents the maximum effort a person is willing to exert, while motivation intensity is the actual effort expended. According to the theory, individuals continue to exert effort in a task until they reach their potential motivation level or deem the task impossible. In this context, exhaustion during exercise is viewed as task disengagement when effort perception meets the critical threshold of potential motivation or when the individual believes further effort is physically impossible. The model suggests that increasing potential motivation or reducing the perception of effort (how hard and heavy a task feels) can enhance exercise tolerance. Factors influencing the perception of effort, like physiological and environmental conditions, indirectly affect exercise tolerance. The theory holds that even with increasing muscle fatigue, central motor command rises to maintain effort, leading to a heightened perception of effort and approaching exhaustion. Studies indicate that both physical conditions like muscle fatigue and mental states like mental fatigue can significantly influence performance and perception of effort, further validating the role of psychobiological factors in exercise performance and endurance (Smirmaul et al., 2013).

Energy Conservation Theory

According to this theory, also called energy depletion, fatigue is a signal from the body to conserve energy for essential bodily functions. It's based on the idea that energy resources are finite, and the body prioritizes their use to maintain homeostasis. Therefore, a highly demanding task will eventually lead to increased use of energy, thus to the decrease in resource availability. When the resources are highly lowered, fatigue will rise, and performance will be impacted (Torres-Harding & Jason, 2005). This theory has been judged to be a bit too simplistic, since such a complete lack of resources has never appeared in this state. However, it should be noted that brain metabolism does change a little due to effort. It could suggest that some other mechanism would compensate and that fatigue could be a consequence of the increased labour provided to keep a consistent performance (Hockey, 2013).

Neurochemical Theory

This theory focuses on the role of neurotransmitters and other neurochemicals in the sensation of fatigue. Imbalances or changes in the levels of serotonin, dopamine, and other neurochemicals in the brain are thought to influence feelings of tiredness and exhaustion. A few of these neurochemicals were already discussed earlier. Two of these theories are the serotonin hypothesis and the 5-hydroxytryptamine-dopamine interaction effects (McMorris et al., 2018).

Regarding the serotonin hypothesis, it suggests that serotonin, also called neuromodulator 5-hydroxytryptamine (5-HT), which is made by the precursor tryptophan could be the reason for the fatigue during exercise. Tryptophan more easily goes through the blood-brain barrier during exercises due to a rise in the levels of free tryptophan. The tryptophan, in the brain, is converted into serotonin in the raphe nuclei, which is thought to increase during exercise, causing a higher serotonin level and thus could contribute to fatigue. However, in human studies compared to animal studies, this process results were inconsistent, but dietary changes were observed including branched-chain amino acids increased. The branched-chain amino acids compete with the serotonin for the transport into the brain. It could be suggested that it may impact fatigue and therefore there could be a complex link between different neurotransmitters in fluctuating fatigue (McMorris et al., 2018).

The 5-hydroxytryptamine-dopamine interaction effects suggest that the ratio of dopamine (DA) to serotonin (5-HT) in the brain impacts fatigue and performance. A low ratio is suggested to enhance performance; however, a high ratio could decrease motivation, arousal, and motor coordination, which could cause central fatigue. However, regarding this hypothesis, the relation between DA and 5-HT is debatable as some studies found contradictory results about the role of dopamine at exhaustion. The interaction between the two neurochemicals could be influenced by many neurotransmitter receptors, which might either inhibit or stimulate DA release in various brain regions (McMorris et al., 2018).

Attentional Focus Theory

From a psychological perspective, this theory suggests that fatigue arises when the brain's capacity to maintain focused attention on tasks diminishes. It's associated with cognitive fatigue rather than physical tiredness. It was suggested that attentional theory has three different levels, one being the level of performance regarding the capacity to manage more than one task at a time. Another level concerns the subjective experience, therefore making a difference between conscious from unconscious events. Even if this distinction can be well-defined, such comprehension could not allow us to know how to time-share two complex skills. The last level is the correlation between the neural systems that cover this and the aspects of conscious attention (Posner, 1982).

E. Sleepiness and boredom

The concept of fatigue has previously been confused with other concepts such as boredom and sleepiness in the literature. It is important to differentiate between all of them as they are distinct concepts with different consequences, though they may share some similar symptoms.

Sleepiness is a widespread experience, not only manifesting as a symptom in various medical, psychiatric, and primary sleep disorders, but also as a normal physiological state encountered by most people at some point during any given 24-hour cycle. Compared to fatigue, there is a definition that is mostly accepted by the literature. Sleepiness is the tendency of someone to fall asleep, also refer as sleep propensity (Shen et al., 2006). There are subjective and objective measures to assess sleepiness. Some examples of objective measurements include the Multiple Sleep Latency Test (MSLT) and the Maintenance of Wakefulness Test (MWT). For MSLT, the sleep latency is measured using standard electrophysiological methods and is defined as the time from lights out to the first stage of sleep. The major goal of the MWT is to examine the strength of the arousal system (Shahid et al., 2010). There are many subjective measures of sleepiness scales (Shahid et al., 2010). A widely used test to measure sleepiness is the Epworth Sleepiness Scale (ESS), which will be further explained in the method section (Shen et al., 2006).

On the other hand, fatigue, which has already been defined earlier, can be induced by physiological, psychological, and physical causes which is represented as a feeling of exhaustion and tiredness. There are various subjective measurements, for example the Fatigue Severity Scale (FSS) or the Visual Analogue Scale for fatigue (VAS-F). The VAS-F will be used in this study and will be explained later. However, for the objective measurements, there is a need to confirm a “gold standard” measurement (Shahid et al., 2010), which is the goal of this study by using the Time-load Dual-back (TloadDback).

The association with boredom has long been somewhat confusing, dating back to the 1930s. Researchers made a distinction between mental fatigue and boredom, acknowledging their similar impact on how we perform tasks. Researchers described boredom as the result of not being able to engage with something interesting enough to keep voluntary or spontaneous attention. On the other hand, fatigue can be characterized as a broader inability to focus attention or to carry out tasks with intention, intelligence, and creativity. Therefore, the key differentiation would be that boredom is about not tuning into a particular information source, while fatigue reflects a widespread difficulty in maintaining focus (Hockey, 2013). Having thoroughly discussed fatigue, we can now shift our focus to cognitive fatigue.

F. Nature of cognitive fatigue.

There are different theories regarding the nature of cognitive fatigue. One is that the nature of cognitive fatigue is unidimensional, which means that during a task when an individual exerts effort and maintains it for an extended period, it leads to cognitive fatigue and eventually disengagement. However, some researchers propose there are two kinds of fatigue: active and passive. Active fatigue arises in scenarios that require continuous and extended effort for task completion. These situations are usually challenging enough to keep us engaged, unlike tasks that are too simple or too hard, which lead to disengagement. The concept of active fatigue aligns with traditional views on cognitive fatigue, emphasizing the accumulation of effort and stress over time (Pickering et al., 2023).

On the other hand, passive fatigue emerges from engaging in repetitive, dull tasks that seldom require clear actions. Passive fatigue is linked to feelings of vigilance, boredom, and drowsiness, suggesting that our attention may wander to more appealing alternatives. Keeping focused on such monotonous tasks requires effort and cognitive control to continually bring our attention back, despite the lure of more interesting activities (Pickering et al., 2023).

The fundamental difference between active and passive fatigue lies in their causes: active fatigue stems from the gradual depletion of our focus and attentional resources, while passive fatigue results from a lack of stimulation leading to an underactive attention system that tends to shut down (Pickering et al., 2023).

Different studies (Saxby et al., 2013; Shigihara et al., 2013) have shown results, using different task complexity, that demonstrate an important difference between active and passive fatigue. Tasks that actively induce fatigue, despite their increased difficulty, seem to sustain attention and certain performance aspects like response time. Conversely, tasks that induce passive fatigue tend to result in a drowsier, less attentive state, where additional declines in performance may occur (Pickering et al., 2023).

G. Effects and causes of cognitive fatigue.

Cognitive fatigue or mental fatigue can refer to a situation of cognitive impairment and low alertness. Cognitive fatigue can lead to many unwanted consequences, such as making an easy task turn into an impossible task or increasingly difficult (Li et al., 2020).

Regarding the causes of cognitive fatigue, it is the objective of this study on how to induce this fatigue. It was found that mental fatigue can be induced by varying levels of cognitive load: a low cognitive load or a high cognitive load. They emphasize the distinction between active fatigue and passive fatigue, which are associated with high mental load conditions and low mental load conditions, respectively. As mentioned before, active fatigue results from “continuous and prolonged perceptual-motor adjustments related to the task,” while passive fatigue arises from “monitoring the system with rare or non-existent perceptual-motor response demands” (P. A. Hancock, 2008). In other words, active fatigue can be caused by a prolonged and demanding task requiring constant perceptual or motor adjustment, whereas passive fatigue occurs during a task with no demands, requiring continuous monitoring and vigilance. Thus, cognitive fatigue can result from cognitive overload due to the task's difficulty or cognitive underload due to monotony (G. M. Hancock et al., 2021).

H. Subjective and objective fatigue

As mentioned earlier, the concept of fatigue has a wide range of definitions and interpretations, which complicate it. It can be defined as a subjective feeling that has physiological performance impairments and psychological decrements (Hossain et al., 2005). It is essential to define fatigue, however, the reliability and validity of measuring fatigue are just as important (Aaronson et al., 1999). Whether fatigue affects cognitive performance or physical, for everyone there can be an objective and subjective expression. Subjective fatigue is typically self-reported using questionnaires, scales, and interviews to capture an individual's personal experience of feeling fatigued. In contrast, objective fatigue is assessed based on observable declines in performance, whether cognitive or motor, that occur during or after engaging in a task that induces fatigue. Because of its quantifiable characteristics, researchers often prefer to study behavioural fatigability (DeLuca, 2005). Fatigability refers to a phenotype that describes the link between how much fatigue a person feels and the level of activity causing that fatigue (Eldadah, 2010). However, in clinical settings, the assessment tends to focus on subjective fatigue since it is directly tied to the patient's perceptions and reported symptoms (DeLuca, 2005).

There are different measurements regarding if there are analyses of subjective or objective fatigue. There have been challenges concerning the measurements as there is a general lack of consensus in the literature, which makes it challenging to compare and study. The measure of fatigue is directly linked to the situation in which fatigue is examined. This lack of a gold standard has been impacting the generalization of findings and the synthesis of fatigue. Nevertheless, few options for the measurement of subjective fatigue have appeared in the literature. There are some options regarding the characteristics that we are looking at. It has been argued that for subjective quantification, the Visual Analog Scale of Fatigue (VAS-F) is quite an adequate scale to measure fatigue. VAS-F is a measure of fatigue within the measurement time. Different scales exist with their specificity, however, the VAS-F is interesting as it evaluates the evolution of fatigue and therefore the participant’s state of fatigue during a specific time

(Aaronson et al., 1999). As mentioned before, VAS-F will be used in this report and will be explained in more detail after.

Regarding the objective fatigue measurement, the determination of which tool to use is still in research. One affirmation is that assessment of the fatigue is mainly based on cognitive performance. Most studies consider the reaction times and the accuracy of the performance to assess fatigability (Hockey, 2013). This report will also focus on the performance metrics of perceptual sensitivity (d') and response bias (C). These outputs will further be explained later. Different approaches have been used in studies to induce fatigue to eventually measure objectively the fatigability of participants. The Time Load Dual Back (TLDB) task will be use in this report. The objective measurement is essential as it is a measure that can be tested and compared between different participants in an unbiased manner compared to the subjective measurement (Hockey, 2013).

Therefore, the over-reliance on subjective measures such as VAS and the other scales is a current issue. By embracing the definition of mental fatigue as a state induced by prolonged and demanding cognitive activity, characterized by subjective sensations of 'tiredness' and 'lack of energy' (Marcora et al., 2009), we can assess participants' mental fatigue by subjecting them to demanding cognitive tasks and determine subjective and objective responses. Relying solely on subjective measures poses challenges due to potential biases from participants responding to experimenters' expectations. Feelings of tiredness and low energy are not exclusive indicators of mental fatigue and might be confused with sensations like boredom or physical fatigue (Pattyn et al., 2008).

Instead of depending entirely on subjective assessments, the presence of mental fatigue in participants should be supported by simultaneous evidence of heightened cognitive demands. One effective method is examining participants' performance during cognitive tasks. If performance deteriorates over time, it indicates that the task is demanding enough to challenge participants' ability to sustain performance as time elapses (Hassan et al., 2023).

Therefore, it is crucial to employ both subjective and performance-based measures concurrently. Focusing only on one measure risks oversimplifying the concept of mental fatigue and introduces the possibility of error if biases influence the measure (Smith et al., 2019). Researchers, adhering to this approach, have utilized a range of subjective, physiological, and behavioural measures to gain more profound insights into how mental fatigue manifests (Cansino et al., 2013; Ishii et al., 2014).

I. Induction and measurement of fatigue

There has been research and different techniques have been developed to induce fatigue. The methods used can vary from one study to the other (Hassan et al., 2023). In this study, the 'Time-on-Task' paradigm with a dual task including an n-back task and an interfering second task (even/odd decision task) will be used (Borragán et al., 2017; Taya et al., 2018; Wang et al., 2014). Combining two tasks with different information processing demands is intended to ensure substantial engagement of working memory resources. The involvement of these resources can be influenced by the speed at which information needs to be processed or the complexity of the N-back task (Borragán et al., 2017).

The 'Time-on-Task' effect refers to the progression of cognitive fatigue over time. More specifically, fatigue is measured by observing a decrease in reaction times and accuracy. Such tasks are divided into different blocks (or parts), which are then compared (Ackerman & Kanfer, 2009). The n-back task is an important task that has been highly researched. The n-back task involves presenting participants with a series of stimuli (such as letters, numbers, or geographical locations) and requiring them to indicate when the current stimulus matches the one from n earlier in the sequence. The “n” in n-back is the number of steps back in the sequence that the participant must remember (Borragán et al., 2017). It is a working memory task. Working memory is an essential concept in cognitive psychology. Working memory has been described as a limited capacity system where certain resource are distributed between storage and processing; therefore, it could lead to the phenomenon of trade-off. This phenomenon illustrates that when concurrent memory load rises, performance tends to decline, leading to a loss of information from short-term memory when processing becomes more challenging. This theory suggests that when tasks, such as the n-back, varies in the cognitive demands they impose on working memory, essentially the resources required to complete them (Barrouillet et al., 2007).

The decision on which test to use is mainly based on the characteristics and the objectives of the study. One issue that is present in the current literature is that there is no agreement on what gold standard or most effective task duration length and workload are to induce fatigue to measure it (Smith et al., 2019).

- *Task duration*

Current strategies to induce cognitive fatigue in experimental settings typically involve manipulating either the duration of the task or its demands. In the time-on-task (ToT) method, participants face a consistent cognitive challenge over an extended period. For example, cognitive fatigue can be induced by having participants reorganize fictional employee schedules for about two hours, engage in a series of cognitive tasks like working memory tests, inhibition tasks, arithmetic problems, and brainteasers for 90 minutes, or solve mental arithmetic problems for up to three hours engaged in a series of cognitive tasks like working memory tests. This approach has proven effective in inducing cognitive fatigue, suggesting that any prolonged cognitive effort can eventually lead to fatigue regardless of the specific cognitive demands of the task. However, not all demanding situations escalate cognitive fatigue to the same degree (Borragán et al., 2017).

In the current literature concerning the effect of mental fatigue on cognitive and physical performance, there is a general agreement on the importance of cognitive activity over prolonged periods of time related to the inducement of mental fatigue. There is however contradiction in the literature concerning the time duration of cognitive activity necessary to induce mental fatigue (O’Keeffe et al., 2020). Some articles highlight the importance of the duration of the task with cognitive tests that were at least 30 minutes long (Van Cutsem et al., 2017). Others in contrast stated that even short tasks can be efficient in reducing cognitive resources such as a 16-min duration (Borragán et al., 2017).

- *Workload*

Different levels of cognitive fatigue are also induced by varying the complexity of tasks, which assumes that higher cognitive demands tax cognitive resources more, leading to increased levels of cognitive fatigue. For instance, altering the complexity of a working memory N-back task for 30 minutes can lead to varied levels of cognitive fatigue, evident in both behavioural changes and physiological responses (O’Keeffe et al., 2020). Higher task demands result in more errors on cognitive flexibility tasks and changes in brain activity patterns, indicating that the cognitive load from the task's demands significantly influences cognitive fatigue induction. Consequently, a higher cognitive load is expected to cause faster and more intense cognitive fatigue, raising questions about the primary factors driving cognitive load (O’Keeffe et al., 2020).

Cognitive load theories suggest that our processing capacity is limited. At the perceptual level, this is examined using paradigms where distractors are presented under different cognitive load conditions. When the task involves a high perceptual load, such as increased complexity, distractors cause less interference, suggesting a limited capacity to process irrelevant information. Increasing cognitive load can also be achieved by adding more elements to a task, such as in the N-back task where the number of elements to be updated in working memory increases (Borragán et al., 2017). Alternatively, the Time-based Resource-sharing (TBRS) model suggests that cognitive load is influenced primarily by the available time to process information (Barrouillet et al., 2004). This model views attention as a limited resource needed for processing incoming information and cognitive demand as a function of the workload divided by the time allowed for it. Limiting the time available to process cognitive demands should, therefore, increase cognitive load, potentially leading to higher cognitive fatigue levels. This concept, although well-established, still requires empirical validation (Borragán et al., 2017).

Using a model that can have different cognitive load situations has been shown to assess the objective fatigability. One method frequently used to heighten cognitive load within a task involves augmenting the number of elements to process. In the N-back paradigm (Kirchner, 1958), elevating cognitive load is achieved by expanding the number of elements to update in working memory, thereby enabling more complex comparisons between the current and preceding elements in the series. For example, Borragán et al., structured their experiment around the Time-based Resource-sharing model (TBRS; Barrouillet et al., 2004), which posits that the allotted time for handling cognitive tasks influences cognitive load. Their assumption was that restricting the time for cognitive processing would elevate cognitive load, potentially resulting in increased cognitive fatigue. To explore this, the researchers employed the Time Load Dual Back (TLDB), a dual-task involving the traditional N-Back working memory update task (Kirchner, 1958) paired with an interfering task (odd/even decision task) (Borragán et al., 2017).

The TloadDback (TLDB) task, used to challenge participants at a personal level of difficulty, and the A-X Continuous Performance Test (AX-CPT) used to test memory were compared. It was found that there are differences in these two tasks concerning the nature of the mental fatigue that is induced. Participants reported significantly higher endpoint motivation, lower sleepiness, and significantly higher energy after the TloadDback task compared to AX-CPT. There was also a difference in mental fatigue responses, with patients showing greater mental fatigue after the TloadDback task than AX-CPT when calculated by the visual analogue scale (VAS). However, mental fatigue was reported to be higher after AX-CPT when assessed by the Brunel Mood scale, a measure of mood states, by the patients (O'Keeffe et al., 2020). Therefore, this demonstrated the importance of choosing a task when inducing mental fatigue. Unfortunately, these differences in results that are dependent on the specific tasks used by researchers are being represented in the variation of results in the literature (Holgado et al., 2020).

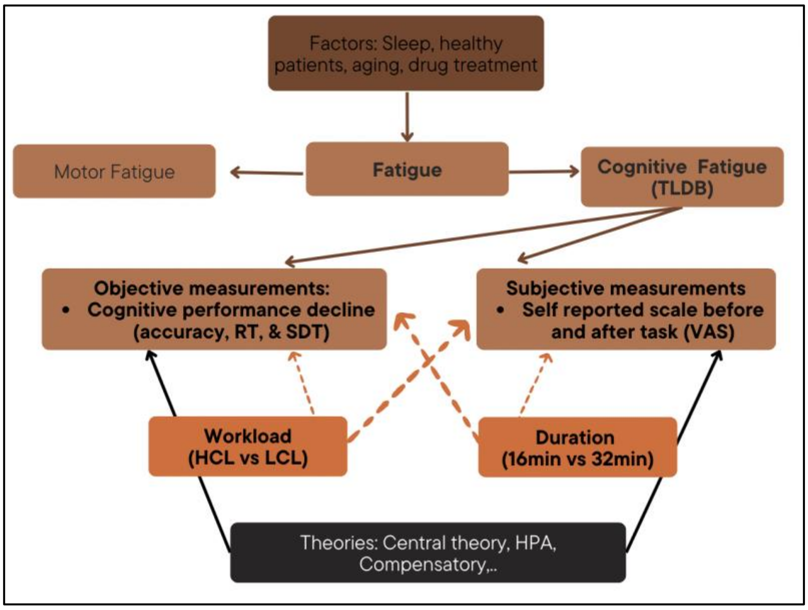

Figure 1: Overview of the study research.

The graph represents an overview of this research study from what is known and the potential effect of workload and duration (Figure 1).

J. Impact of cognitive fatigue on young population.

Fatigue is a natural reaction to prolonged activities, even in young healthy humans, it limits performance (Wang et al., 2014). However, when compared to the older population, it has often been shown that young adults perform better (Pergher et al., 2021). After a single session of cognitive performance testing, younger individuals showed higher accuracy and lower reaction times compared to older individuals (Christensen, 2001). Some studies linked lower accuracy to task demand (Cansino et al., 2013). However, cognitive fatigue has been shown to lead to some negative outcomes, as demonstrated in results that focused on young adults (Boksem et al., 2006). As cognitive fatigue sets in, young individuals tend to struggle more with correcting the errors that they made compared to other population. They also find it harder to adjust after making mistakes (Boksem et al., 2006) (Wang et al., 2014). Overall, working memory performance worsens with age, indicated by increased reaction time due to slower information processing or greater difficulty in suppressing irrelevant information (Pergher et al., 2021).

A young, healthy population will be used in this study to take a stable population and in addition to remove some factors that could influence the performance, such as disease or ageing.

II. Aim & objective of the study.

The study aims to examine the impact of mental fatigue on cognitive performance and subjective status. To accomplish this objective, an examination of the behavioural outcomes of a working memory cognitive task, the Time Load Dual Back (TLDB), was conducted. This task has been administered in different contexts and versions which varied in duration and workload, within different samples of young healthy adults.

The TLDB performance comparison will be systematically assessed across different conditions (high vs. low cognitive load) and durations (16-min vs. 32-min task length) to investigate its performance dynamics and effects on subjective mental fatigue.

Initially, we aim to examine the effects of time on mental fatigue based on the time-on-task paradigm (Ackerman & Kanfer, 2009). Thus, in our case, whether varying the task duration influences both objective performance decrement and subjective fatigue. This will involve comparing the performance evolution and feeling of fatigue between a 16-minute version of the TLDB and a 32-minute task duration within a low cognitive load (LCL) condition.

Subsequently, our focus will shift to exploring the impact of varying cognitive load on task-related objective and subjective fatigue levels, based on the Time-Based Resource Sharing paradigm (Borragán et al., 2017). This investigation will entail a comparison between a low cognitive load (LCL) condition and a high cognitive load (HCL) condition during a fixed 32-minute task duration.

Lastly, a correlation analysis will be conducted between objective performance and subjective output performance to examine any association between TLDB performance and VAS scores. This aim is to address a controversial topic in the literature: whether there is a relationship between cognitive performance decline and an increase in the feeling of fatigue, or vice versa.

- Hypothesis

The main hypothesis is that the highest workload and duration of the task will induce high mental fatigue, which will be observed by a decrease in the performance of the task and an increase in the subjective feeling of fatigue. It is also expected that a 16-minute duration will not significantly induce fatigue or significantly increase the sensation of fatigue. Regarding the correlation, we expect a relation between objective performance and subjective outputs, where an increase in the feeling of fatigue will correlate with an increase in cognitive performance.

III. Methodology & Design

A. Participants

This study is a comparative analysis of three young adults' data sets that all performed the TLDB task on populations with different task-specificities. The data sets came from three distinct studies and were divided into three groups according to the task modality (cognitive load and duration). All the data was processed and acquired in the Aging & Memory laboratory GIGA-CRC in Vivo Imaging Research Unit Psychology & Neurosciences of Cognition, University of Liège. The studies were conducted after receiving approval from the Ethical Committee of the Faculty of Psychology, Speech Therapy, and Educational Science at Liège University. There was no financial compensation provided for participation in data sets 1 and 3. Data set 2 participants received compensation since MRI scan sessions were included in the study. The description of each study including their specific aim, characteristics, inclusion, and exclusion criteria is in the appendix 1.

Table 1: Description of the groups.

Study	**Group 1**	**Group 2**	**Group 3**
Sample (N)	40	61	101
Sex (Female)	29	44	73
Education (mean (SD), years)	15.1 years (1.9)	13.6 years (2.1)	14.2 years (2.1)
Age groups (mean (SD), min-max years old)	23.4 years old (2.9), 19-30	25.4 years old (5.6), 18- 43	24.62 years old (4.8), 18-43
Task duration	16 min (short group)	32 min (Long group)	32 min (Long group)
Cognitive Load	LCL (low cognitive load)	LCL (low cognitive load)	HCL (high cognitive load)

As shown in Table 1, the groups have different sizes of samples with different cognitive load, and duration conditions. Group 1 is characterized by a 16-min task length in a low cognitive load condition. Group 2 and Group 3 include a 32-min task length, with a low cognitive load condition and a high one's, respectively.

There were some inclusion criteria for our study which are being between 18 and 40 years old, being native French speakers, preserving cognitive efficacy, and not having any knowledge of the objectives of the study. The exclusion criteria were history of head trauma, the presence of psychiatric and/or neurologic diseases, medications (such as antidepressants, anxiolytics, anticholinergics), and drug use.

B. Setting

There were three meetings with the participants. The sessions lasted approximately 1 hour each and took place one week apart. When feasible, sessions were planned at consistent times for each participant, aligning with their preferred comfort zone. Participants were instructed to uphold a consistent sleep schedule throughout the study duration and abstain from caffeine and stimulants 24 hours before each session. To ensure compliance, participants maintained a fatigue diary, recording wake-up and bedtime, nap occurrences and durations, as well as their daily levels of physical and mental fatigue and sleepiness throughout the study.

At the first session, the participants received the informed consent and the essential information about the study. During this session, participants also filled in different questionnaires regarding the sleeping habit (PSQI) or sleepiness level (ESS). The individual adjustment and evaluation of the maximal capacity at the TLDB, which will further be explained, was during the first session. During the two other sessions, the TLDB task and VAS were administered. Fatigue and sleepiness were measured using VAS before and after the task in both sessions. The low and high conditions were randomly assigned to the participants. The participants were blinded to the conditions they were doing. Sessions were counterbalanced between subjects. They were not aware of the objectives of the study; they only knew that it was about cognitive functioning.

C. Materials

- Time Load Dual Back (TLDB) task

The Time Load Dual Back (TLDB) is a cognitive task used to induce mental fatigue in an experimental setting (McMorris et al., 2018). The task assesses the working memory and attention, which are part of cognitive ability. TLDB is a dual task, with one task being a number parity judgment task and the other being an N-back working memory task. In the task, a sequence of digits and letters appears on the screen in a pattern (alternating between letters and numbers). Participants are given instructions to either (a) press the space key with their left hand whenever the displayed letter matches the previous one (1-back task), or (b) determine whether the displayed digit is odd or even by pressing “2” or “3” on the numeric keypad with their right hand. This task utilized a set of 8 numbers (1, 2, 3, 4, 6, 7, 8, and 9) and 8 letters (A, C, T, L, N, E, U, and P). All selected letters had a frequency of occurrence exceeding 2.5% in French Grammar. Letters that could be visually mistaken for numbers (such as O, I, S, Z) were excluded. Additionally, the digit “5” was omitted to balance the count between odd and even digits. Each block contained 30 letters and digits that were randomized (Borragán et al., 2017).

This task allows the adjustment of the cognitive load (either low or high) by manipulating the available processing time for each item shown on the screen, known as Stimulus Time Duration (STD). Each participant's STD was adjusted individually to maintain accuracy above 85%. This adjustment occurred in a pre-test session divided into two parts. First, participants practised odd/even judgments and a 1-back task. Once they achieved over 85% accuracy in each of the two tasks at an STD of 1500 msec, they started the dual-task blocks at the same STD. The training stopped when they consistently reached the 85% accuracy threshold within 90 to 360 seconds (Borragán et al., 2017).

The second part introduced progressively complex blocks to measure maximal cognitive capacity. Participants completed blocks with adaptive STD. If performance exceeded 85%, the STD decreased by 100 msec in subsequent blocks. This continued until performance fell below the 85% threshold, indicating the cognitive load limit. To refine the pre-test, participants were allowed three cumulative errors before maintaining a performance >85% at a given STD. The last successful STD became the High Cognitive Load (HCL) condition. The Low Cognitive Load (LCL) condition was set at 50% longer than the HCL (Borragán et al., 2017).

The calculation of performance per block was carried out using a weighted formula, in which the accuracy for letters contributed to 65% of the overall score, while digits accounted for 35%. This approach was adopted to underline the task's information-retrieval aspect, drawing on established research which indicates that the functions of encoding, maintaining, and manipulating information in working memory demand a greater attentional cost compared to just encoding and manipulation (Johansen, 2008).

In addition to the manipulation of the cognitive load, the duration of the task varied depending on the participant's group. There were two groups. The “long” group had the TLDB for 32 minutes and the “short” performed the task for 16 minutes.

- Questionnaires

- Epworth Sleepiness Scale (ESS)

The ESS consists of an 8-question self-administered questionnaire, assessing the sleepiness propensity of participants during the past week. Participants rate, using a 4-point scale (ranging from 0 description of not at all to 3 being extremely sleepy), their typical likelihood of dozing off or falling asleep during eight different activities commonly performed, not necessarily daily. The ESS score, derived by summing the scores of the 8 items, varies between 0 and 24. A higher ESS score indicates a greater average tendency to fall asleep during daily activities, known as 'daytime sleepiness' or Average Sleep Propensity (ASP). The maximum score is 24 which is categorized by having excessive sleepiness. The minimum score is 0 which is in the range of 0 to 10 which is considered as normal level of sleepiness (Johns, 1993).

- Pittsburgh Sleep Quality Index (PSQI)

This self-reported questionnaire was assigned to each participant in the first session. This questionnaire assesses the sleep quality of participants during the last month. Nineteen items contribute to the creation of seven distinct 'component' scores, encompassing subjective sleep quality, sleep onset latency, total sleep duration, habitual sleep efficiency, occurrence of sleep disturbances, use of sleep medication, and daytime dysfunction. The cumulative sum of scores across these seven components generates a single global score. The maximum score is 21 which is categorized as having big difficulties sleeping. The minimum score is 0 which means no difficulties (Buysee et al., 2016).

- Visual Analogue Scales (VAS)

To track subjective state experiences of mental fatigue and sleepiness, self-reported measures were employed. VAS is measured before and after the task to evaluate the evolution of the felling of fatigue of the participants at a given time. Mental fatigue was evaluated using a 10-point Visual Analogue Scale of fatigue (VASf), where 0 indicated 'no fatigue,' and 10 indicated 'the most extreme fatigue possible.' The level of fatigue was measured by calculating the means of the scores (Shahid et al., 2011). Recent research by Smith et al. (2019) highlighted the Visual Analogue Scale as the most effective means of assessing mental fatigue.

D. Analyses

Four behavioural metrics were analysed including the accuracy, the raw reaction time (RT), criterion (C) and d prime (d’). Accuracy was determined by the ratio of trials where the correct response was made to the total number of trials, along with the reaction times (RTs) for those correct trials, and metrics from signal detection theory (Wylie et al., 2021). Signal detection analysis helped distinguish between discrimination sensitivity (d’) and response bias (C) (Anderson et al., 2011).

Signal detection theory (SDT) is a conceptual model that clarifies how accurately decisions are made by explicitly addressing the decision-making process. This theory proposes that the observer represents information in a certain way, associating some aspects of this representation with the concept of sensitivity or the innate accuracy, and other aspects with factors related to responses. It fundamentally posits that the intensity of sensory and cognitive events varies continuously. Included in the signal detection metrics, there is the perceptual sensitivity (d') and the criterion (C) that will be analysed (Gescheider, 1988). Discrimination sensitivity, the ability to accurately identify target stimuli, was quantified using the perceptual sensitivity (d'), which is derived from the formula (zFA - zHR). Here, "z" represents the inverse of the standard normal cumulative distribution, "FA" is the rate of false alarms (responses to non-target stimuli), and "HR" is the hit rate (the rate of correctly identified target stimuli). Within this experiment's framework, where stimuli could be easily distinguished, d' essentially reflected perceptual certainty rather than sensitivity to the stimuli. Response bias was assessed through the "criterion" (C), calculated as −1/2(zHR + zFA). Higher criterion values, indicating fewer false alarms and hits, suggested a reduced response bias or a more conservative approach. Conversely, lower criterion values, reflecting more hits and false alarms, pointed to an increased response bias and a more liberal response strategy (Wylie et al., 2021).

- Data Segmentation and Trial Exclusion:

There was a segmentation of the task into bins (or blocks) based on time, allowing for detailed analysis across different periods of the task. The groups with the HCL 32-minute condition are segmented into 8 blocks of 4 minutes. The short group with the LCL 16-minute condition is divided into 4 blocks of 4 minutes. The 60 first trials were removed to focus on the core task period and thus remove the beginning of the task to exclude the time of adaptation of the task. There was also an identification and separation of anticipated trials (those with extremely short RTs (<.1 sec)) into a distinct dataset, to remove any bias to the analyses.

The delta calculation was done in Excel. The delta was used for the objective and subjective measurement to analyse the time processes. The delta was made by subtracting the performance mean of the last block from the first one. Delta is used to quantify the change or difference between two durations length or conditions. The aim was to observe if there was a difference in performance between the end and the beginning of the task.

E. Statistics

The manipulation of the data, including the merging of data sets 1 and 2, and delta calculations were made in Excel and R statistical package (version 3.4.3). All the statistical analyses were performed on JASP (version 0.18.1).

- **Demographic’s measure**

Concerning demographics, an ANOVA was performed on age, educational level as well as on the means scores obtained at the sleep and sleepiness questionnaires (PSQI and ESS) to compare the three groups on these variables. More precisely, the fixed factors used were the groups which includes the group 1 (short group in LCL), group 2 (long group with LCL), and the group 3 (long group with HCL). The test of equality of variances (Levene’s) was significant for the age and PSQI measurements, therefore the non-parametric test Kruskal-Wallis test was used. Post-hoc tests were used to determine which specific means or groups differ from each other. The commonly used Tukey test was applied to the education variable, while the Games-Howell test was employed for the PSQI variable due to a violation of the assumption of equal variances.

- **Objective cognitive fatigue: TLDB**

Task duration was divided into eight blocks of 4 min for the long groups and four blocks of 4 min for the short group. There were calculations of various metrics, including accuracy, reaction time, and signal detection theory (SDT) metrics, namely d' and criterion (C). For reaction times (RT), we process the data to remove incorrect trials and calculate average RTs, both in milliseconds. For each output, the delta was calculated as explained before.

As mentioned previously, there are two sets of groups: one comparing two groups with different cognitive load conditions (high vs. low cognitive load) but same task duration (32 minutes), and another with the same cognitive load (low) but with different task durations (16 min vs. 32 min).

Effect of time

Before analysing the effects of task duration and workload manipulations on performance, we aimed to check if performance varied over time spent on the task in our 3 groups.
To do so, paired-sample t-tests were conducted individually for each group (LCL-16min, LCL-32min, HCL-32min) to compare the performance obtained at the first and last blocks. The paired variables were block 1 with blocks 4 (for 16-min task length) and 8 (for 32-min task length), respectively. The test of normality suggested a deviation from normality, so the Wilcoxon test was used. These analyses are only there as a confirmation of the effect of time on the different groups by the task.

Evaluation of the task duration

Independent sample t-tests were performed to assess the effect of the duration of the task (either 16 min or 32 min) on the delta mean performances in the low cognitive load. The dependent variables were the delta mean scores of the four behavioural metrics (accuracy, RT, d’ and C) of the task and the grouping variables were the group with the different duration (16 min vs 32 min). The aim was to observe if there were differences in the performance of the task between the two groups, therefore if varying the duration of the task has an impact on the performance evolution. The test of normality suggested a deviance from normality. Therefore, the Mann-Whitney test was used.

Evaluation of the workload

Independent sample t-tests were performed to assess the effect of the cognitive load (either high or low) on the delta mean performance in the 32-min task version. The dependent variables were the four behavioural metrics (accuracy, RT, d’, and C) of the task and the grouping variables were the groups condition (LCL vs HCL). The aim was to observe if there were differences in the performance of the task between the two groups in each condition, thus if varying the cognitive load of the task influences the performance evolution. The test of Normality suggests a deviance from normality; therefore, the Mann-Whitney was used.

- **Subjective cognitive fatigue: VAS-f**

To test the task-induced feeling of fatigue in the two different sets of groups (workload or duration), a repeated measure ANOVA was performed to compare the VAS fatigue subjective measure before and after the task. The repeated measure factor was the time of assessment (before & after the task). The dependent variables were the score of the VAS fatigue test. Workload (HCL vs LCL) or Duration (16 min vs 32 min) were the between-subject factor. A post-hoc test was used to determine if specific groups differ from each other. The commonly used Holm test was applied. The aim is to analyse the feeling of fatigue before and after the task in different conditions and duration of the task.

- **Correlation of measures between objective & subjective cognitive fatigue.**

To observe any correlation between the objective and subjective measurements, a Pearson’s r correlation was performed. The Shapiro-wilk test suggested a deviation from the normality. To correct this deviation, the Kendall’s tau-b test was applied. The dependent variables were the delta mean scores of the four behavioural metrics (accuracy, raw RT, d’ and C) of the cognitive task and the VAS-f delta score. The VAS-f delta was calculated by subtracting the VAS-f score after the task from the VAS-f score before the task, thereby obtaining an estimation of the feeling of fatigue subsequent to the task, while taking into account the feeling of fatigue prior to taking it. The delta mean of objective performances were also obtained to check the differences of performances comparing the start and end of the task. The objective was to analyse the correlation between the evolution of the feeling of fatigue and the evolution of the performance at the cognitive task based on the condition and duration of the task.

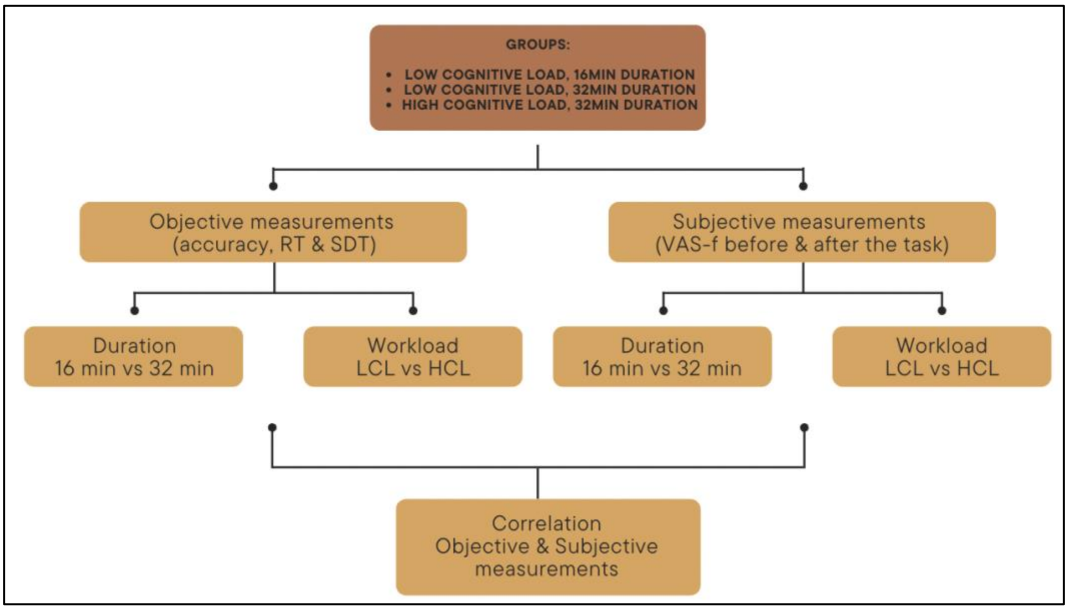

Figure 2: Representation of the main objective research of the study.

IV. Results

The structure of the result's section is divided into the impact of the time effect confirmation then the analysis of the impact of the task workload and the task duration on objective and subjective measurements and end by the correlation between them. As mentioned previously, there are two different comparisons of different groups. These comparisons were made to compare two groups with the same cognitive load condition (low workload) but different durations (16 or 32 minutes) and the same duration (32 min) but with different cognitive load conditions (high and low workload).

A. Demography and questionnaire

Firstly, analyses of the demographics (age and education) and the sleeping questionnaire (PSQI and ESS) were conducted between the three research groups (Table 2).

Table 2: Participants' demography (age and education) and questionnaires (PSQI and ESS)[1].

	Group	Mean	SD	P-value	Effect size
Age, years	LCL, 16 min	23.4	2.9	0.266[a]	0.013
	LCL, 32 min	25.4	5.7		
	HCL, 32 min	24.6	4.8		
Education, years	LCL, 16 min	15.1	1.9	0.002**	0.06
	LCL, 32 min	13.6	2.1		
	HCL, 32 min	14.2	2.1		
PSQI	LCL, 16 min	6.8	3.2	0.002**[a]	0.062
	LCL, 32 min	4.8	1.8		
	HCL, 32 min	5.6	2.6		
ESS	LCL, 16 min	9.6	2.9	0.25	0.014
	LCL, 32 min	8.5	3.1		
	HCL, 32 min	8.9	3.1		

PSQI: Pittsburgh sleep quality index, **ESS**: Epworth sleepiness scale.
[1] ANOVA with dependent variable (age, education, PSQI, and ESS scores) and three different groups as fixed factors.
*** p <.001, **p <.01, *p <.05
[a]Kruskal-Wallis test due to deviation of equality of variance.

Table 2 shows the demographic characteristics of the participants, including age and education level. The analysis indicates that while age does not significantly differ among the groups, there are significant (p=0.002, effect size= 0.06) differences in education levels (Table 2). Post hoc analyses show that the 16 minutes duration in LCL group had significantly (p=0.001, effect size=0.728) higher education scores compared to the 32 minutes duration in LCL group (Table 3, Fig 3). No difference was founded in the 32 minutes duration in HCL group compared to the others.

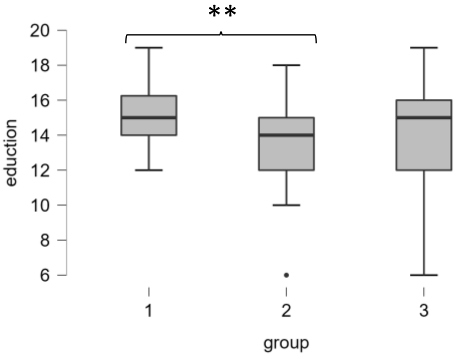

Figure 3: Mean education (in years) in the three research groups.

1: Low cognitive load 16 minutes**, 2:** Low cognitive load 32 minutes, **3:** High cognitive load 32 minutes**.**

Table 3: Post hoc comparisons of education between groups[1].

		Mean difference	**SE**	**Cohen's d**	**Ptukey**
LCL, 16 min	**LCL, 32 min**	1.518	0.424	0.728	0.001**
	HCL, 32 min	0.917	0.39	0.44	0.051
LCL, 32 min	**HCL, 32 min**	-0.601	0.338	-0.288	0.180

LCL: Low cognitive load**, HCL:** High cognitive load.
[1] Post hoc test comparison of groups.
*** p <.001, **p <.01, *p <.05

When examining sleep quality and sleepiness, as measured by the Pittsburgh Sleep Quality Index (PSQI) and the Epworth Sleepiness Scale (ESS), there are notable variations. There are significant (p=0.002, effect size=0.062) differences in the PSQI questionnaires between the groups (Table 2). Post hoc analyses show that the 16 minutes duration in LCL group had significantly (p=0.003, effect size=0.728) higher PSQI scores compared to the 32 minutes duration in LCL group (Fig 4, Table 4). No difference was founded in the 32 minutes duration in the HCL group compared to the others. In addition, no significant difference was found in the levels of sleepiness measured by ESS with values ranging from 8.5 to 9.6 (Table 2).

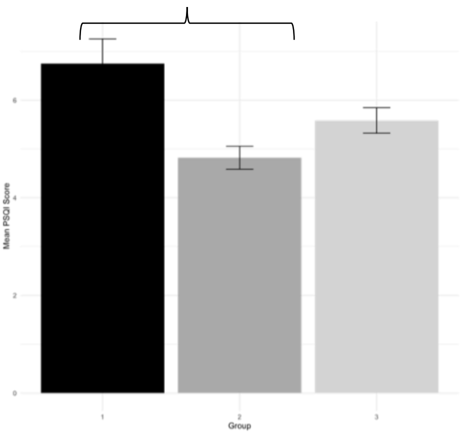

Figure 4: Mean PSQI (Pittsburgh sleep quality index) scores in the three research groups.

1: Low cognitive load 16 minutes**, 2:** Low cognitive load 32 minutes, **3:** High cognitive load 32 minutes**.**

Table 4: Games-Howell Post hoc comparisons of PSQI scores between groups[1].

		Mean difference	SE	Cohen's d	Ptukey
LCL, 16 min	**LCL, 32 min**	1.930	0.557	0.759	0.003**
	HCL, 32 min	1.166	0.568	0.458	0.109
LCL, 32 min	**HCL, 32 min**	-0.764	0.351	-0.301	0.078

LCL: Low cognitive load**, HCL:** High cognitive load.

[1] Games-Howell Post hoc test comparison of groups was used due to violation of the assumption of equality of variance.

*** p <.001, **p <.01, *p <.05

B. Impact of time by the task

As said earlier, the impact of time was first analysed to assess performance difference over time-on-task. In the low cognitive load both 16- and 32-minutes, there were significant declines in performance in the accuracy, reaction time and perceptual sensitivity as time progresses (Block 1 vs Block 4/8). However, the response bias did not show significant changes. In the high cognitive load in 32 minutes, there were significant decline in accuracy, perceptual sensitivity and response bias over time (Block 1 vs Block 8). However, no significant effect on the reaction time in the high cognitive load was found (Appendix 2).

C. Objective measurements

The objective measurement will consider the accuracy, the reaction time, the metrics of signal detection theory (SDT)— perceptual certainty (d'), and response bias (C). To analyse the difference between the beginning and end of the task, thus analysing the impact of the task, the delta for each measurement will be used.

Duration analyses

Moving on to cognitive performance in the context of task duration, it can be observed that delta reaction time (RT) significantly (p=0.003) differs between the two groups, with the low cognitive load and 16 minutes length task having a shorter score (Table 5, Fig 5). A shorter reaction time score indicates that participants responded more quickly to the task. Delta accuracy and signal detection metrics (d' and C) did not show significant differences (Table 5). The effect size for the delta reaction time was -0.232 (Table 5).

Table 5: Cognitive performance analyses on objective measurements regarding duration[1].

	Group	Mean	SD	P-value[a]	Effect size
Delta Accuracy	16 min	-0.035	0.053	0.120	-0.131
	32 min	-0.023	0.062		
Delta RT	16 min	0.011	0.045	0.003**	-0.232
	32 min	0.035	0.006		
Delta Metric (d')	16 min	-0.575	1.008	0.422	-0.096
	32 min	-0.39	1.161		
Delta Metrics (C)	16 min	-0.066	0.513	0.341	-0.114
	32 min	0.05	0.518		

RT: Reaction time, **d'**: perceptual sensitivity, **C**: response bias.

[1] Independent sample t-test with the dependent variables' behaviour performance (delta mean of accuracy, RT, metric (p') and metrics (C)) and duration (16 min vs 32 min) as the grouping variable.

**p <.01

[a]Mann-Whitney test due to deviation of normality.

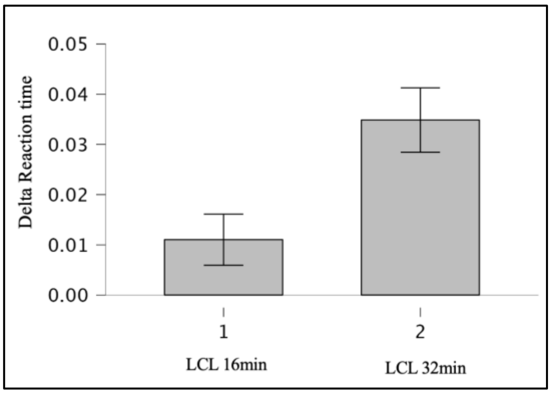

Figure 5: Cognitive performance analyse of the delta reaction time (RT) regarding duration (16 min vs 32 min).

Workload analyses

In the workload-based performance analyses, significant differences were observed between LCL and HCL in terms of delta accuracy, reaction time, and signal detection measures (d' and C) (Table 6). Specifically, accuracy and reaction time scores were significantly (p<.001) lower under high workload conditions compared to low workload conditions (Fig 6a and b). As mentioned, a shorter reaction time indicates quicker responses, while lower accuracy signifies more errors made by participants. Similarly, the perceptual sensitivity and response bias also showed lower scores under high cognitive load, with p value of 0.010 and less than 0.001 respectively (Fig 6c and d). A decrease in perceptual sensitivity indicates poorer ability to distinguish between target and non-target stimuli, and a decrease in response bias reflects a more liberal response strategy. The effect sizes for accuracy and the metrics criterion were moderate, at 0.459 and 0.436 respectively (Table 6).

Table 6: Cognitive performance analyses on objective measurements regarding workload^1.

	Group	**Mean**	**SD**	**P-value^a**	**Effect size**
Delta Accuracy	LCL	-0.023	0.062	<.001***	0.459
	HCL	-0.096	0.113		
Delta RT	LCL	0.035	0.070	<.001***	0.313
	HCL	0.009	0.088		
Delta Metric (d')	LCL	-0.390	1.161	0.010*	0.247
	HCL	-0.809	0.997		
Delta Metrics (C)	LCL	0.05	0.518	<.001***	0.436
	HCL	-0.407	0.571		

RT: Reaction time, **d'**: perceptual sensitivity, **C**: criterion, **HCL**: high cognitive load, **LCL**: low cognitive load.

[1] Independent sample t-test with the dependent variables' behaviour performance (delta mean of accuracy, RT, metric (p') and metrics (C)) and workload (High Cognitive Load vs Low Cognitive Load) as the grouping variable.

*** p <.001, **p <.01, *p <.05

[a] Mann-Whitney test due to deviation of normality.

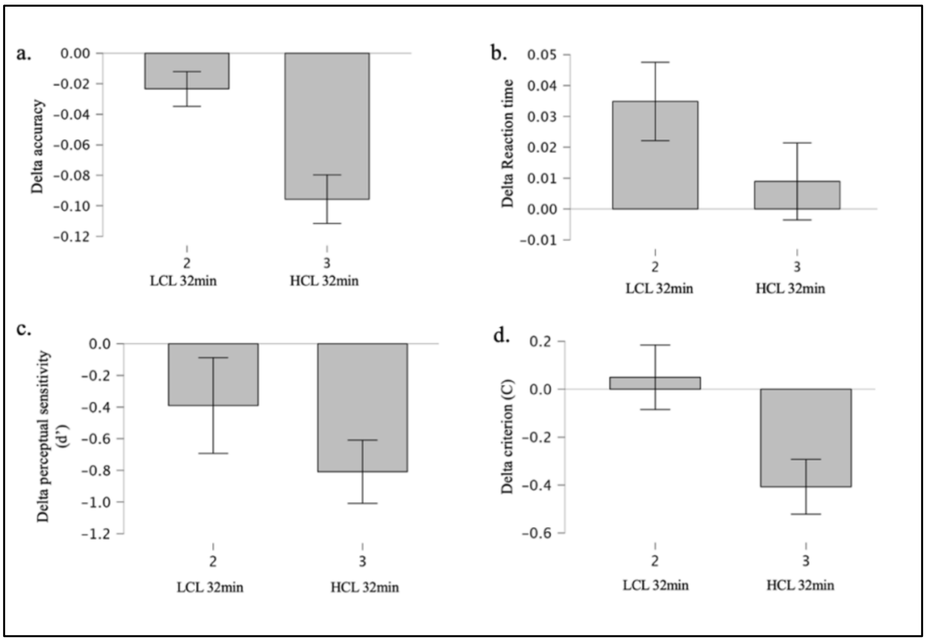

Figure 6: Cognitive performance analyses on objective measurements regarding workload (LCL vs HCL). (a) Delta accuracy. (b) Delta reaction time (RT). (c) Delta perceptual sensitivity (d'). (d) Delta criterion (C).

D. Subjective measurements

Analyses were conducted to examine the evolution of subjective measurements obtained from the Visual Analogue Scale of Fatigue (VAS-f) as a function of task duration and task workload, separately.

Concerning the manipulation of task duration, repeated measures ANOVA comparing two time points (pre-task vs. post-task) revealed a significant effect (p < .001, effect size = 0.07), indicating an increase in fatigue over time from pre-task to post-task (Fig 7 and Table 7). Post-hoc analyses demonstrated that the subjective increase in fatigue over time (pre-task vs. post-task) was observed in both groups (Table 8). No significant effect of group was found.

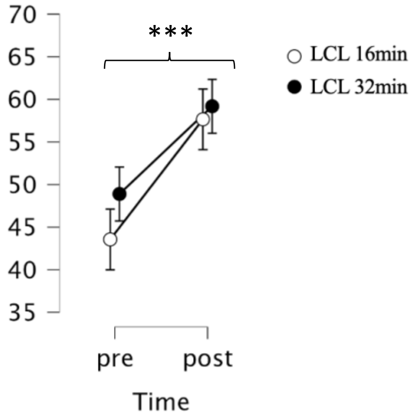

Figure 7: VAS-f scores of pre- and post-task from each group, evaluating the duration condition (16 min vs 32 min).

Table 7: Subjective measurements pre- and post-task regarding duration analyses.

Within subject's effects			
Cases	**Mean square**	**p-value**	**Effect size**
Time	7073.450	<.001***	0.07
Time*Group	172.543	0.266	0.002
Between subjects effects			
Group	562.521	0.410	0.006

[1] Repeated measure ANOVA, with the repeated measure factor being timing (before and after the task of the VAS score) and duration (16 min vs 32 min) as the between subject factors.
*** p <.001

Table 8: Post hoc comparisons of the interaction of time and group in the duration analyses[1].

		Mean difference	**SE**	**Cohen's d**	**Pholm**
16 min, pre	32 min, pre	-5.337	4.485	-0.244	0.473
	16 min, post	-14.100	2.627	-0.644	<.001***
	32 min, post	-15.633	4.485	-0.714	0.003**
32 min, pre	16 min, post	-8.763	4.485	-0.400	0.159
	32 min, post	-10.295	2.163	-0.470	<.001***
16 min, post	32 min, post	-1.533	4.485	-0.070	0.733

[1] Post hoc test comparisons with the factors Time (Pre- and post-task) and Group (16 min and 32 min). 16 min represents group 2 (low cognitive load and 16 min length); while 32 represents group 3 (low cognitive load and 32 min length).
*** p <.001, **p <.01, *p <.05

Similar to task duration, the two groups with different workloads showed a significant effect of time (p < .001, effect size = 0.085), indicating an increase in fatigue from pre-task to post-task (Figure 8). However, in the workload manipulation condition, a significant interaction between time and group was found (Table 9). The effect sizes were 0.085 for the main effect of time and 0.005 for the interaction between time and group (Table 9). Post-hoc tests revealed that subjective fatigue measurements increased significantly over time in the HCL condition (Table 10). Additionally, post-intervention scores were significantly higher in the HCL condition compared to LCL (Table 10). No main effect of group was found.

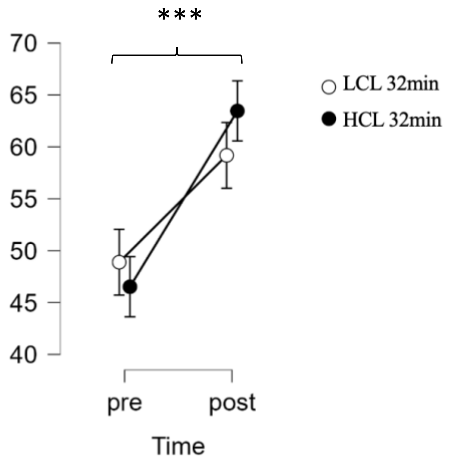

Figure 8: VAS-f scores of pre- and post-tasks, each group evaluating the workload condition (LCL vs HCL).

Table 9: Subjective measurements pre- and post-task regarding workload analyses[1].

Within subject's effects			
Cases	**Mean square**	**p-value**	**Effect size**
Time	1370.365	<.001***	0.085
Time*Group	815.530	0.039*	0.005
Between subjects effects			
Group	67.673	0.765	4.175×10^{-4}

[1] Repeated measure ANOVA, with the repeated measure factor being timing (before and after the task of the VAS score) and workload (HCL vs LCL) as the between subject factors.
*** p <.001, **p <.01, *p <.05

Table 10: Post hoc comparisons of the interaction of time and group in the workload analyses[1].

		Mean difference	**SE**	**Cohen's d**	**Pholm**
LCL, pre	HCL, pre	2.364	3.576	0.109	0.509
	LCL, post	-10.295	2.520	-0.474	<.001***
	HCL, post	-14.573	3.576	-0.670	<.001***
HCL, pre	LCL, post	-12.660	3.576	-0.582	0.001**
	HCL, post	-16.938	1.946	-0.779	<.001***
HCL, post	LCL, post	-4.276	3.576	-0.197	0.466

[1] Post hoc test comparison with the factors Time (Pre- and post-task) and Group (LCL and HCL). LCL represents group 2 (low cognitive load and 32 min length); while HCL represents group 3 (High cognitive load and 32 min length).
*** p <.001, **p <.01, *p <.05

E. Correlation

A correlational matrix was performed to test links between objective and subjective measures of cognitive fatigue for all groups, separately.

In the low cognitive load condition with a 16-minutes task duration, there were no significant correlations between objective and subjective measurements. However, positive correlations were found between accuracy and perceptual sensitivity. Additionally, negative correlations were observed between perceptual sensitivity with reaction time and criterion (Table 11).

Table 11: Correlation between objective and subjective measurements variables in the 16-min duration task of low cognitive load[1].

Variables	Mean	SD	VAS-f	Accuracy	RT	d’	C
VAS-f	14.100	15.731	-				
Accuracy	-0.035	0.048	-0.043	-			
RT	0.011	0.030	0.038	-0.179	-		
D’	-0.575	1.008	0.148	0.433***	-0.228*	-	
C	-0.066	0.513	-0.153	0.149	-0.113	-0.264*	-

RT: Reaction time, **d’**: perceptual sensitivity, **C**: criterion, **VAS-f**: Visual analogue scale of fatigue.

[1] Pearson's r correlation with the dependent variables' behaviour performance (delta mean of accuracy, RT, metric (d’) and metrics (C)) and VAS-f delta score. Kendall’s tau-b test was used due to deviation of normality.

*** p <.001, **p <.01, *p <.05

Regarding the 32-minutes task with low cognitive load, significant negative correlations were found between reaction time with accuracy and perceptual sensitivity. A significant positive correlation was found between accuracy and perceptual sensitivity (Table 12). No significant correlations were observed between objective and subjective measurements.

Table 12: Correlation between objective and subjective measurements variables in the 32-min duration task of low cognitive load[1].

Variables	Mean	SD	VAS-f	Accuracy	RT	d’	C
VAS-f	10.295	17.184	-				
Accuracy	-0.023	0.048	0.050	-			
RT	0.035	0.056	0.001	-0.212*	-		
D’	-0.390	1.161	-0.014	0.544***	-0.287**	-	
C	-0.050	0.518	-0.008	0.085	0.100	-0.135	-

RT: Reaction time, **d’**: perceptual sensitivity, **C**: criterion, **VAS-f**: Visual analogue scale of fatigue.

[1] Pearson's r correlation with the dependent variables' behaviour performance (delta mean of accuracy, RT, metric (d’) and metrics (C)) and VAS-f delta score. Kendall’s tau-b test was used due to deviation of normality.

*** p <.001, **p <.01, *p <.05

For the high cognitive load with 32-minute task, there was a significant (p=0.009, effect size=-0.182) negative correlation between the accuracy and the VAS (Table 13). Meaning that a decline in accuracy was negatively associated with an increase in self-reported fatigue score (Fig 9).

Table 13: Correlation between objective and subjective measurements variables in the 32-min duration task of high cognitive load[1].

Variables	Mean	SD	VAS-f	Accuracy	RT	d’	C
VAS-f	16.938	20.938	-				
Accuracy	-0.096	0.095	-0.180** (-0.182)[2]	-			
RT	0.009	0.062	-0.056	0.008	-		
D’	-0.809	0.997	-0.016	0.079	-0.052	-	
C	-0.407	0.571	-0.050	0.017	-0.043	-0.115	-

RT: Reaction time, **d’**: perceptual sensitivity, **C**: criterion, **VAS-f**: Visual analogue scale of fatigue.

[1] Pearson's r correlation with the dependent variables' behaviour performance (delta mean of accuracy, RT, metric (p’) and metrics (C)) and VAS delta score. Kendall’s tau-b test was used due to deviation of normality.

[2] Effect size

**p <.01

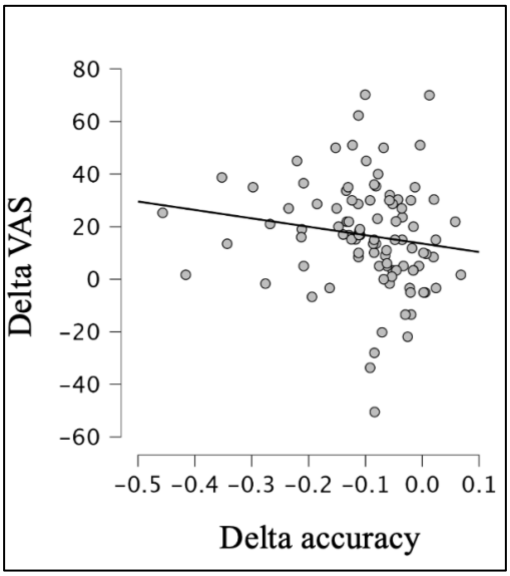

Figure 9: Correlation between delta VAS-f score and delta accuracy in HCL with 32-min duration task.

These findings collectively underscore the interplay of demographic factors, cognitive performance, and time in determining task outcomes across different workload and duration conditions.

V. Discussion

The purpose of this study is to investigate the impact of mental fatigue on cognitive performance and subjective status by using a working memory task, the Time Load Dual Back (TLDB). This study aims to compare task performance and subjective output across different versions and durations in a healthy young population. The different versions and durations encompass a high compared to a low cognitive load and a 16 compared to a 32-minute task duration.

A. Demography and questionnaires

The detailed information on the study population showed that it was representative of a large sample of young, healthy participants. Regarding the education level, there is a significant difference between the groups. The low cognitive load with a 32-minutes length group has a smaller mean, representing a lower level of education compared to the 16-minutes length group. Often, the level of education is not associated with a significant impact on fatigue (Delva et al., 2022). However, a study analysing fatigue in the general population in northern Sweden found that a high level of education was significantly related to lower scores of fatigue (Engberg et al., 2017). Despite some contradictory findings in the literature, a high effect size was observed between the two groups, indicating that education level significantly influenced the outcomes for the low cognitive load groups. In contrast, the high cognitive load group did not show significant differences compared to the other groups, suggesting that education level did not impact this group.

Sleep quality and mental fatigue have been found to be linked, it was demonstrated that disturbed sleep quality is an important predictor of mental fatigue (Åkerstedt et al., 2004). The PSQI questionnaires revealed significant differences between the groups, with higher PSQI scores observed in the low cognitive load group performing the 16-minutes task compared to the longer task duration. A high effect size indicated a substantial impact. However, the mean score was 6.8, which falls within the normal range of sleep difficulties on the PSQI scale, where scores range from 0 (no difficulties) to 21 (severe difficulties) (Buysee et al., 2016). We can then suggest that the impact of sleep quality in the low cognitive load with 16-minuite group is moderate.

B. Objective measurements

To evaluate the objective measurements, the accuracy, reaction time, and metrics (d’ and C) were evaluated. Research on cognitive fatigue often employs a block design method to analyse changes in mean reaction time (RT) and/or accuracy levels before and after engaging in a task that induces fatigue. Alternatively, researchers may compare these outputs between the initial and final blocks of the fatigue-inducing task itself. These studies operate under the assumption that a general decrease in speed or accuracy represents the primary feature of cognitive fatigue. While mean performance levels have provided insights into the characteristics of cognitive fatigue from both phenomenological and physiological standpoints, they have not demonstrated a correlation with the perceived sense of fatigue, whether directly or as a lasting trait (Wang et al., 2014).

The disappointing lack of correlation between subjective feelings of cognitive fatigue and objective measures of performance such as response time (RT) and accuracy has impeded research in this field. However, fatigue has been linked to reductions in perceptual sensitivity, which refers to a diminished ability to distinguish between stimuli requiring a response (targets) and those that do not (non-targets). This measure, known as d', is derived from signal detection theory (SDT). In human factors literature, decrements in d' have been associated with vigilance tasks. For instance, it was found that perceptual sensitivity decreased, and fatigue increased following a challenging simulated driving task compared to an easier one. Therefore, while RT and accuracy do not correlate well with fatigue, SDT tools, particularly perceptual sensitivity, may provide better objective indices of fatigue (Wylie et al., 2021).

However, although reductions in d' have been observed after inducing fatigue, it has not been shown that progressive increases in fatigue correspond to progressive decreases in perceptual sensitivity. Demonstrating such a correlation would offer researchers a valuable tool for understanding fatigue better. While perceptual sensitivity (d') worsens after fatigue induction, the effect of fatigue on bias, or criterion, another key SDT measure, has not been explored. In SDT, criterion refers to the amount of evidence required before making a response: a liberal criterion means needing less evidence to respond to a target, while a conservative criterion means requiring more evidence. It is surprising that changes in criterion have not been investigated in fatigue research, especially since recent studies suggest that fatigue reflects, at least partially, a shift in the balance between effort and reward. SDT predicts that changes in this balance will be reflected in changes in criterion. It has been repeatedly shown that altering the payoff matrix by increasing rewards reduces fatigue, but there have been no studies examining whether changes in fatigue correlate with changes in criterion (Wylie et al., 2021).

Impact of time

As previously described, cognitive fatigue suggests that when an individual exerts and maintains effort over an extended period, it leads to cognitive fatigue (Pickering et al., 2023), which can be described by a decrease in cognitive performance (Behrens et al., 2023). Based on the time-on-task (TOT) paradigm, which demonstrates the progression of cognitive fatigue over time (Ackerman & Kanfer, 2009), it can be assumed that time affects performance. An initial analysis was conducted to determine the impact of time on cognitive performance. Even if it is well known to be the case (Wang et al., 2014), it is still important to evaluate if the task we used induces changes in cognitive performance over time. The goal is to observe if the task, which is the TLDB that we proposed, will indeed induce a change in cognitive performance over a period of time. Analyses were done in the different groups, and it was proven that there was indeed an impact of time on the objective measurements, but not in all condition. The criterion and reaction time were not significantly impacted in low and high cognitive load, respectively. There has been only little research on the criterion changes in fatigue; however, it was already found that criterion was affected in more complex memory tasks (Román et al., 2022; Wylie et al., 2021). However, no research regarding the changes in low cognitive load could be founded. Therefore, it could be that criterion changes can only be observed in high cognitive load induce. Regarding the reaction time in the high cognitive load group, it is quite surprising as RT has usually been associated with a decrease in speed over time when inducing fatigue (Wang et al., 2014). However, this could be explained as we had young participants. A study comparing first and last rounds of an N-back task did not find any significant differences in the reaction time in younger, which was the opposite for older adults (Pergher et al., 2021). Therefore, maybe that younger adults are not as affected by higher cognitive load than older adults. More research will be done later on reaction time and its performance in this report.

It can then be assumed that the TLDB task globally impacts cognitive performance ; this assumption was also validated by many studies (Borragán et al., 2016, 2017; O'Keeffe et al., 2020).

However, it is important to note that only the impact of time is analysed here, not comparisons between the different conditions and duration can be assumed. We can only assume that the time process impacts cognitive performance due to induced cognitive fatigue (Ackerman & Kanfer, 2009).

The main objective of this study is to measure the impact of fatigue induced by the working memory task TLDB on objective and subjective measurements. The objective measurement was included in the context of duration (16 minutes or 32 minutes) and workload (high or low cognitive load).

Duration analyses

In the context of duration, the delta reaction time between the short (16 minutes) and long (32 minutes) group was shown to be significantly different. The short group had a shorter delta score, suggesting that participants took less time at the end of the 16 minutes compared to the group with a 32-minute task length. It can be assumed that it was harder for participants to react after a longer exposure to the task. This outcome had a small effect. However, the other behavioural performance variables, such as accuracy and SDT metrics, did not show any difference when having a longer time exposure. Even if there are different findings in the literature (Ackerman & Kanfer, 2009; Borragán et al., 2017) about the time required to induce fatigue, it can be observed in this report that between a 16 minutes task and a 32 minutes task, there were no impact on the behavioural performance of accuracy, perceptual sensitivity, and response bias. Only the reaction time is impacted, which had a small effect size on the groups. There is very little research in the literature that compares cognitive performance measurements between tasks of different durations. Most studies focus on the time-on-task (TOT) paradigm, where performance measurements are compared across different blocks to evaluate the effects of time evolution. This report also follows that approach but additionally compares two tasks of different durations, a comparison that, based on our literature review, has not been previously explored. Therefore, we can only compare our results to studies that examine the evolution of TOT. A study has founded that participants showed significant TOT effects, with progressive slower reaction time over time (Lim et al., 2010). This decrease in reaction time is usually founded in TOT analyses. Another study that analysed impaired cognitive control and reduced cingulate activity during mental fatigue showed that response time (RT) was influenced by the duration of the task. Participants maintained consistent performance for the first 90 minutes, but after this period the RT increased (Lorist et al., 2005). The results were similar to ours in terms of reaction time, which slowed down after a certain period. However, this was observed after a 90-minute task, whereas our findings were based on a comparison between the 32 minutes task and 16 minutes task. Based on the results from this report, the differences of duration does not seem to highly impact the behavioural performance measures, with only the reaction time having a small to moderate effect. There could be a bigger impact if the task was even longer than 32 minutes, but it was not the objective in this report. Additionally, no comparisons could be made with previous studies, as there have been no findings focusing on task durations similar to ours. It is important to note that the lack of differences between task durations may be influenced by the fact that the 16-minutes group had a higher level of education and more sleep difficulties compared to the 32-minutes group under low cognitive load. These factors could have impacted our results.

Workload analyses

Regarding the different cognitive loads, performance decreased more significantly in the high cognitive load group compared to the low cognitive load group, over time. Specifically, accuracy declined substantially, indicating a large negative effect of high cognitive load. Surprisingly, reaction time under high cognitive load was lower than in the low cognitive load. This suggested that the participants were significantly slower in the LCL at the end of the task than in HCL. This result is in contradiction with the general assumption that a higher cognitive load will decrease the speed response over a period of time (Wang et al., 2014). However, there have been recently doubts on the effectiveness of the reaction time as an objective measurement of mental fatigue (Le Mansec et al., 2019; Wylie et al., 2021). Researchers have even reconsidered the use of reaction time as a valid indicator of fatigue (Völker et al., 2016). The results in this report concerning the reaction time are also emphasizing on the re-examination of reaction time as an objective measurement of mental fatigue. Even in the examination of the impact of time, there was no significant difference between the start and end of the task in the HCL for the reaction time. One reasoning for these results for reaction time could be due to boredom induced by low cognitive load for a longer duration. As mentioned before, boredom could be defined due to not being able to engage with something stimulating enough to keep spontaneous or voluntary attention (Hockey, 2013). It was founded that boredom could be induced by low cognitive load (Ji et al., 2022). A study was done comparing the 0-back or 2-back task, thus task complexity. They founded that while task performance, as measured by the mean reaction time during the 2-back task trials, remained consistent over time, an increase in reaction time was observed during the 0-back task trials (Shigihara et al., 2013). Therefore, a less complex task induces an increase in reaction time compared to the other one. This could, in addition to possible age effect on RT, explain why we founded lower speed reaction in the LCL in a 32-minutes duration task.

Perceptual sensitivity (d') decreased moderately, thus indicating lower sensitivity with high cognitive load. A lower sensitivity represents a shorter distance between hit rate (target) and false alarm rate (non-target). The response bias (C) also deteriorated substantially under high cognitive load, further highlighting the significant impact of cognitive load on performance. Negative response bias indicates that the participant tends to have a more liberal strategy; therefore, participants tend to response more frequently to a signal even if it means possibly increasing false alarm. Thus, participants were less sensitive and adopted a liberal strategy in HCL.

Individuals under high cognitive load experienced greater declines in performance of accuracy, perceptual sensitivity, and response bias over time compared to those under low cognitive load. These results follow the general findings that cognitive performance fatigue can be quantified by changes in accuracy induced by a cognitive task, especially in a high cognitive load (Behrens et al., 2023; Wang et al., 2014). Borragán et al. demonstrated using the TLDB task that the performance of accuracy was significantly higher in the LCL compared to the HCL (Borragán et al., 2017). Concerning the criterion, it was found that there was a higher response bias (conservative bias) during the LCL compared to the HCL. For the sensitivity (d'), there was a higher sensitivity during the LCL compared to the HCL (Wylie et al., 2021). Our results agreed with the recent literature that compared to a low cognitive load, the accuracy declines, sensitivity decreases, and a more liberal behaviour arises in a high cognitive load. However, the reaction time did not show an increase in high cognitive load.

C. Subjective measurements

In this report, the visual analogue scale for fatigue (VAS-f) was used. In the duration analyses, there was a significant increase in the VAS-f score from before to after the TLDB task. This demonstrates that participants felt significantly more fatigue after the task. The same was observed in the difference of workload, with a significant increase in the VAS-f scores over time. In addition, it was observed that there was a significant interaction within the subject about the time and group, which was not the case in the duration analyses. The results indicate that the interaction had a differential impact on the groups over time, with the HCL group experiencing more fatigue than the LCL group. The impact of a cognitive task on the feeling of fatigue has been well researched, with many findings showing that the VAS-F scores tend to be higher after the task compared to before (Borragán et al., 2017; Jacquet et al., 2021). It was even found that the TLDB task produced the highest subjective scores of mental fatigue from pre- to post-task with the visual analogue scale compared to three other cognitive tasks (O'Keeffe et al., 2020).

However, no differences between the groups were found. This means that whether the condition was high or low and whether the task length was 16 or 32 minutes long, the participants did not feel a difference in the feeling of fatigue. These results contradict general knowledge, which usually finds that subjective fatigue tends to be more present in the HCL compared to the LCL condition (Ackerman, 1988; Borragán et al., 2016, 2017; Wylie et al., 2021). For task length, less research have been done, but it is still surprising that no difference in subjective fatigue was noticed between the short and long duration tasks. In a study focusing on subjective cognitive fatigue in multiple sclerosis, it is mentioned that a strong predictor of cognitive fatigue is the time spent on task (Sandry et al., 2014). Another study found that the amount of time on a task could lead to an increase in subjective cognitive fatigue (Johnson et al., 1997).

These results demonstrated the need to have a reliable objective measurement, as the subjective measurement demonstrated that the participants did not feel more fatigue regarding the condition and duration, whereas the objective measurement showed a decline in cognitive performance.

D. Correlation

In the short group with low cognitive load, there were significant negative correlations between changes in perceptual sensitivity with reaction time and response bias scores. In addition, there was a significant positive correlation between accuracy and perceptual sensitivity. Therefore, the better the accuracy of the score was, the higher the sensitivity. The same goes for perceptual sensitivity: the better it can be, the lower the reaction time and lower the response bias, which represent faster response and more liberal bias. For the long group with low cognitive load, there was again a significant negative correlation between the reaction time and perceptual sensitivity but also with accuracy. Thus, if there is a shorter reaction time, then there will have a lower sensitivity and worst accuracy. There was also a significant positive correlation between accuracy and perceptual sensitivity. These results indicated no significant correlations between objective and subjective measurements in the low cognitive load condition. Therefore, whether the task had a duration of 16 or 32 minutes in LCL, there were no link between the behavioural performance and the feeling of fatigue.

The long group with high cognitive load, however, have a significant negative correlation between accuracy and the Visual Analogue Scale for fatigue (VAS-f). No other correlation was observed between the measurements. Therefore, the better the accuracy score, the worse the feeling of fatigue, which is what we would have expected. Therefore, there is a correlation between the objective and subjective measurements regarding the condition (HCL). However, only the accuracy of behavioural performance is correlated to the subjective feeling of fatigue.

The general literature has most of the time failed to find or prove a correlation between subjective and objective measurements (Bailey et al., 2007; Lim et al., 2010). Research with correlation between cognitive fatigue and TLDB task performance also showed no correlation (Borragán et al., 2017). In a study focusing on the relation between subjective and objective measurements, they found no correlation between reaction time and mental fatigue (Völker et al., 2016). As mentioned before, it was then proposed to analyse the relationship between subjective measures and mental fatigue with metrics such as perceptual sensitivity and criterion. Research has found a correlation of VAS-F with sensitivity and criterion. They show a positive and negative correlation with VAS-F for criterion and sensitivity, respectively (Wylie et al., 2021). It was not the case in this report. The difference of task duration in low cognitive load did not show any correlation between subjective and objective measurements, which is similar to the general literature. However, there is a negative correlation between accuracy and VAS-F in the HCL. This could be explained by a stronger induction by the task TLDB of mental fatigue in the high cognitive load.

E. Hypothesis

The study's main hypothesis posited that higher workload and longer task duration would induce greater mental fatigue, which would be observable through a decrease in task performance and an increase in subjective feelings of fatigue. Additionally, it was hypothesized that a 16-minute task duration would not significantly induce fatigue. Finally, it was expected that there would be a correlation between objective performance measures and subjective fatigue, where an increase in perceived fatigue would correlate with a decrease in cognitive performance.

Only the higher workload (HCL) could influence mental fatigue as shown with the impact on different behavioural performance measurements, including accuracy, perceptual sensitivity, and response bias. It was not the case in the longer duration (32 min), as only the reaction time was slightly affected. However, the reaction time in the higher cognitive load was not impacted.

For the subjective outcomes, there was an increase in the feeling of fatigue induced by the task, but it did not differ between the groups.

In contrast to the hypothesis, the 16 minutes task duration did not differ from the 32 minutes duration in both the objective and subjective measurements.

In the duration analyses, no significant correlations between these objective and subjective measures were found. In workload context, a significant negative correlation was found between accuracy and subjective fatigue for fatigue (VAS-f) in HCL, indicating that higher accuracy was associated with higher perceived fatigue. Therefore, the hypothesis met the expectation only in the higher cognitive load.

F. Limitations and strengths

There were some limitations to this report. Firstly, there was no comparison of all the different conditions and durations together, as there was no group that experienced a short task duration with a high cognitive load. Therefore, we could not directly measure the combined impact of condition and duration. Additionally, there was deviation in variance and normalization in the statistical analyses; however, it can be explained by the comparisons of different groups from different studies. The situation was addressed with non-parametric analyses or corrections. Significant differences were found in the two low cognitive load groups regarding education and sleep tendencies. A more profound understanding of the impact of these factors would have provided more insight into their effect on our results. Moreover, the study only controlled for sleep quality and tendencies. While this is an important measure, other factors such as motivation, anxiety, and depression were not considered. Additionally, there were no analyses regarding gender, which could also play a role.

Despite these limitations, the study has several strengths. We were able to partially confirm our hypothesis and found unexpected results, such as the fact that a 16-minute task duration is sufficient to induce mental fatigue. This finding could save time and money in the research field. The data came from different groups and were collected at different time points, which varied our results and did not restrict them to one population or period. Our results confirm that the TLDB task induces mental fatigue under different conditions and with a large sample size. The large sample size is a significant strength, as it is rare in this field with the characteristics of our study.

VI. Conclusion & perspectives

A. Conclusion

In summary, the study's hypotheses were partially supported. A high cognitive load task is effective in inducing mental fatigue but do not increase the reaction time; however, the length of the task alone does not significantly impact the outcomes. Subjective feelings of fatigue were induced by the TLDB task but did not differ across conditions. Surprisingly, the 16-minute duration was sufficient to induce fatigue, suggesting that even shorter task durations can lead to cognitive fatigue. Only a high cognitive load demonstrated a correlation between objective and subjective measurements, where the accuracy was negatively correlated with the feeling of fatigue. Our results validated the TLDB task as a working memory task that induces mental fatigue in young, healthy adults. As previously mentioned, the field of mental fatigue has struggled to establish a gold standard task. The TLDB task could address this issue and harmonize findings in this field. Since our research group consisted of healthy, young adults, factors such as ageing and disease were not considered. It is important to have reliable outcomes for healthy individuals to later analyse the effects of ageing and disease. More research on reaction time as a valid objective measurement should be done, since our outcomes in addition to recent literature have found conflicting results. The workload condition, however, has proven to be an effective method of inducing and measuring mental fatigue.

B. Perspectives

As it is an expanding research domain with many unknowns, there is much more to be explored.

Our results demonstrated some correlations between different metrics. More research focusing on these outputs could analyse potential recurrences from some factors to others. For example, a negative correlation between perceptual sensitivity and response biases was found in the short group with low cognitive load. This correlation was also found in a study analysing Signal Detection Theory (SDT) to better understand cognitive fatigue. They found a strong negative relationship between criterion and d', demonstrating that the two SDT metrics were not independent (Wylie et al., 2021). Analysing these behavioural measurements could enhance our understanding of how fatigue affects the brain.

The same study assessed brain areas' sensitivity to changes in response bias and perceptual sensitivity using structural and functional magnetic resonance imaging (fMRI) while participants performed the task (Wylie et al., 2021). This approach allows for a deeper search into neural mechanisms. Studies involving behavioural analysis, electrophysiology, and various neuroimaging techniques such as fMRI, magneto encephalography (MEG), and positron emission tomography (PET) have shed light on the neural mechanisms underlying physical fatigue and fatigue related to human diseases and syndromes (Ishii et al., 2014). Several physiological indicators have been identified that may serve as objective measures to help understand the mechanisms of mental fatigue. These include biochemical analyses of salivary cortisol, electrocardiography, and measures of brain activity such as electroencephalography (EEG), MEG, and fMRI. EEG is considered the most reliable of these physiological indicators, with significant fatigue-related changes in brain activity observed across several frequency bands (Alpha, Beta, and Theta) in the frontal, central, and posterior brain regions (Smith et al., 2019).

Recent research has also focused on pupil response speed as a marker of cognitive fatigue in early Multiple Sclerosis. A study had found that when comparing healthy controls to newly diagnosed patients with Multiple Sclerosis, performance measurements and fatigue sensations were similar. However, eye metric data showed a susceptibility to cognitive fatigue in patients with Multiple Sclerosis (Guillemin et al., 2022). Therefore, eye metrics could be a more effective objective measurement and more research should focus on this parameter.

Another way to deepen our understanding, especially in working memory tasks, is to analyse the letter and number effects of the TLDB task. As said earlier, performance per block was calculated using a weighted formula, with accuracy for letters accounting for 65% and digits for 35% of the total score. This weighting was chosen to emphasize the information-retrieval aspect, based on research showing that encoding, maintenance, and manipulation in working memory demand more attention than encoding and manipulation alone. Main effect of Component (letters and numbers) was found, with performance being higher for digits than for letters. This indicates a slightly greater complexity of the working memory task (1-back task on letters) compared to the interfering task (odd/even task on digits). This finding justifies the use of a weighted composite score that places greater emphasis on the working memory component (Borragán et al., 2017). Therefore, considering the component factor could add up to our founding and deeper understanding of the brain function

There were no significant differences between task lengths of 16 to 32 minutes. It could be interesting to analyse even longer task lengths. Very little research has been done comparing task length differences to obtain a more efficient task. More research should focus on these parameters, a greater difference of time could induce more significant changes.

Although task performance is considered the gold standard for assessing fatigue, high levels of motivation can enable individuals to maintain performance even under fatiguing conditions. Therefore, solely measuring task performance may not accurately reflect a state of mental fatigue. Analysing more subjective measurements is crucial (Smith et al., 2019). Motivation, depression, and anxiety also impact fatigue (Mozuraityte et al., 2023). The visual analogue scale was used in this report to monitor fatigue, but it can also be used to monitor motivation, depression, and anxiety (Ahearn, 1997).

Finally, a factor that was not tested in this report is the impact of gender. Research founded that some significant differences were observed between women and men on the perceptual sensitivity, with women having a higher score than men (Román et al., 2022). It was also found that gender had a significant impact on response time (Ji et al., 2022). However, in another study, this founding can be contradicted by results showing similar decrease in performance in the reaction time between women and men (Migliaccio et al., 2022). In any case, it would be interesting to analyses the difference of gender.

As stated, the field concerning mental fatigue is still in its research phase, and much more can be done.

VII. Bibliography

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VIII. Appendix:

Appendix 1:

- Data set 1

This study aimed to analyse the effect of mental fatigue on mind-wandering propensity in young adults. In this data set, the age inclusion is between 18 and 30 years old. In the context of this thesis, only the part regarding mental fatigue will be addressed.

- Data set 2

This study had the aim to analyse the effect of the cognitive load on mental fatigue in multiple sclerosis. To do so, 19 multiple sclerosis and 20 matched healthy controls (HC) were recruited in the study. The MS group was recruited at the specialized outpatient clinic of the University Hospital of Liège. The age inclusion was between 18 and 65 years old in both groups. In the context of this thesis, only the group of HC will be analysed and will be categorized as young, which represents the range of 18 to 39 years old.

- Data set 3

The objective of the study was to explore the impact of cognitive load on mental fatigue across the adult lifespan. To do so, the study recruited different age groups, namely young aged between 18–39 years, 40–60 years old for middle-aged, and 60–75 years old for older participants. The age, sex, education level, and chronotype were assessed. The study enrolment took place from February 2019 to May 2022. Participants were recruited through social media and a database of healthy volunteers accessible at the GIGA-CRC in vivo Imaging.

Appendix 2:

The influence of time on performance was analysed for every group. In Group 1 (low cognitive load with 16-minute duration task), accuracy declines as time progresses by comparing the first and last block of the task, while reaction time increases, and signal detection scores for d' decrease, all were significant (Table 1). The effect sizes were quite high for the metric (d') with 0.559 and especially for the accuracy with 0.718. The signal detection score for the criterion decreased over time, however it was not significant (Table 1). Similar trends are observed in Group 2 (low cognitive load with 32-minute duration task), with significant accuracy deterioration and bigger reaction time over time (Table 2). Signal detection scores also drop over time, with significant results for again the d' but not for the criterion (Table 2). The effect sizes were smaller in group 2 with the highest effect size being 0.585 for the reaction time (Table 2).

Table 1: Impact of time from low cognitive load in the16-minutes duration task.[1]

	Group	**Mean (score)**	**SD**	**P-value (Wilcoxon)**[a]	**Effect size**
Accuracy	Bin 1	0.95	0.036	<.001***[2]	0.718
	Bin 4	0.92	0.065		
RT	Bin 1	0.54	0.088	0.034*[2]	-0.273
	Bin 4	0.56	0.101		
Metric (d')	Bin 1	3.749	0.897	0.002**[2]	0.559
	Bin 4	3.174	0.988		
Metrics (C)	Bin 1	-0.468	0.456	0.519[2]	0.120
	Bin 4	-0.535	0.432		

RT: Reaction time, **d'**: perceptual sensitivity, **C**: criterion.

[1] Paired-sample t-test with the variable paired (mean score of the first and last block of the task).

[2] *** p <.001, **p <.01, *p <.05

[a] Wilcoxon test due to deviation of normality.

Table 2: Impact of time in low cognitive load in the 32-minutes duration task.[1]

	Group	**Mean (score)**	**SD**	**P-value (Wilcoxon)**[a]	**Effect size**
Accuracy	Bin 1	0.94	0.056	<.001***[2]	0.403
	Bin 8	0.92	0.064		
RT	Bin 1	0.55	0.098	<.001***[2]	-0.585
	Bin 8	0.58	0.113		
Metric (d')	Bin 1	3.431	0.954	0.031*[2]	0.324
	Bin 8	3.041	1.060		
Metrics (C)	Bin 1	-0.538	0.423	0.490[2]	-0.104
	Bin 8	-0.488	0.379		

RT: Reaction time, **d'**: perceptual sensitivity, **C**: criterion.

[1] Paired-sample t-test with the variable paired (mean score of the first and last block of the task).

[2] *** p <.001, **p <.01, *p <.05

[a] Wilcoxon test due to deviation of normality.

Regarding the high cognitive load in 32 minutes duration task, there was significant difference between the first and last block of the task in the performance of accuracy, perceptual sensitivity, and criterion (Table 3). The effect size for each of these outcomes were ranging from 0.737 to 0.874 (Table 3). There was no significant difference for the reaction time.

Table 3: Impact of time in high cognitive load in the 32-minutes duration task.[1]

	Group	**Mean (score)**	**SD**	**P-value (Wilcoxon)**[a]	**Effect size**
Accuracy	Bin 1	0.864	0.098	<.001***[2]	0.874
	Bin 8	0.769	0.144		
RT	Bin 1	0.507	0.086	0.535	-0.052
	Bin 8	0.503	0.097		
Metric (d')	Bin 1	2.591	0.975	<.001***[2]	0.792

	Bin 8	1.782	1.069		
Metrics (C)	Bin 1	-0.597	0.358	<.001***[2]	0.737
	Bin 8	-1.004	0.561		

RT: Reaction time, **d’**: perceptual sensitivity, **C**: criterion.

[1] Paired-sample t-test with the variable paired (mean score of the first and last block of the task).

[2] *** p <.001, **p <.01, *p <.05

xon test due to deviation of normality.