CBUSO2000E (contract no: 30397)

THE INFLUENCE OF FATIGUE ON SUBJECTIVE USABILITY OF DIGITAL PRODUCTS

Master thesis

Business Administration and Ebusiness

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Number of characters: 102801

Number of pages: 56

Date of submission: 15/05/2023

1. Introduction

Background and motivation for the study

The advent of technology has brought about significant changes in the world over the past century. In particular, the widespread availability of smartphones has revolutionised the way people interact with digital technologies. According to recent data, the majority (85%) of users in developed countries own a smartphone, with daily usage averaging over three hours and frequent checking occurring every 15 minutes while awake (Howarth, J. 2022). In Europe, mobile subscriptions have reached 86% of the population, with further growth projected in the coming years (Greenwood, 2022a,b). These trends highlight the increasing importance of understanding the impact of the growing presence of digital technologies on user experience, including the potential for fatigue and its effects on cognitive and physical functioning.

Reasonably, the question arises whether the human brain is physiologically equipped to handle such technological advancements. Neuroscience contradicts this notion, stating that 200,000 years of brain evolution have made it an exceptional tool to deal with various sets of challenges and endowed it with an impressive ability to adapt. Nevertheless, scientists often refer to it as "an ancient brain in the modern world" (Gazzaley, A., 2017), referring to its inability to cope with the overwhelming amount of information it must process on a daily basis. “So many technological innovations have enhanced our lives in countless ways, but they also threaten to overwhelm our brain’s goal-directed functioning with interference”(Gazzaley, A., 2017).

The feeling of tiredness, or fatigue, is one of the universally recognized states that is experienced by everyone on a regular basis. There is not a single person in the world who does not get tired. It may feel like a low mood - tiredness, weariness, or an unfocused state of mind - distraction, discomfort, frustration, or a bodily state of tension, headache, eye strain, and pain in muscles and joints. Under the umbrella of fatigue, mental fatigue is defined as a subjective feeling of tiredness or exhaustion resulting from prolonged cognitive activity, characterised by reduced motivation, attentional capacity, and cognitive flexibility, and accompanied by physical symptoms listed for tiredness, as well as sleep disturbances.

The notion of mental fatigue as a subjective experience of exhaustion resulting from prolonged cognitive activity, has not always been experienced and recognized as a problem. Rather, it emerged as a societal issue during the 1900s as a consequence of the Industrial Revolution and the introduction of organised and supervised work at factories. This state of fatigue was reported to adversely affect work productivity, leading to decreased performance and financial losses. Consequently, the first investigations into fatigue aimed to determine the duration of work or study that could be undertaken without incurring negative consequences in the form of reduced productivity. Subsequently, researchers also aimed to find out the consequences of such a decrease in output and the ways to counter them.

The majority of ergonomic norms regarding the recommended duration of study and work hours stem from these early years of research in the beginning of the 20th century and are still in use (Wickens, 2002).

In contemporary times, mental fatigue has become a prevalent issue due to the unlimited source of information, entertainment, and distraction provided by the World Wide Web. Similarly to the physical fatigue becoming “the problem” of the 20th century, “mental fatigue” is generally used to address the state of mind that reduces the quality of life and therefore has negative economic impact. This mental state can also significantly impact an individual's cognitive and physical functioning, leading to decreased productivity, impaired decision-making, and subjective feeling of happiness.

In the context of user experience studies (UX), fatigue can also influence how users interact with digital technologies. Therefore, understanding the relationship between fatigue and UX is critical for designing effective and engaging digital experiences that promote user satisfaction and well-being.

The relationship between mental fatigue and the use of digital products has received limited attention from both cognitive science and UX perspectives (Hockey, 2013; Benyon, 2019; Enders, 2016; Yablonsky, 2020; Grant, 2018; Allen et al., 2012; Lacey, 2018). However, given that many digital products are likely to be used by individuals who are fatigued, such as those using food and other service delivery apps, taxi and transport-related apps, e-commerce sites and government services sites, it is important to address this concept.

This paper aims to explore the current state of research on fatigue and UX by examining the factors that contribute to mental fatigue in digital contexts, the effects of fatigue on user behaviour and performance, and the strategies for mitigating fatigue in UX design.

Research questions and hypotheses

Research question: The impact of cognitive (mental) fatigue on subjective perception of usability of digital products.

Hypothesis: mental fatigue is expected to negatively impact subjective perception of usability, due to:

- reduced cognitive resources and attentional capacity, leading to increased cognitive strain,
- difficulty concentrating, processing information, and making decisions
- reduced impulse and emotion control.

These factors are expected to lead to frustration and decreased satisfaction with the usability of a website, resulting in lower scores on the System Usability Scale, which would indicate that the website is perceived as less usable and less satisfying to use.

Significance and contribution to the field

As will be shown in the literature review, fatigue is a very complex state that affects cognition in several ways. The mechanism of fatigue is not fully understood, research says that it seems to use shared underlying mechanisms (neural paths) similar to sleep deprivation, although these states are not identical (Dongen et al, 2011)).

Knowing that fatigued users are more likely to experience cognitive difficulties while using digital products, User Experience designers can create interfaces that are more accessible and inclusive for users with other (temporary or permanent) cognitive disabilities. Since fatigue manifests in ways that are similar to sleep deprivation, attention disorder, and executive function disorder, digital design for tired users has a potential to simultaneously increase accessibility for the following group of users:

- Fatigued users, who access digital products after or during daily work. Busy professional environment often requires juggling multiple tasks and responsibilities, leading to decision fatigue and cognitive overload. Designing for tired users can help reduce the cognitive demands of using the system and make it easier to complete tasks efficiently.

- Older adults: older adults may experience cognitive decline and fatigue, so designing for tired users can help make the interface more accessible and usable for them.
- Users with chronic health conditions, associated with chronic fatigue
- Shift workers: Shift workers may have irregular sleep schedules and experience fatigue, so designing for tired users can help them stay focused and productive during their work hours.
- Users with various sleep disorders.
- Users with cognitive impairments, such as short time memory issues.
- Users with executive functions issues and deficits in cognitive control (ADHD, PTSD, traumatic brain injury (TBI), major depression, schizophrenia, Alzheimer’s disease (Nieoullon A. 2002).
- Users in high-stress environments: users in high-stress environments, such as emergency responders or military personnel, may experience fatigue due to the demands of their work.

Overall, the principles of simplicity, clarity, and consistency can benefit all users, regardless of their cognitive abilities or levels of fatigue. Designing for tired users must take into account the performance changes associated with fatigue, and aim to reduce the cognitive demands of using the system and facilitate their ability to make quick and accurate decisions, as well as make errors easily reversible.

2. Literature Review

Fatigue

Definition and historical perspective

Common present-day understanding of fatigue is usually framed in terms of the depletion of energy resources from work (or overwork). The definition from The Oxford English Dictionary defines fatigue as “weariness resulting from bodily or mental exertion” (OED, 2006).

However, historically researchers have taken several different approaches to the definition of mental/cognitive fatigue over the past century or so. The terms “cognitive fatigue”, “cognitive workload”, “mental fatigue” and “mental load” have been used in a similar context over the available literature.

The Industrial Revolution was followed by the rapid rise of research on work and fatigue, with early studies of fatigue focused on the question of how long can the school day last without fatigue-related decrement in performance and learning (Ebbinghaus1896-1897).
Ebbinghaus (1896-1897), being an early researcher, was mainly interested in the measurable effects that prolonged work days had on the performance of cognitive functions of memory, judgement, and reasoning.

With the changing format of work, from majorly self-paced work rhythm to the industry standards of rigidly planned and supervised workdays at the factories, the phenomenon of worker fatigue has attracted the attention of economists and researchers (Hockey, 2013). Due to the major decrease in performance attributed to fatigue, it was recognized as a major problem in the society around the 1900s, “the disease of the modern age” (Rabinbach, 1992).

At the same time, the term “mental fatigue” was first used as early as 1900 (Thorndike,1900).

Overall, during the period between 1900 and 1940, a plethora of detailed empirical studies were conducted, with the application of knowledge to both educational and industrial practice (Hockey, 2013).
Early research tended to concentrate on objective measuring of fatigue, without separating it into physical and cognitive aspects, whereas later (e.g. Muscio, 1921a, 1921b) more attention was paid to the subjective aspects of mental fatigue, such as attitude and motivation.
In the 1940s, due to World War II, fatigue was recognized as an issue of high importance for both the military and industry (Patankar et al, 2022). In fact, a significant amount of research was carried on during World War II or shortly after (Ackerman, 2011).
Since the 1980s, the rise of new models and theories of cognitive processing, attention, and motivation has led to increased research.

According to Ackerman (2011), the progress in fatigue studies and the variety of approaches can be more accurately presented through the dependent variables that the researchers studied:

- Performance effects (with cognitive ability tests and information-processing assessment). The most frequently used measures are the number of items answered correctly in a fixed period of time; error frequency or proportion; time spent to complete the task.
- Reaction times for responses in test situations; aim - to evaluate the blocks in attention (Bills, 1931)
- Changes to the number of items attempted in a fixed period of time; (e.g. Huxtable et al., 1945)
- Patterns of error over time; (e.g. Starch et al., 1917 found that under fatiguing conditions "....when an error does occur it is followed immediately by other errors more and more frequently as the period of work continues." Desmond and Matthews' (1997) crossover study and Schellekens et al., 2000 both studied the effects of tiredness and found that fatigued subjects had slower reaction times, made more errors, and may have exerted less effort on a task.)
- Quality of responses. (e.g. Vodanovic, 1967, found that under fatigue subjects started giving more and more conformed associations. Webster et al, 1996, found that fatigue

can increase the “need for cognitive closure”; Klein et al, 2003, observed the issues of changes in judgement during an extended performance on a task.)

- Changes in the riskiness of responding, such as a shift from purposive responding to random responding (e.g. Yamamoto, 1995).

Hockey (1997) proposed a model that explains the processes underlying mental fatigue and its relationship with performance during continuous operations. The model assumes that there is a physiologically-based limit to mental resources, and as these resources become depleted, mental effort increases, leading to performance deficits. The supervisory controller decides whether to compensate for diminished mental resources with increased effort or alter the performance goals to utilise fewer resources. Cognitive load or task difficulty may also mediate mental fatigue effects, with more difficult tasks requiring greater mental effort and producing fatigue faster than easier tasks. It is important to note that overt performance deficits are not a necessary consequence of fatigue, as increased effort can compensate for declining mental resources. Therefore, the subjective aspect of cognitive fatigue is the perception that mental effort must be increased to maintain performance.

Fischler (1999) provided a comprehensive definition of fatigue as the decline in performance that occurs during prolonged or repeated tasks, accompanied by a subjective sensation. This subjective aspect of fatigue is the individual's awareness of the increasing mental effort required to maintain cognitive performance during extended periods.

Schellekens et al. (2000) conducted a study comparing the effects of mentally demanding workdays to less demanding ones and found that subjects had slower reaction times, made more errors, and may have exerted less effort on a subsequent memory-search task after the more demanding workdays. This suggests that greater fatigue was caused by a relatively increased cognitive load, resulting in performance deficits on the following task, similar to Desmond and Matthews's (1997) findings.

With the advent of medical research on chronic conditions, a new form of weariness has emerged, namely chronic fatigue, which is characterised by persistent and extreme exhaustion. Chronic fatigue is a multidimensional construct that encompasses physical and mental fatigue, as well as reduced activity levels and motivation, as evidenced in studies on chronic illnesses like cancer (Smets et al., 1996).

Alongside medical professionals, the patients themselves conducted their own research aimed to clarify the concept of chronic fatigue to non-affected individuals. One such theory, widely used by patients to communicate the idea of energy preservation strategies that chronically fatigued people employ, is the Spoon Theory (Miserandino, C.,2020), a metaphorical concept of limited energy supply experienced by people with chronic illness. It was created by Christine Miserandino, who lives with lupus, a chronic autoimmune disease that causes fatigue, joint pain, and other symptoms. It provides the internal perception of chronic fatigue and corroborates the theory of limited physiological resources offered by Hockey (1997), which suggests that there is a biological limit to mental resources, and as these resources are depleted, mental effort must be increased, resulting in a decline in performance, therefore the Spoon Theory is worth an in-detail explanation.

The Spoon Theory is centred around the idea that people with chronic illness or fatigue have a limited amount of energy or "spoons" to use each day. The metaphorical “spoons” represent units of energy that are required to complete daily tasks such as getting dressed, taking a shower, cooking a meal, or going to work. People with chronic illness or fatigue have to carefully manage their “spoons” throughout the day to ensure they have enough energy to complete essential tasks. They may have to make choices and prioritise activities based on how many “spoons” they have available.

The Spoon Theory has become a popular way for people with chronic illness or fatigue to explain their experiences to others and raise awareness about the challenges they face. It has also been used in UX, by designers and developers to create interfaces that are more accessible and inclusive for people with disabilities or chronic conditions.

The Information Age, sparked by the digital revolution, has introduced another profound change for human brains: now we are surrounded by technology, the information itself becoming an ultimate commodity. This “ever-expanding explosion in the variety and accessibility of technologies with enticing sounds, compelling visuals, and insistent vibrations that tug at our attention while our brains attempt to juggle multiple streams of competing information" (Gazzaley, A., 2017), contributes to the widespread mental fatigue pandemic. Technological intrusions like smartphones were found to have "unintended consequences of fatigue". (Ackerman, 2011). Gazzaley, (2017), writes that there is a growing tendency for modern technology users to "media multitask". He quotes the study of Dr. Rosen's laboratory, having discovered that the typical teen and young adult believes they can multitask using six to seven different forms of media at the same time (Carrier et al, 2009). There are also studies showing that up to 95 % of the population report media multitasking each day (Anderson et al, 2012). And another study reports that US adults and teenagers check their phones up to 150 times a day, or every 6 to 7 minutes that they are awake (Ahonen, T, 2011). Similar studies in the UK show that more than 50% of adults and ⅔ of young adults and teens check their phones no less than every hour (Gazzaley, A., 2017).

One of the main questions the researchers are still trying to understand is why we use digital devices so much and why we find the information they provide us so compelling and irresistibly attractive. Gazzaley (2017) argues that humans are, at their core, information-seeking creatures, and this behaviour favours the accumulation of information. "This notion is supported by findings that molecular and physiological mechanisms that originally developed in our brain to support food foraging for survival have now evolved in primates to include information foraging" (Hills T, 2006). Data to support this assertion rests largely on the observation that the dopaminergic system, which is crucial for all reward processing, plays a key role in both basic food-foraging behaviour in lower vertebrates and higher-order cognitive behaviour in monkeys and humans that are often dissociated from clear survival benefits (Wise, R. 2004, van Schouwenburg et al, 2010, Watanabe et al, 1997).
A study of primates has shown that Macaque monkeys responded in a similar way both to receiving information and food or water. Bromberg-Martin et al (2009) found that "single dopamine neurons process both primitive and cognitive rewards".

Correspondingly, within UX this theory has shaped the "information scent" model, referring to the degree to which the information presented on a digital interface matches the user's goals and expectations. It is a measure of how well the user can predict the relevance and usefulness of the information based on the cues provided by the interface, that directs users' attention with cues just like the scent guides foraging/hunting behaviour in animals. In UX design, information scent is used to guide users toward their goals, increase engagement, and improve the overall user experience.

Numerous studies in psychology, physiology, and neuroscience have established that mental exhaustion is an inevitable consequence of humans' pursuit of dopamine-fueled information gathering, as well as a response to the more taxing demands of the modern world, which inundated our minds with an abundance of information both at work and during leisure time. The human brain, being primordial in nature, is not ideally adapted to the novel digital milieu and thus tends to become fatigued and distracted with ease.

According to Ackerman (2011), the major factors that affect subjective fatigue, can be divided in four groups:

1. Affective factors associated with baseline (pre-task) subjective fatigue: type A neuroticism/anxiety/impulsivity, extroversion, chronic fatigue, negative affect.
2. Factors associated with cognitive resources available, such as time on task, ability, arousal, recency of last meal, off-task distractions, amount of sleep/rest, drugs.
3. Transient affective factors, such as mood, current concerns, evaluation apprehension.
4. Conative factors: task interest, approach motivation, avoidance motivation, performance utility and effort utility.

Mental fatigue represents a psychobiological state with subjective (e.g., an increase in feelings of tiredness), behavioural (e.g., motivation decrease or reaction time increase), and physiological (e.g., alterations in the electroencephalogram signal) derivations in humans (Díaz-García et al, 2021). This state may be caused by brain-demanding tasks (mental, or cognitive load), affected by emotional state (stress, anxiety) and cognitive (cognitive flexibility, the state of working memory) aspects.
Furthermore, it is important to consider that mental fatigue can vary among individuals due to personal differences, which may explain why the same task does not induce the same level of mental fatigue in different people or why mental fatigue manifests differently (i.e., subjective, behavioural, or physiological) among participants. Van Cutsem et al (2017) suggest that using a combination of several measures (namely, subjective, behavioural, and physiological) is the

best approach to identify the presence of mental fatigue. However, changes in all three areas may not necessarily appear in mentally fatiguing conditions and could depend on the individual's characteristics. For instance, cognitive performance may not necessarily decline in the presence of mental fatigue due to the compensatory effort system. Therefore, using different measures of mental fatigue can help identify its causes and explain why it impairs performance.

Additionally, it is important to consider the context in which mental fatigue occurs. For example, mental fatigue may be more likely to occur in a monotonous or repetitive task, or when there are time pressures or high cognitive demands. Environmental factors such as noise levels, temperature, and lighting may also contribute to mental fatigue. Therefore, it is important to consider both individual differences and contextual factors when studying and addressing mental fatigue.

Summary: mental fatigue is a complex phenomenon that is associated with a decline in subjective resources and sometimes a decrease in overt performance, which likely has a physiological basis in the depletion of mental resources during cognitive tasks. Research suggests that fatigue effects are due to the reduction in the efficiency with which mental resources are allocated rather than a decrease in the actual amount of available resources. This is supported by studies such as Desmond and Matthews' (1997) and Schellekens et al., (2000), which found that a fatiguing task resulted in poorer performance on a subsequent unrelated task.

It is important to use a combination of subjective, behavioural, and physiological measures to identify its presence and consider individual and contextual factors when studying and addressing mental fatigue.

By better understanding the causes and effects of mental fatigue, we can develop strategies to prevent or mitigate its negative impacts on users’ performance and well-being.

Conceptual overlap of fatigue with concepts of sleepiness, stress and motivation deficits

The frequent association of sleepiness with fatigue in research literature can be attributed to the challenge, if not impossibility, of discerning between their effects. Once fatigue sets in, the circadian rhythms induce sleepiness, and these two distinct and possibly separable sources exhibit comparable impacts on performance. (Balkin Wesensten, 2011). The research indicates that both states are likely to use shared underlying mechanisms (neural paths), although these states are not identical (Dongen et al, 2011). One of the major differences between these two states seems to be the fact that fatigue can be reversed by rest, in contrast to sleepiness which cannot be reversed by rest alone.

"Sleep deprivation, psychological stress, and alcohol intoxication are three common factors that induce powerful influences on cognitive control" "Just one night of poor sleep can lead to less efficient filtering out of important information from junk as well as inefficient visual tracking (Gazzaley, A. 2017) - in this, otherwise very detailed work written by a neuroscientist, fatigue is not even mentioned, its place fully taken by sleep deprivation. Sleep deprivation can affect memory, creativity, verbal creativity and even things like judgement and motivation and being engaged.

"Perusal of the scientific literature over the past 20 years reveals a tendency for several authors to use the word fatigue as a synonym for sleepiness or as a synonym for tiredness (with the latter connoting general decrements of alertness, performance, motivation, and/or mood without implying a particular causal factor). In fact, the word fatigue has been applied so inconsistently in the scientific literature that it has actually been suggested that "the term [fatigue] . . . has yet to be defined in a concrete fashion"" (Balkin & Wesensten, 2011)

To summarise the above, sleep deprivation is found to cause time-on-task-dependent performance deficits (a progressive decrement of performance across the duration of a cognitive task), even if the tasks are not cognitively challenging. But time-on-task effects can also be detected in subjects that are not sleep deprived.

Subsequent performance of two tasks, first one being cognitively challenging, reduces performance for the second task in the sequence, suggesting some sort of depletion of mental resources during task 1, or issues with resource allocation (Balkin Wesensten, 2011)
Performance deficits are exacerbated in case of extended time on task and sleep deprivation combined. Time-on-task effects are evident prior to significant sleep loss, are reversed by rest (time off task), and exacerbated as the sleep deprivation increases (Wesensten et al, 2004).
In real life, however, sleepiness and fatigue effects are typically confounded (and, as the results of Gunzelmann et al, 2011) confirm, the declines observed in individuals deprived of sleep are qualitatively similar to the declines observed as a consequence of prolonged time on task, and to date, the nature of interactions between these two factors remains relatively unexplored.

Failing to differentiate between performance deficits caused by sleep loss and circadian rhythmicity (i.e., sleepiness) versus those caused by time on task (fatigue) during continuous operations is more than just a matter of words. It represents a failure to identify the effects of two distinct and separate sources of potential variation in performance. When there is no clear distinction between the effects of sleepiness and fatigue, it is impossible to determine the exact nature of performance deficits during continuous operations. These deficits could potentially be due to either sleepiness, fatigue, or a combination of both (Balkin & Wesensten, 2011). Without specifying the relative contributions of sleepiness and fatigue, it is difficult to identify the most effective countermeasures to sustain and optimise performance during continuous operations.

Summary: fatigue as a complex construct that includes physical and mental exhaustion, reduced activity levels, and motivation, is often used alongside or even interchangeably with sleepiness, but they are distinctly different sources of potential variation in performance. Historically, there was and still is a lot of interference between the effects of sleep deprivation and tiredness, and both these states are likely to use similar neural paths. Sleep deprivation, psychological stress, and alcohol intoxication are common factors that induce powerful influences on cognitive control that cannot be reliably separated from fatigue and exacerbate it. The impact of stress on cognitive control is such that some amount of it can be beneficial (as mentioned in tiredness and resources allocation theory) while excessive amounts are harmful to performance.

Fatigue-associated performance changes

Under fatiguing conditions, performance sometimes declines, sometimes remains unchanged or sometimes even increases as time on task increases (Ackerman, 1988). This confusing statement is perfect to address the changes in performance associated with tiredness.

The literature review indicates that there are few, if any, replicable changes in mean performance levels associated with cognitive fatigue.

Although performance decrements are generally regarded as the gold standard of fatigue research, they are by no means routinely observed...because performance may be protected by the use of effortful strategies that help maintain task goals, especially when individuals are highly motivated. (Hockey, 2013).

Desmond and Matthews (1997) conducted a study to investigate the impact of cognitive work-related depletion on subsequent task performance. They hypothesised that if fatigue effects were caused by the depletion of physiologically based cognitive resources, then performing a fatiguing task would negatively affect performance on subsequent unrelated tasks. In their crossover study, they compared the effects of a fatiguing simulated driving task with a control driving task that did not require a secondary task. Towards the end of each simulated drive, a third task was introduced, which required subjects to detect visual stimuli in the periphery of the visual display.
It was found that the fatiguing condition resulted in poorer performance on this third task, indicating that the subjects' previous exposure to the secondary task had been more fatiguing. Desmond and Matthews interpreted their results as suggesting that fatigue effects reduce the efficiency with which mental resources are allocated rather than reducing the actual amount of available resources. However, their study did not provide a definitive test of these possibilities, which are not mutually exclusive. Similarly, Schellekens et al. (2000) compared

the effects of workdays involving mentally demanding tasks with less demanding ones on subsequent memory-search task performance as an indicator of fatigue effects. They found that subjects had shorter reaction times, made more errors, and may have expended less effort on the postwork task following more demanding workdays.

The studies conducted by McAllister et al. (1999, 2001) utilised fMRI to examine working memory in individuals with mild traumatic brain injury (TBI). There were no performance differences found between the mild TBI and healthy control groups during the working memory task. McAllister and colleagues suggest that individuals with mild TBI require additional cerebral resources (increased activation in the right cerebral hemisphere in regions homologous to left hemisphere activation observed in healthy controls) "to compensate for processing inefficiencies," despite similar objective performance. Subsequent functional imaging studies in individuals with multiple sclerosis (MS) and Chronic Fatigue Syndrome (CFS) have reported similar results to those observed in TBI subjects (Staffen et al., 2002; Hillary et al., 2003; Chiaravalloti et al., 2004; Schmaling et al., 2003).

Ackerman (1998) points out that an individual's subjective fatigue is determined by the initial level of attentional resources. As the said level goes low, subjective fatigue will increase, and the individual perceives that they have few resources available for the task, or anticipate a high degree of off-task distractions. If additional, reserve resources are allocated to the task, then performance may not decrease, but fatigue will increase at an even faster rate. When the level of subjective fatigue reaches a critical threshold, the individual is expected to reduce effort; motivation to perform the task may override these subjective fatigue concerns and ignore them in order to continue/finish the task.

In this concept, performance deficits constitute sufficient evidence of fatigue, but these deficits are not necessary consequences of fatigue (Balkin&Wesensten, 2011).

In addition to a gradual reduction in commitment to the continuing task, fatigue inculcates a preference for low effort strategies in the period following a demanding or stressful work session (Hockey, 2013).

In a research by Schellekens et al, (2000) the subjects were engaged in mentally demanding extended tasks one day, and much less demanding “jobs' ' on the other day. Then, after each workday, they performed memory-search tasks as an indicator of fatigue effects. It was found, that after more demanding workdays, subjects had shorter reaction times, made more errors and likely expended less effort on the post work task (based on a heart rate variability measure).The conclusion was that relatively increased cognitive load during the workday caused greater fatigue, leading to performance deficits on a subsequent task. Like Desmond and Matthews's study, Schellekens et al.'s findings suggest that greater fatigue can be inferred from performance deficits on a subsequent task resulting from a relatively increased prior cognitive load.

The impact of fatigue on the executive functions

Executive functions are ”mechanisms that control the content and progression of cognitive processes” (Persson et al, 2007). These processes are essential for goal-directed behaviour, decision-making, and problem-solving. The executive functions include a range of cognitive processes such as working memory, inhibitory control, selective attention, overall cognitive flexibility, planning, and reasoning. These functions work together to enable individuals to manage their behaviour, emotions, and thoughts in an adaptive and flexible manner (Diamond, A., 2013). Considerable neuropsychological and neuroimaging evidence has emerged to indicate that these central executive functions can be differentiated into several relatively independent functions, as reported by Smith and Jonides (1999). While a definitive taxonomy is yet to be established, executive functions such as response inhibition, selective attention, and task-switching are widely recognized to regulate cognitive processes for successful task completion. Recent neuroimaging studies suggest that these functions may be localised in discrete regions of the prefrontal cortex. The prefrontal cortex is the brain region responsible for executive functions. This region is located at the front of the brain and is involved in a range of cognitive processes such as attention, memory, and decision-making. The prefrontal cortex is also responsible for regulating emotions, inhibiting inappropriate behaviours, and planning and executing complex actions.

Furthermore, various tasks designed to isolate specific executive processes activate common regions of localised activation, as observed in the study by Thompson-Schill et al. (1997). These findings indicate that distinct executive mechanisms involve fundamental and dissociable processes that may be shared across different cognitive tasks.

Working memory is a key component of executive functions. It refers to the ability to hold and manipulate information in the mind over a short period of time. "Holding information in mind and mentally working with it" (Wilson et al, 2021) It is a critical component of many everyday tasks, such as learning, problem-solving, reading comprehension and decision-making. Individuals with poor working memory may struggle with these tasks and may require additional support to succeed.Mental fatigue can impair working memory performance, which can have negative consequences on an individual's ability to complete tasks effectively.

Several studies have investigated the effects of mental fatigue on working memory performance. For instance, Van Cutsem et al (2017) found that participants who completed a mentally fatiguing task showed a decline in working memory performance compared to those who completed a non-fatiguing task.

The mechanisms underlying the effects of mental fatigue on working memory are not fully understood. However, it is believed that mental fatigue may reduce the availability of cognitive resources needed to perform working memory tasks effectively. For example, the prefrontal cortex, which is responsible for working memory, may become less active under conditions of mental fatigue.

Inhibitory control refers to the ability to inhibit or suppress inappropriate behaviours or responses. Inhibitory control is essential for self-regulation and impulse control. Individuals with poor inhibitory control may struggle with behaviours such as impulsivity, aggression, and addiction.

Selective attention refers to the ability to focus on relevant information while ignoring distractions. It is essential for tasks such as reading, driving, problem-solving and listening to a conversation in a noisy environment. Individuals with poor selective attention may struggle with tasks that require sustained focus and may be easily distracted.

Studies have shown that mental fatigue can impair selective attention performance. Mentally fatigued individuals demonstrate reduced selective attention capacity as well as impaired ability to selectively attend to relevant information in a visual search task.

The mechanisms underlying the effects of mental fatigue on selective attention are not fully understood. However, it is believed that mental fatigue may reduce the ability to filter out distractions and focus on relevant information. This may be due to reduced activity in brain regions responsible for selective attention, such as the parietal cortex.

Cognitive flexibility refers to the ability to switch between different tasks or mental sets and to adapt to changing situations. It is essential for problem-solving, decision-making, and creativity.
Research has shown that mental fatigue can also impair cognitive flexibility. For example, a study by Hockey et al (2003) found that participants who were mentally fatigued showed reduced cognitive flexibility compared to non-fatigued participants. Mental fatigue also impaired participants' ability to switch between tasks in a task-switching paradigm. It is believed that mental fatigue may reduce the ability to inhibit irrelevant information and to shift attention between different tasks. This may be due to reduced activity in brain regions responsible for cognitive flexibility, such as the prefrontal cortex.
Individuals with poor cognitive flexibility may struggle with rigid thinking and may find it difficult to adapt to changes in their environment.

Planning and reasoning are also important components of executive functions. These processes involve the ability to set goals, plan actions, and make decisions based on available information. These cognitive processes are essential for achieving long-term goals and for making informed decisions.
Mental fatigue impairs the ability to plan and execute a sequence of actions, the ability to reason logically and make decisions in a complex task. It is attributed to mental fatigue possibly reducing the ability to maintain attention and to process information efficiently.

Individuals with poor planning and reasoning skills may struggle with tasks such as time management, organisation, and decision-making.

Summary:

Under fatiguing conditions, the following impact on performance is expected:

- Decline of performance or unchanged ("protected") performance with more cognitive resources allocated to the task (same amount of work done "costs" more in a fatigued state.
- Shorter reaction times, more errors, and oftentimes adoption of less effort strategy for a subjectively less important task.
- Cognitive functions:
    - Working memory under fatigue can be responsible for poorer reading comprehension and decision-making. Mental fatigue can impair working memory performance, which can have negative consequences on an individual's ability to complete tasks effectively.
    - Inhibitory control is decreased under fatigued decreases under fatigued conditions, leading to poorer self-regulation and impulse control.
    - selective attention capacity is reduced in fatigued individuals, as well as the ability to selectively attend to relevant information in a visual search task.
    - cognitive flexibility is reduced under fatigue, as well as the ability to switch between tasks in a task-switching paradigm. Fatigue may reduce the ability to inhibit irrelevant information and shift attention between different tasks.
    - planning and reasoning. Mental fatigue impairs the ability to plan and execute a sequence of actions, the ability to reason logically, and make decisions in complex tasks.

UX design principles and theories

How is mental fatigue addressed in UX

It is a well-known fact in Human-Computer Interaction studies, that the amount of cognitive effort that a person has to apply to ensure the interaction, affects said interaction in many ways. The cognitive effort required for an interaction is usually defined as the amount of mental resources a user needs to allocate in order to complete a task or achieve a goal using a computer system. This cognitive effort can be influenced by various factors such as the complexity of the task, the user's prior knowledge and experience with the system, the system's design and interface, and the user's cognitive abilities.

In the context of this work, that researches fatigue, the concept of "user's cognitive abilities" encompasses a range of mental states and capacities that can influence the level of effort required for an interaction, including fatigue.

Designers must take into account the potential impact of fatigue on a user's cognitive abilities when creating computer systems. Strategies such as providing breaks or designing interfaces that minimise the need for sustained attention can help reduce the cognitive effort required for interactions.

When users have to exert more cognitive effort, they may take longer to complete tasks and make more errors. This is because their mental resources are being depleted, leading to reduced attention and concentration levels. Furthermore, high cognitive effort can lead to frustration and cognitive overload, causing users to abandon the task or the system altogether.

Furthermore, it is important to note that cognitive abilities can vary widely among individuals, depending on factors such as age, health, and cognitive style. Therefore, designing for the users that may have difficulty focusing on tasks, recalling information, and making effective decisions (all of the performance changes, associated with fatigue and leading to slower performance and higher error rates), would make the system more accessible for wider audience, namely those who cannot withstand higher cognitive load due to age, mental health, chronic fatigue or disorders akin to ADHD.

This issue is usually tackled in UX by providing users with multiple modes of interaction or adapting interfaces based on user preferences.

In addition to affecting user performance, cognitive effort also influences user satisfaction and engagement. Users who have to apply less cognitive effort tend to have more positive experiences with the system, leading to higher levels of satisfaction and engagement. Conversely, when users have to apply excessive cognitive effort, they may feel overwhelmed and disengaged from the system.

To mitigate the negative effects of cognitive effort on interaction, designers strive to create systems that require minimal cognitive effort from users. The strategies used to achieve this, contain simplifying interfaces, reducing the number of steps required to complete a task, providing clear and concise instructions, and leveraging user's prior knowledge and experience.

Cognitive load relates to the amount of information that working memory can hold at one time (Wilson et al, 2021). Originally Cognitive Load Theory was developed by John Sweller, highlighting that difficulty in understanding any material depends on the number of required elements to be simultaneously processed in our working memory, meaning that if large amount of elements are to be simultaneously processed in working memory, the task is considered to be of a high cognitive load (Sweller, 1988, 2010).
Miller's work (1956) has suggested that humans are generally capable of holding seven plus or minus two units of information in short-term memory.

Cognitive workload has been approached in physiology studies by Rozado & Dunser (2015), as a concept that can be identified by observed delays in information processing capabilities when a considerable amount of mental effort is exerted by an individual.

Cain (2007) in his review of the mental workload literature synthesised a definition of mental workload as "a mental construct that reflects the mental strain resulting from performing a task under specific environmental and operational conditions, coupled with the capability of the operator to respond to those demands".

Wickens (2002) defined cognitive workload as “relation between the (quantitative) demands for resources imposed by a task and the ability to supply those resources by the operator”.

In ergonomics mental workload has been studied as a phenomena that happens when the required capacity of the information-processing system exceeds the available capacity (De Rivecourt et al, 2008).

In aviation, while studying mental workload, Abbass et al. (2011) defined cognitive load as “the amount of mental resources needed to perform the task” and made an important distinction between the different concepts used in the literature, singling out the mental load imposed by the work environment (workload) and that related to the exogenous environmental factors such as an operator’s personal life (environmental load). This seems to be the most comprehensive theoretical approach, with the equations explaining the relations between the factors influencing cognitive workload: CL = WL + EL and WL = TL + IL + OF, where CL stands for cognitive load, WL for workload (referred to as mental workload in literature), TL for task load (also referred as task workload), IL for interface load (used to define usability of interfaces in UX), EL for environmental load, and OF for other work related factors.

Debie et al, (2021) used a working definition of a cognitive workload, a multidimensional concept that consists of four components: 1) task complexity; 2) mental workload; 3) performance; and 4) depletion factors.

Task complexity is an inherent property of the task independent of the person involved in the task, and means the difficulty of the task. Mental workload indicates the level of mental resources an individual can allocate (supply) to maintain a high-performance level while performing the task. The performance component relates to the interaction between task complexity and operator mental workload, meaning the quality of performance. Depletion factors can be any external factors affecting the operator’s mental capacity, such as stress, fatigue, motivation, task importance, and attitude (Debie et al, 2021)

The impact of fatigue on user experience: previous research

The mental workload imposed by systems is important to their operation and usability (Hertzum & Holmegaard, 2013)
Users change their behaviour when they experience high mental workload by, for example, responding more quickly to catch up, lowering their performance criteria, postponing minor tasks to preserve resources for major tasks, or experiencing distress (Eggemeier et al, 2020),
There is also a subjective perception of time that has repeatedly been found to explain variations in mental workload (Block et al., 2010). It has been found that “time flies”, being perceived as less than the actual time passed, for high-workload tasks, if users know in advance that they will be asked to estimate time. (Brown, 1997, 2008). If users were not warned beforehand that they need to track the time, they use memory to assess it. Therefore, the bigger the cognitive load imposed by the system, the more inaccurate self-assessed time on task is expected to be.
It is also well known that time constraints affect mental workload and the perceived usability of a system (Díaz-García et al, 2021)

As an example of how little the actual concept of fatigue is addressed in user experience textbooks, I have checked the most popular HCI textbooks, such as “Interaction Design Beyond Human-Computer Interaction (Sharp et al, 2019), “Designing user Experience” (Benyon D.,2019), “Designing UX Forms” (Enders, 2016), “Laws of UX: Using psychology to design better products & services” (Yablonsky, 2020), “The gamer’s brain: How neuroscience and UX can impact video game design” (Hodent, 2017). In all of them the words “fatigue” or “tiredness” are only briefly mentioned as a factor affecting attention, or in the context of decision fatigue, without explanation or elaboration.

I continued the search for fatigue in HCI literature, regarding accessibility, and could finally see some examples of how fatigue and chronic fatigue impacts lives and user experiences of disabled users. It was also mentioned in the terms of visual representation and contrast of the font and background in “ A Web for Everyone: Designing accessible user experiences” (Horton& Quesenbery, 2020).

Unfortunately, there is also a significant amount of renown UX textbooks, where fatigue or tiredness are not mentioned at all (Grant, W. (2018), Allen, J., Chudley, J., Maier, A., & Kammerer, M. (2012) Lacey, M. (2018)) to name just a few.

Summary: fatigue as a state, preceding the human-computer interaction, is rarely addressed in UX, but the concept of cognitive load, that has an impact on post-interaction fatigue, user satisfaction and engagement, is well studied in the field. Designers in UX strive to create systems that minimise cognitive effort to ensure optimal user experiences.

Ux researchers aim to consider both subjective and objective measures of mental workload when evaluating the cognitive demands of an interaction. While subjective measures may provide valuable insight into the user's experience, objective measures such as eye tracking or physiological monitoring can offer more precise and reliable data. Additionally, designers should be aware of the potential limitations and biases of subjective measures and use them in conjunction with other evaluation methods. By considering both subjective and objective measures of mental workload, designers can create systems that are optimised for the cognitive abilities of their users.

Reducing mental workload is a well-studied subject in HCI, and is usually tackled by providing users with multiple modes of interaction or adapting interfaces based on user preferences. Cognitive load indicates the level of mental resources an individual can allocate (supply) to maintain a high-performance level while performing the task and is defined by four components: 1) task complexity; 2) mental workload; 3) performance; and 4) depletion factors.

Users who have to apply less cognitive effort tend to have more positive experiences with the system, leading to higher levels of satisfaction and engagement. Conversely, when users have to apply excessive cognitive effort, they may feel overwhelmed and disengaged from the system. Therefore, UX designers strive to create systems that require minimal cognitive effort from users by simplifying interfaces, reducing the number of steps required to complete a task, providing clear and concise instructions, and leveraging users' prior knowledge and experience.

Users change their behaviour when they experience high mental workload by, for example, responding more quickly to catch up, lowering their performance criteria, postponing minor tasks to preserve resources for major tasks, or experiencing distress. Subjective perception of

time on task has repeatedly been related to the amount of mental workload imposed by the system.
Unfortunately, the actual concept of fatigue is rarely addressed in user experience textbooks, unless they specifically tackle the principles of accessibility in UX design.

Measures of fatigue and mental workload in user experience research

In User Experience research, the widely used measures of mental workload usually belong to one of three classes: performance-based measures, physiological measures, and subjective measures (Eggemeier et al., 1991; Tsang & Vidulich, 2006).
It is widely accepted among researchers that various measures assess distinct aspects of mental workload, and utilising multiple measures, ideally from different categories, is recommended to enhance diagnostic accuracy (Eggemeier & Wilson, 1991; Tsang & Vidulich, 2006).

Performance-based measures. It is considered that users have a finite capacity for dealing with task demands. So, the mental workload can be assessed by observing a user's performance and noting how it depends on changes in task demands (e.g. strategy shifts). One drawback of using performance-based measures is that they may not accurately reflect how much effort a user is putting into maintaining their performance when the task becomes more challenging, according to Tsang and Vidulich (2006). Instead, mental workload can be determined by assessing the user's remaining capacity during the task. To do this, a secondary task can be introduced and the user's performance on it can be monitored to see how it changes with changes in the demands of the primary task. Such a secondary task is carefully chosen in order not to degrade primary-task performance, but still consume sufficient residual capacity to indicate the changes in primary-task demands. Time estimation during the task has been found to fulfil this requirement and may therefore be a suitable secondary task (Block et al., 2010).

Physiological measures: measuring mental workload can be done through event-related brain potentials, heart rate, skin conductance, and pupil diameter. These measures provide continuous data recording and high temporal sensitivity, but require more instrumentation than other measures and may be affected by variables such as lighting conditions. Changes in pupil diameter are considered a reliable measure of mental workload. Studies have shown an increase in peak pupil dilation with increased demands in tasks related to memory, language, reasoning, and perception (Beatty, 1982, Eggemeier & Wilson, 1991).

Subjective measures typically involve self-report questionnaires or interviews and can provide valuable information about the user's perception of their mental workload, including their level of stress, frustration, and mental effort. These measures are easy to administer and can be used in real-time, allowing for immediate feedback on the user's experience. Subjective measures “have generally demonstrated good concurrent validity with performance” (Tsang & Vidulich, 2006). However, subjective measures may be influenced by factors such as social desirability, bias or individual differences in self-awareness. Therefore, it is important to combine subjective measures with other measures of mental workload to obtain a more comprehensive understanding of the user's cognitive state.

In summary, assessing the user's cognitive abilities and mental workload is considered crucial for designing effective and usable computer systems. Researchers employ multiple types of measures (performance-based, physiological, and subjective) to obtain a comprehensive understanding of the user's cognitive state.

3. Methodology

Research design and approach

This study utilises positivism as a research philosophy that emphasises the use of empirical evidence to understand the world. Positivists believe that knowledge can only be gained through observation and experimentation, and that the scientific method is the most reliable way to discover truth. This philosophy came from natural sciences and deals with the objective phenomena that can be captured, quantified and compared.

Deduction is used as a method of reasoning in which conclusions are drawn from premises or assumptions. Deductive reasoning starts with general principles and uses logical reasoning to arrive at specific conclusions. This approach is often used in mathematics and philosophy.

In research, positivism and deduction are often used together to develop hypotheses based on existing knowledge, and then test these theories through empirical data, such as observation and experimentation. This approach works well for quantitative research, where data is collected through surveys or experiments and analysed using statistical methods.
Overall, the combination of positivism and deduction provides a rigorous and systematic approach to research that emphasises objectivity and empirical evidence. While this approach has its limitations, it has been highly influential in shaping modern scientific inquiry and continues to be an important tool for researchers across a wide range of disciplines.

Experiment design

Experiments were conducted with each participant individually, in person or over Zoom. The time gap between each session was 2-3 days for every participant. At the beginning of each session, participants stated their subjective feeling of fatigue or rest, which was reflected in their interview transcripts.
The experiment started with researcher presenting the research purpose (worded in the terms of “we evaluate the usability of these websites”), the first task being to fill in the Visual Analogue Scale to Evaluate Fatigue Severity (VAS-F) questionnaire (Lee et al, 1991), to

document their subjective feeling of fatigue or the lack of it. Said questionnaire was filled in from participants' own computer through Google forms, with the numeric results exported to Google sheets for further analysis.

After assessing the fatigue level, the task set number 1 or 2 was randomly assigned to the participant, and the first set of the task presented to the participant (printed version and a message with links for in person testing and a message with both task and links for online version.

Each task set had three websites to evaluate, starting with food delivery service, plane tickets order and holiday booking service. An example of a food ordering website with the following task: you have friends coming over today, so you decided to order food instead of cooking. Make sure that you have options for both your vegetarian and meat-eating friends, that one person who is gluten-intolerant and a girl who only drinks diet cola. Find out if there is an option of scheduled delivery, say 2 hours from now so you can order it and go about your day without having to think about it.
Go all the way with the order up until the payment, then I will ask you to give me feedback about the website you just used.
The examples of other task instructions and links to the websites can be found in Appendix 1

The websites that were part of the task sets (set 1: JustEat, Momondo, Booking.com; set 2: Wolt, Skyscanner, AirBnB) , were chosen among large and popular web-services that have reasonably good usability. Understanding, that not all of the test subjects have the same experience with the services, chosen to be part of the tasks, the decision was made to include three services in the set of tasks, so even if the user was well familiar with one of them, they were less likely to be frequently using all three of the websites that the task comprised of. Additionally, plane tickets and holiday bookings are not the services people use daily, so even if they were familiar to the users, they were unlikely to have in-depth knowledge of those.

After the trial run, originally proposed four websites were reduced to three, because of time constraints (the whole task without the interview was expected to take about 30 minutes), and four tasks were nearing that time closer to 40 minutes.

During the task, researchers were viewing the participants' screen, either in person or via screen sharing option in Google meets (this application does not require installing or registration to participate, therefore it was used the most during the research).
The main purpose of this observation was to get a better understanding of the strategies that have been employed, identify sources of frustration and the moments when participants were stuck or circled around between the same 2-3 pages of the website. During the observation researcher did not comment on the participants' actions, but did respond to any direct questions related to the task if there were any.

Participants were not asked to talk aloud during the tasks, but some of them did so unprompted, this information has been saved in interview transcripts as "unprompted talk-aloud during the test"

After the first task in the set of 3, participants were requested to fill in a SUS questionnaire in Google Forms, evaluating their experience of the website they just interacted with. The questionnaire had a field for the participant's code and the name of the website they were evaluating and similarly to the fatigue scale data was automatically transferred to Google sheets.
Then, similarly to the first task, second and third ones were performed, with both of them being followed by the System Usability Scale (SUS).

After the final, third task, a short standardised interview was conducted. The questions asked were along the lines of the following:

- How do you evaluate the task? Is it something you would normally do in this state?
- What was the easy/difficult part for you?
- What kind of emotions did you feel while doing the tasks?
- Do you think you could have been more efficient?
- Did you make any errors and if yes, how did you feel about them?
- Did you, at any point of doing the tasks, feel the urge to abandon it?
- How long do you think the task lasted?

Post-task interview aimed to obtain qualitative data regarding subjective usability evaluation. Time on task was measured by the researcher, after administering VAS-F, so from the beginning of the first task till the end of the last one, before the final interview, but including SUS forms being filled. Same time frame was offered to the participants to evaluate how much subjective time had passed while they were going through the tasks. The difference between objective and subjective times on task has been proven to reflect the amount of cognitive load inflicted by the task. (Block et al, 2010)

Two task sets with similar tasks but different websites were established necessary to avoid the effect of learning and memory of completing the task during the next evaluation in a different state of fatigue. Tasks were similar in nature and took a comparable amount of time to complete. So, if the participant was assigned task 1 (3 websites) at the first session, while in tired state, they would receive task set 2 (3 websites) several days later, while participating in the session in rested state. Researcher also made sure that equal amount of participants would complete each task set in each state of tiredness (7 participants for task set 1 would be fatigued, and another 7 will do this task while being rested, and same goes for task set 2)

Objective usability of the products in the task sets is not the subject of current study, therefore we are only interested in the detectable difference between the evaluations given by users in their respective states of fatigue or rest. This means that only the data regarding difference between the evaluations in fatigued and rested states was compared.

Participants and sampling methods

Fourteen adults (6 male, 8 female; age range 27-44) recruited in Copenhagen through personal acquaintances and social media posts, making it a convenience sampling due to constraints present in the study. Saunders et al (2016) confirm that in the case of exploratory or pilot study, convenience sampling is acceptable. Since the aim of this research is to establish whether the variable (fatigue) has any detectable influence on the subjective perception of usability, the constraints of such sampling methods are expected to have minimal effect on the results.

All participants of the study gave informed consent regarding the study requirements. 13 participants use English as their second language and one is a native speaker. During the experiment they were not limited to the language options, using English or their mother tongue to navigate. All of them took part in the usability testing twice, one test session in the state of fatigue, and one test session while feeling rested (not necessarily in this order). The state of fatigue was not induced artificially, participants scheduled interviews on the afternoons and evenings of the days, when they had expanded workload and therefore expected to be fatigued. Before the interview it was confirmed that they, as expected, were feeling fatigued. Some of the participants rescheduled the meetings earlier than we originally planned them to the days, when they felt very tired, and these meetings were carried on by zoom, as the purpose was to conduct the usability testing while the test subject felt subjectively fatigued. One of such tests failed to complete, because the participant was too tired and opted out of the experiment in the middle of it, stating that she was too tired to continue that day. This experimental data was discarded as it was unfinished and replacement participants had been recruited.

Similarly, the “rested” test sessions were scheduled for the mornings that test subjects had off work, and just as the “fatigued” test sessions, several of them were rescheduled for later, because test subjects informed the researcher, that despite expectations, they do not feel as refreshed as they hoped to be. So the research took place in a situation, close to natural, when users interact with digital products in their everyday lives, including the times when they experience fatigue. The questionnaire System Usability Scale (SUS), (Brooke, 1996) was measuring the above mentioned interactions at the extreme points of rather severe subjective fatigue and distinctively rested, not sleep deprived states to discover if fatigue had any significant influence on perceived usability.

Data collection methods and procedures

Visual Analogue Scale (Appendix 2) is a tool used in research and clinical settings to measure subjective experiences such as pain, anxiety, and mood. It typically consists of a horizontal line with endpoints labelled with opposing descriptors (e.g. "no pain" and "worst pain imaginable"). Participants are asked to mark on the line where their experience falls between the two endpoints, with the distance from the left endpoint indicating the intensity of the experience. The Visual Analogue Scale is a widely used and validated measure for assessing subjective experiences.

Visual Analogue Scale to Evaluate Fatigue Severity (VAS-F) developed by Lee et al (1991), was used as a means of assessing fatigue. The assessment comprises 18 items, each scored between 0 and 10, with the 6th to 10th items focusing on the participant's energy level and the remaining items assessing fatigue. Participants rate statements such as "tired," "energetic," and "desire to lie down " by choosing a place on a 0 to 10 scale between the most positive and negative statements. The fatigue subscale items are arranged from most positive to most negative, while the energy items are arranged in the opposite order. A higher score on the fatigue subscale and a lower score on the energy subscale indicate greater fatigue severity.

In 1996, John Brooke created the **System Usability Scale (SUS,** Appendix 3**)** as a way to evaluate usability (Brooke, 1996). The SUS was designed to be a practical and cost-effective solution for evaluating usability since other methods like contextual analysis were not feasible. The SUS is a one-dimensional tool that consists of ten items on a five-point Likert scale. The Likert scale ranges from strong disagreement to strong agreement and includes both positive and negative statements to account for biases. The final score ranges from 0-100 and has been proven to be reliable across various sample sizes when compared to other usability scales such as the Questionnaire for User Interface Satisfaction (QUIS) and Computer System Usability Questionnaire (CSUQ) (Tullis & Stetson, 2004), while being shorter and faster to fill in. For nearly two decades, the System Usability Scale (SUS) has been utilised by practitioners and scholars as a "quick and dirty" technique for assessing the usability of a diverse range of human-machine systems, including websites and software.

Standardised interviews are a widely used data collection method in various fields, including psychology, sociology, and user experience research. This method involves asking a set of predetermined questions to all participants in a structured manner. The questions are designed to elicit specific information providing a standardised approach to data collection, which minimises the potential for interviewer bias and ensures that all participants are asked the same questions in the same way. This type of interview allows to collect both quantitative and qualitative data, providing a comprehensive understanding of the research topic. It is known that some participants may feel uncomfortable or unwilling to answer certain questions, which can lead to incomplete or biassed data. However, this was tackled by the type of questions asked, none of them being about sensitive topics and focused on the experience of human-computer interaction.

Observation is another commonly used data collection method in various fields, including anthropology, psychology and user experience design. This method involves systematically watching and recording behaviours, events, or phenomena in a natural setting or laboratory environment. Observation offers several advantages over other data collection methods. Firstly, it allows for the collection of rich and detailed data that can provide insights into the complexities of social interactions and behaviours. Secondly, just like standardised interview, observation can be used to collect both quantitative and qualitative data. It can also be used to study phenomena that are difficult to measure using other methods, such as nonverbal communication, screen interactions, user strategy and problem-solving. One of the important limitations of this method, however, is the fact that the presence of an observer may influence the behaviour of those being observed, leading to biassed data.

Data collection was conducted using Google forms, where each participant was coded with the first letter of their name, age, gender and state (fatigued or not). In this example it is someone whose name starts with T, 40 year old male, first tested in the state of fatigue, (T40M fatigued), and then in rested state (T40M rested).

Data analysis methods and procedures

With the experiment design that provides 2 task sets, I ended up having 7 sets of sample data for task 1, retrieved from the users in a state of fatigue and rest, and 7 sets of sample data for task 2, retrieved from the users in a state of fatigue and rest.
Since the purpose was to compare mean values of participants' usability evaluations in the state of fatigue and rest to see if there is a statistically significant difference between the two, statistical data analysis methods were applied. Spearman's rank correlation coefficient, which is a widely used statistical measure in social sciences and psychology, also adopted and used by UX practitioners, was chosen for the task. This coefficient is particularly useful when studying the relationship between two variables that are not normally distributed.
This coefficient, introduced in 1904, was an important development in statistics because it provided a way to measure the strength of the relationship between two variables without making any assumptions about their distribution. Calculating the rank correlation coefficient allows us to conclude whether there is a significant relationship between the two variables, in case of this study the variables would be subjective states of fatigue and rest.

The formula for Spearman's rank correlation coefficient is straightforward and easy to calculate. The coefficient is calculated using the differences between the ranks of paired observations and the number of observations. The rank correlation coefficient ranges from -1 to +1, with a value of -1 indicating a perfect negative correlation, a value of +1 indicating a perfect positive correlation, and a value of 0 indicating no correlation.

The interpretation of Spearman's rank correlation coefficient depends on its value. If the value of rs is close to +1, then there is a strong positive correlation between the two variables. If the value of rs is close to -1, then there is a strong negative correlation between the two variables. If the value of rs is close to 0, then there is no correlation between the two variables.

Ethical considerations

The state of fatigue was not induced artificially, and the participants gave informed consent to partake in research in the state of subjective fatigue and rest. The state of fatigue did induce certain negative emotions, but none of them were expected to have any long-lasting impact on subjects' mood.

4. Results

Overview of the data collected

Quantitative data overview

Time on task (self-estimated after the task is complete versus objectively measured) raw numbers can be found in Appendix 4.

Due to the small sample number, normalising data would radically increase error, so the decision was made to only analyse the tendencies, represented visually later on, in the analysis part.

VAS-F score (%) fatigued	
task set 1	
A,33F	65.38461538
J,32M	59.23076923
F, 44M	76.92307692
J, 29F	76.15384615
S, 27M	60.76923077
J, 30F	47.69230769
D, 40M	66.15384615
task set 2	
T, 40M	86.15384615
Z, 31F	62.30769231
S, 30M	63.84615385
A, 34F	50
V, 27F	68.46153846
J, 36F	60.76923077
J, 42F	66.15384615

VAS-F score (%) rested	
task set 1	
T, 40M	33.84615385
Z, 31F	40
S, 30M	19.23076923
A, 34F	32.30769231
V, 27F	3.846153846
J, 36F	16.92307692
J, 42F	0.7692307692
task set 2	
A,33F	26.92307692
J,32M	11.53846154
F, 44M	10
J, 29F	16.92307692
S, 27M	17.69230769
J, 30F	19.23076923
D, 40M	10.76923077

SUS usability scores (fatigued evaluations)

Websites	Just Eat (f)	Momondo (f)	Booking (f)	Wolt (f)	Skyscanner (f)	Airbnb (f)
Scores for set 1 and set 2 both performed in fatigued state	72.5	12.5	100	55	10	22.5
	65	12.5	40	72.5	10	92.5
	65	62.5	87.5	70	42.5	90
	57.5	92.5	90	85	77.5	92.5
	75	57.5	62.5	27.5	50	82.5
	72.5	40	70	55	70	85
	37.5	22.5	72.5	100	55	80
Mean values	63.57142857	42.85714286	74.64285714	66.42857143	45	77.85714286

SUS usability scores (rested evaluations)

Websites	Just Eat (r)	Momondo (r)	Booking (r)	Wolt (r)	Skyscanner (r)	Airbnb (r)
Scores for set 1 and set 2 both performed in rested state	50	25	42.5	77.5	97.5	90
	92.5	77.5	82.5	82.5	25	75
	92.5	97.5	95	70	60	75
	62.5	72.5	90	87.5	55	97.5
	80	37.5	42.5	95	95	70
	87.5	90	95	65	70	62.5
	90	87.5	95	57.5	77.5	55
Mean values	79.28571	69.6428571	77.5	76.4285	68.5714285	75

	429	4		7143	7	

Qualitative structured interview data (Appendix 1, 4) **overview**

Tendency to voice over (narrate) the actions in fatigued state

All 14 of the participants talked aloud during the test in fatigued state, unprompted. Several of them said in one way or another that saying things aloud helps them stay focused and remember the task. As one of the participants phrased it, “I will talk out loud because my brain is hardly working and it is easier this way (J32M fatigued).“

In rested state, none of the participants consistently narrated their actions out loud, but instead there were exclamations whenever the website caused frustration or behaved unexpectedly.

Task evaluation

In fatigued state, 7 out of 14 participants defined the set of three tasks as “difficult”, 5 as “neutral/somewhat difficult” and 2 as “easy”.

Quotes: A32F, fatigued “It was difficult, most of it. My brain is a mush”. Z31F, fatigued “I felt like it was such a huge task when really it was something very mundane like three tasks, something that people do constantly, tools that people use everyday. And just because I was so exhausted I felt that it was absolutely overwhelming.” V27, fatigued. It was hard to do because I was feeling hungry and my brain was not working. ”

In rested state, all 14 participants evaluated the set of three similar tasks as “easy”

Emotions

During the task, all of the fatigued participants expressed frustration with the web sites both in emotional exclamations during the test and in the interview after. In the interview, 9 participants characterised their emotions as “frustrated” (2 of them highly frustrated, angry, and 2 - “mildly frustrated”), 3 as “neutral” and 2 as “annoyed, irritated”. Several examples of the experienced emotions, that are illustrative, are quoted in the next paragraph.

A32F, fatigued “I felt frustrated and also kind of stupid, I know it should be easy but it wasn’t, and happy at the booking app cause I could do it fast and I knew it already.”
Z31F, fatigued “Mainly frustration. i was like, ugh this is so complicated, I was frustrated and overwhelmed and bit angry cause it’s a task that everyone can do and it felt like [doing] a PhD at some point”
J32M, fatigued “The second task just made me feel stupid, I don’t appreciate that [in websites] All I had to do was one stupid thing and then I was like okay I don’t like you anymore (momondo). It was not friendly at all. I kind of want to go back and give it an even lower grade. That’s how angry it made me. I wasn’t even feeling tired anymore, just adrenaline angry and I carried that to the third website and maybe that’s why I was stuck with 33 days and could not figure out how to change it for 3 days. I wanted to take a nap after this [interview] but now i am not even sure, i am al jumpy with angry energy.”
S30M, fatigued “it’s frustrating to not find what i was looking for, I would just go to the other website if I was on my own.”
S27M, fatigued “Most [emotion] was that kind of surprise like you hit the wall and what are those images graphs and all.”
J42F, fatigued “A bit of anxiety, especially when there were a lot of choices, annoyed when I could not immediately do what I wanted to”

Participants, who were rested, expressed “neutral” emotional state (11 out of 14), and “positive emotions” - 3 out of 14. 6 out of 14 expressed mild frustration, attributed to the particular design flaws, such as, for example, loss of the whole basket after signing in to the website.

Self-perception

All participants were asked a question whether they think they could have been more efficient.

Fatigued users mostly thought they would have been a lot more efficient if they were rested (11 out of 14), 2 of them thought that they could have been more efficient had they been more familiar with the particular websites they tested, and one user stated that they were at their normal efficiency level.

A, 33F (fatigued) “If it was real, I would absolutely not book a flight or hotel, only if it was super urgent. I would choose both and buy them the next morning after some sleep.”

F, 44M (fatigued) “ I would not go to any unfamiliar website this late at night”.

J, 29F (fatigued) “if i used them before.. Like booking was faster than other ones”.

D,40M (fatigued) “If I did it on my lunch break instead of after work”.

Rested users were confident that their efficiency is on a decent level (12 out of 14), 2 said they would have done better if they were more familiar with the particular websites they tested.

F44M (rested) “I was at my good performance”. J36F (rested) “I was rather efficient. ”

V27F (rested) “I think I did a good job and fast enough for my liking”

Errors

13 out of 14 fatigued users recalled making mistakes (pressing random or wrong buttons, not filing in data or filters properly and so on).

S27M, (fatigued) while filling in the fatigue scale he tried to fill in the unclickable picture that was an example of replies - instead of actual questions, “haha see how tired I am”.

Z31F, (fatigued) “[wolt] used it before, here it knows me. Okay, done! Oh ….!!! I have ordered. Just automatically. Now i need to call to cancel.[there was a call]”

The majority of errors were just random clicks in hope to find needed information.

J,32 y. male, (fatigued) “I didn’t understand why in booking I could not book for 3 days, it kept giving me 33 days. That was weird I probably did something wrong”.

S,30 y. male, (fatigued) “i was not very concentrated in the beginning, I just started pressing all the buttons I could find and just switching between 3 buttons for like 3 minutes”.

F, 44 y.o. male, fatigued, yes, with the basket, and I circled around the same buttons several times in momondo. It's okay, I am tired and my brain doesn't work so I just click my way through the task I need to do and hopefully it works out.

S, 27 y.o. male, fatigued : yeah, selected the wrong category (expected to reach the end of the list but something else happened instead. And price thing in flats, did something with the price and it messed up i had to go back

V, 27y.o. female, fatigued: Wolt I made some mistakes, [felt] frustration. Same with luggage, bit angry. When it was redirecting me on other site *airbnb) I didn't notice it and my brain felt like it was offended.

J, 42 y.o. female, fatigued yes, circling around with tickets, frustrated for just returning to the same place.

J, 36 y.o. female, fatigued yeah, accidentally so I had to press back to get rid of mistake and then accidentally closed the site and had to open it again from link

D, 40 y.o. male, fatigued: I think I clicked a couple of wrong buttons, and I remember scrolling through things when I could not find obvious things, like parking. Could have been solved with just one filter. I got angry, I feel like I have to go back in step, and then worry like I have lost what I have already done. When I used Just Eat I almost felt like throwing my computer from the window. In my head, I had hungry people and could not find a gluten-free dish for my friend! Or vegan stuff.

11 out of 14 rested users did not recall making errors, and 3 out of 14 made a few.

Subjective desire to abandon task

Out of 14 fatigued users, 7 expressed the desire to abandon task at the beginning/during task 2 in the set, plane tickets booking. 4 would abandon the task within 2-3 minutes of the first task, or after the first error within 5 minutes of the first task. 1 user would abandon the task during the third website testing, and 2 would not abandon it.

A33F (fatigued) "The flight booking, absolutely!"

J32M (fatigued) “yeah …! I have changed the search to include the bags, I found the quickest flights and then that site just shuffled them away! Was super frustrating. Instead of just showing me the bag charge it just reset the entire work that I did. ”
F44M (fatigued) “[would abandon just eat] they didn’t let me know that I could not order at that place at that time of the day so I wasted my time choosing. That was not nice.”
V27F (fatigued) “[I had the urge to abandon it] every 5 seconds. I would not do any of it in this state. Honestly, after the very first mistake at Wolt.”
A,34F (fatigued) “I had the urge to abandon the task] right after I got the second task and understood there will be several of them”.
J,29F (fatigued) “the booking one, I am hungry, and I know I will pick the fast option, not the best one”.
D,40M (fatigued) “Two minutes in, with Just Eat, when I could not find the gluten-free. I expected pizza to be gluten-free but it was not there. I don’t have the attention span for that now!”

Rested users would not abandon the task (9 out of 14), 4 would switch to a different site during the fly tickets purchase (second task in the experiment), and one would go to another food ordering service, so would have abandoned it within the first 5 minutes of the experiment.

J32M (rested) “I would not waste my time on skyscanned, would have [abandon it and] switched to a different one.”
T40M (rested) “[i would abandon] the one I just told [momondo], because it was so stupid. And the link wasn’t working and I felt like I was just going in circles. That was not fun.”
D,40M (rested) “ The wolt one. After the third time I had to sign in. I could not quite understand if it was my error or the website’s. I spent a good minute trying to understand where my basket went.”

The majority of the fatigued participants had to look back to the task to remember the details. All of them struggled with remembering their flight dates when it came to booking the accommodation for the trip. Fatigued users also struggled to remember the name of the website they just used a couple of seconds after they closed it. Foodwise, the absolute majority chose pizza or burgers, even if that was not preferred food for them in their normal state.

Analysis of the data in relation to the research questions and hypotheses

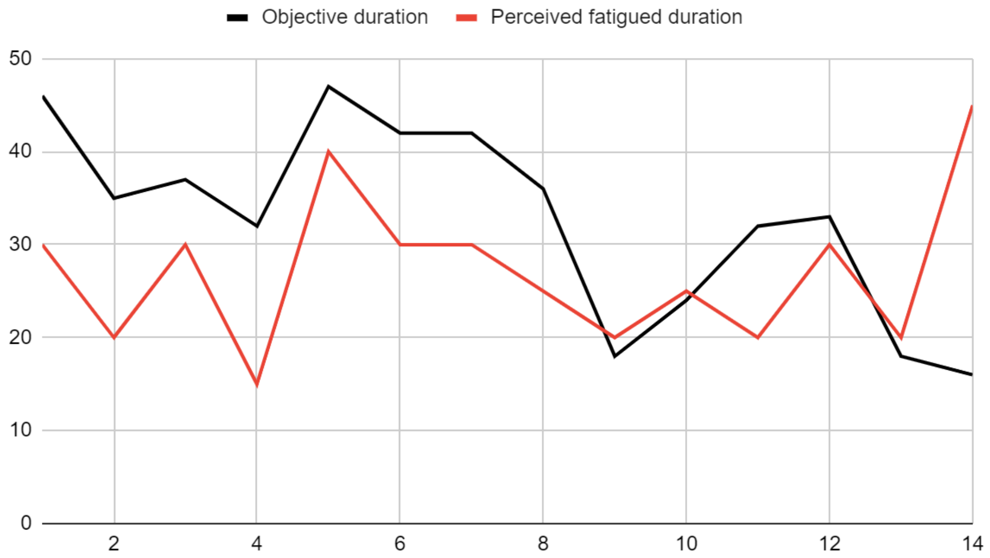
Quantitative data analysis

Time on task (Appendix 4)**:** discrepancies between the objective measures and subjective estimations.

According to Block et al (2010), users who were not warned beforehand that they need to track the time, have to resort to memory to assess it. Therefore, the bigger the cognitive load imposed by the system, the more inaccurate self-assessed time on task is expected to be. Since each of the task consists of similar types of websites with comparable objective usability, the bigger discrepancies between self-assessed and objective time on task can be attributed to the higher mental load due to pre-existing state of fatigue, rather than the complexity of the websites themselves (in this case, there would be detectable difference between the subjective time estimates of the task set 1 versus task set 2 in both fatigued and rested states, which is not supported by actual data.

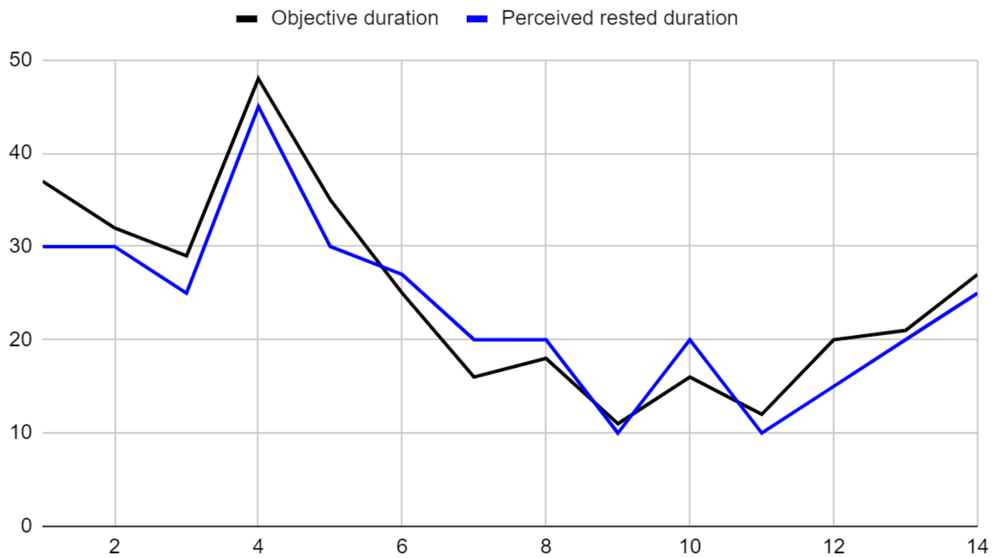
This graph demonstrates noticeable discrepancies between objective and subjective task duration in fatigued versus rested users, who tended to evaluate duration as shorter than it objectively was.

Fatigued users time on task subjective and objective duration



And this graph refers to the rested users, who tended to be consistently quite precise with their time on task subjective evaluations.

Rested users time on task subjective and objective duration



Spearman's rank correlation coefficient calculation

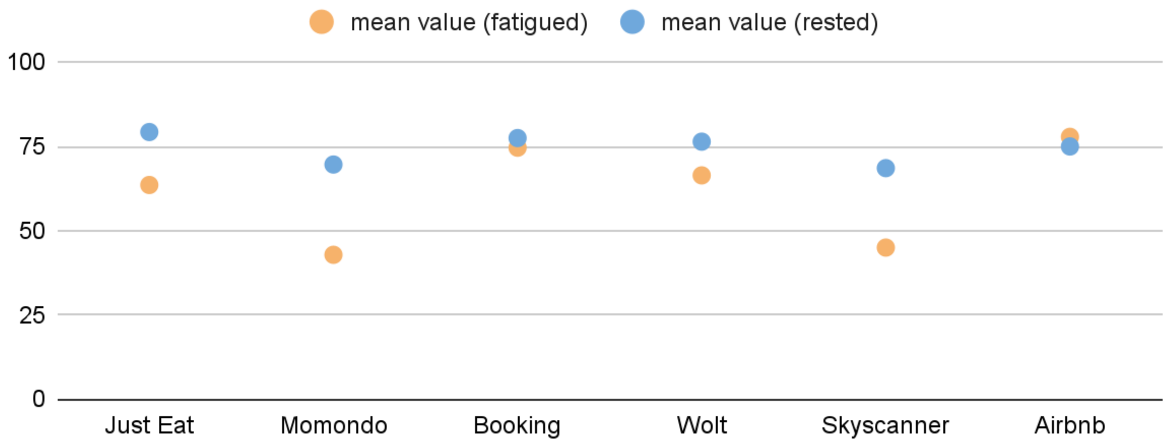
tired	rank	rested	rank	d	D2

Just eat	4	Just eat	1	3	9
momondo	6	momondo	5	1	1
booking	2	booking	2	0	0
wolt	3	wolt	3	0	0
skyscanner	5	skyscanner	6	-1	1
airbnb	1	airbnb	4	-3	9
SUM					20

Spearman's rank correlation coefficient	$r_s = 1 - \frac{6\sum D^2}{n(n^2-1)}$	r_s=1-6*20/6(6^2-1)	**0.4285714286**

The resulting Spearman's rank correlation coefficient is 0, 43, which is considered to be a moderate positive correlation.

Graph of the mean SUS values for fatigued and rested users.

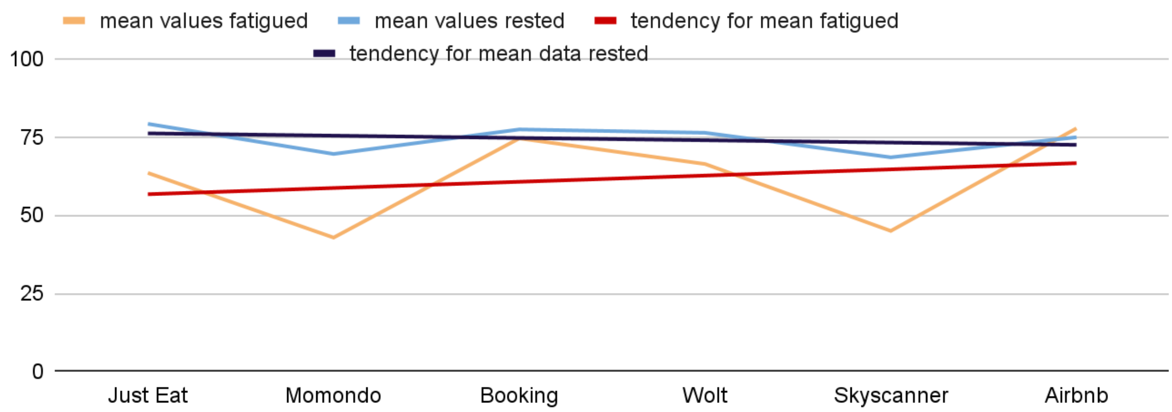


With a small dataset like this (only 6 SUS evaluations for each state, fatigued and tired), it might be difficult to see a clear tendency, therefore I used linear fit formula as a way to find the best straight line that fits a set of data points. It uses a mathematical formula to calculate the slope and intercept of the line that most accurately represents the relationship between two variables. The formula is $y = mx + b$, where y is the dependent variable, x is the independent variable, m is the slope of the line, and b is the y-intercept. The goal is to minimise the distance between the observed data points and the predicted values on the line. Once the line is established, it can be used to make predictions about future values of one variable based on known values of the other variable.

Table of mean SUS values and calculated linear fit tendencies

Name	Fatigued mean value	Fatigued tendency	Rested mean value	Rested tendency
Just Eat	63.57142857	56.75170068	79.28571429	76.2414966
Momondo	42.85714286	58.7414966	69.64285714	75.50680272
Booking	74.64285714	60.73129252	77.5	74.77210884
Wolt	66.42857143	62.72108844	76.42857143	74.03741497
Skyscanner	45	64.71088435	68.57142857	73.30272109
Airbnb	77.85714286	66.70068027	75	72.56802721

Graph of mean SUS values alongside with linear fit tendencies



Linear fit tendencies corroborate the Spearman’s rank correlation conclusion regarding subjective perception of usability being connected to the state of mental fatigue and rest: fatigued mean values are consistently lower than the rested ones. This cannot be attributed to the objective usability of the websites, because both task set 1 and task set 2 were performed and evaluated by users in a state of fatigue and rested state, and if the difference in objective usability is was found (e.g. both Momondo and Skyscanner websites consistently received lower usability scores, but their respective scores are still hire for the rested population), it was irrelevant for this research, because it is the difference in subjective perception that was assessed. .

Qualitative data analysis

Tendency to voice over (narrate) the actions in fatigued state

Unprompted voice narrating of one's actions in fatigued state can help with the limitations of the short-time memory, as hearing their own voice repeating the task, important dates and so on helps to recall them better within a couple of minutes of the first mention. As mentioned in literature review, talking out loud, also known as "self-talk," for memory retention. This cognitive process can reinforce information by solidifying memory through repetition, engage multiple senses, including hearing and speaking, to create a more immersive experience that enhances memory retention, organise thoughts and ideas in a structured manner that improves memory recall, and improve focus and attention on the information being remembered, ultimately leading to better memory retention. The fact that all 14 fatigued participants engaged in self-talk unprompted versus none of the rested participants (which are the same people who were in the tired group, so this cannot be attributed to the personal preferences since the only variable that changed, was the fatigue level), is likely to corroborate the higher cognitive load experienced by fatigued users.
The majority of the fatigued participants had to look back to the task to remember the details. All of them struggled with remembering their flight dates when it came to booking the accommodation for the trip. Fatigued users also struggled to remember the name of the website they just used a couple of seconds after they closed it. Foodwise, the absolute majority chose pizza or burgers, even if that was not preferred food for them in their normal state. This confirms the strain that was experienced by short-time memory and previously mentioned tendency to employ low-effort strategy to reduce cognitive resources depletion in fatigued states.

In rested state, participants would not necessarily experience short term memory issues, therefore there was no real need to narrate their action. The exclamations were short and likely explained by the presence of the observer, to whom they wished to explain their frustration with user interface.

Task evaluation

Both sets of tasks were of similar complexity, both having one food ordering website, one flight tickets booking and one accommodation booking. Task set 1 was completed by 7 fatigued and 7 rested users, and the same happened to task set 2. Therefore, the difference in task evaluation cannot be attributed to the objective difficulty of it, but was defined by the state of fatigue that users were in. The very same tasks that were considered “difficult” in fatigued state, were described as “easy” in rested state.

Emotions

Fatigued state seemed to exacerbate any negative emotion caused by interaction with the website, due to the lack of the negative emotions expressed by fatigued users were far more intense (stronger adjectives and corroborating facial expressions and tone of voice) than their emotions caused by a similar interaction in rested state. This corroborates the inhibitory control deficiency experienced by fatigued users, meaning reduced ability to inhibit or suppress inappropriate behaviours or responses.

Self-perception

Self-perceived ability to efficiently fulfil the task corresponded highly with the state users were in, fatigue state was seen as the one in which they should not be working with a lot of information, taking risks or making financial decisions, as they know from previous experience that they would tend to go for low-effort strategies, regardless of their monetary cost.

This observation lines up with the existing knowledge of the cognitive processes being affected by fatigue, namely goal-directed behaviour, decision-making, and problem-solving. It also reflects participants’ self-knowledge of fatigue affecting their ability to reason logically and make decisions in a complex task.

The factor of learning was referred to as the one that helps to reduce “thinking” (cognitive load) by remembering how the site works instead of actively figuring it out and therefore makes digital products easier to use even in fatigued states. This makes sense as with the knowledge of the system the cognitive load it inflicts tends to reduce, therefore even fatigued users can complete their task while using less cognitive resources that they would with the unfamiliar system.

Rested users had very good trust in their ability to be efficient and make satisfactory financial decisions.

Errors

Fatigued state seems to be consistent with objectively (observation) and subjectively (self-report) high error rate.

The error that participants made, reflect narrower attention span (e.g. inability to find out the source of mistake and just resetting the whole page instead, or looking straight at the date selector, having selected a month and 3 days, and wondering why it's 33 days instead of 3, shorter reaction time that encourages automatic actions that user did not intend to do (the example with an accidental placing of the order of Z, 31F (fatigued)). Any obstacles (both errors and experienced design flaws) in the state of fatigue were perceived very emotionally, provoked anger, frustration and even urge to resort to physical action ("I almost felt like throwing my computer from the window" D40M fatigued)

In rested state, errors were quickly reverted, and users did not feel strong emotions about them. Design flaws were recognized and either dealt with, or, if users had a preferred website for that task, they would express the wish to achieve their goal with the help of that other site.

This corroborates the previously known data regarding errors that users make in fatigued state: the attempt to perform the task faster, by demonstrating shorter reaction times, which causes more errors, and oftentimes adoption of less effort strategy for a subjectively less important task.

Overall, in a tired state participants tended to go with the first/easiest choice, whereas in a rested state they would try to be efficient, save money and read reviews in order to make the optimal choice.

Subjective desire to abandon task

In fatigued state, the tasks that were perceived as absolutely necessary (food order for the guests) were mostly performed although with a low-effort strategy, but anything deemed unnecessary, like ticket/accomodation booking, users were ready to sacrifice in order to get rest and do the task in a better state. This observation corroborates previously referred evidence of fatigue-related reduced activity levels and motivation (Smets et al., 1996).

Rested users, on the other hand, tend to abandon tasks much less, and even if they wanted to do so, they would not drop the whole task, like fatigued ones, but rather carry on the task with different tools (resort to other, familiar service that does the same job) So the goal-oriented behaviour is not affected in rested state.

Summary:

Under fatiguing conditions, the following impact on performance was observed:

- adoption of less effort strategy and "protected" performance with more cognitive resources allocated to the task when the task was subjectively important (e.g. ordering food seemed like a less effort comparing to cooking it)
- Shorter reaction times, more errors,
- Cognitive functions:
    - Impaired working memory required self-narrating to help retain information. Participants also demonstrated poorer reading comprehension and decision-making.
    - Inhibitory control was found to be decreased leading to poorer self-regulation and feeling of frustration.
    - selective attention capacity was observed to be reduced as well, reflected in inability to detect an error or relevant information.
    - It was also observed that impairs the ability to make decisions in complex tasks was affected as well, leading to users either simplifying their strategies or delaying the decision till the time they feel rested.

5. Discussion

As a result of the research conducted in this work, the impact of cognitive (mental) fatigue on subjective perception of usability of digital products was analysed using Spearman's coefficient of rank correlation and is moderately positive (0,43). Linear fit tendencies of the mean SUS evaluations also show the consistently lower subjective usability scores for the websites that were interacted with in fatigued state.

Mental fatigue, experienced by the participants, therefore is likely to be linked to their subjective perception of the digital product's usability. Fatigued users were observed to employ less cognitive resources and attentional capacity, alongside with difficulty concentrating, processing information, and making decisions. They made more errors and were less likely to smoothly recover from them than rested users. These factors seem to be responsible for subjectively worse user experience in fatigued state due to increased cognitive strain, that could not be attributed to the objective usability of the digital product, but rather to the pre-existing state of fatigue, which was reflected in lower mean scores on the System Usability Scale.

Negative emotions (reduced impulse and emotion control leading to frustration, anger, anxiety) seemed to exacerbate the detrimental impact of cognitive strain and damaging impact on the subjective usability of digital products, leading to subjective perception of the website as less usable and less enjoyable to interact with.

Implications for UX design of digital products

It is important that UX designers account for pre-existing states like fatigue, because even though an average user is likely to account for their mental state and approach complex tasks while rested, there is a significant group of users who experience chronic fatigue and can not simply take rest to avoid it impacting their performance negatively. Any condition that affects cognitive functions (e.g. stress, sleep deprivation), is likely to affect perceived usability negatively due to the depletion of mental resources that it causes.

Another group of users demonstrate decreased performance of cognitive functions due to age-related changes, executive functional deficits (e.g. ADHD), traumatic brain injury (TBI), major depression, schizophrenia, Alzheimer’s disease.
Therefore, digital products which strive to reduce cognitive load are inherently more accessible to the users with permanent, temporary and situational disabilities.
It is important to account for pre-existing mental states that subjectively increased cognitive load, alongside with the objective cognitive load inflicted by the digital product itself, as the former has a significant impact on the latter.

Limitations of the study

Due to the experiment design, that required pre-existing state of fatigue, and lack of funding, the researcher struggled to acquire sufficient numbers of participants for a full-scale research, which led to a decision to conduct a pilot study instead. Pilot project is a small-scale study that is conducted before the main study to test the feasibility of the research design, methodology, and data collection tools.
Therefore, the limitations are typical for a pilot project: a small sample size, limited scope of the study, and lack of generalizability to a larger population.

It is worth mentioning that the results of a pilot project may not be representative of the main study due to differences in the sample selection and data collection methods.
However, despite these limitations, a pilot project can provide valuable insights into the feasibility and effectiveness of a research study and help researchers refine their approach before embarking on the main study.

The nature of study design applied in this work is also not meant to establish causation, only the correlation.

Suggestions for future research

As the pilot study showed statistically significant rank correlation between mental fatigue and subjective perception of usability, future research may replicate the experiment with a bigger and more diverse sample size to improve the generalizability of the findings.

Research may also continue to explore other pre-existing mental states that affect cognitive functions and therefore are likely to affect subjective user experience, such as the state of alcohol intoxication. This has a lot of potential implications, as many digital products are likely to be used by intoxicated users (transport apps, food delivery, payment systems)

6. Conclusion

In conclusion, this pilot study has provided valuable insights into the impact of mental fatigue on subjective perception of usability. The findings suggest that mental fatigue can negatively affect users' perception of usability, which has important implications for the design and evaluation of user interfaces.

Fatigue is a very complex state that affects cognition in several ways. User Experience designers can create interfaces that account for fatigued users who are more likely to experience cognitive difficulties while using digital products, making them more accessible and inclusive for users with other (temporary or permanent) cognitive disabilities. Since fatigue manifests in ways that are similar to sleep deprivation, attention disorder, and executive function disorder, digital design for tired users has a potential to simultaneously increase accessibility for the wide group of users with the conditions that affect executive functions.

Furthermore, designers should consider incorporating features such as breaks, reminders, and personalised settings to help users manage their mental fatigue levels and maintain their focus and engagement. Finally, it is important for designers and evaluators to recognize the dynamic nature of mental fatigue and its impact on usability, and to continuously monitor and adapt their designs to ensure optimal user experience. By taking these factors into account, it is possible to create interfaces that are more accessible, usable, and enjoyable for all users, regardless of their cognitive state.

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8. Appendices

(Supporting materials, such as questionnaires and interview transcripts)

4 documents, in total, submitted separately