CONQUERING FATIGUE: THE BATTLE FOR ENGAGEMENT

Jesper F. Hopstaken

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CONQUERING FATIGUE: THE BATTLE FOR ENGAGEMENT

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Voor mijn ouders.
Onvoorwaardelijke liefde en rots in de branding.
Jullie hebben me leren lopen en nu ren ik op mijn dromen af.

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CHAPTER 1

Introduction

Sustained performance on cognitively demanding tasks often leads to mental fatigue, which is a complex state characterized by a reluctance for further effort and changes in mood, motivation and information processing (Meijman, 1997; van der Linden, Frese, & Meijman, 2003). Levels of experienced mental fatigue may fluctuate due to normal everyday activities (e.g., as a consequence of daily job demands), but can also be chronic and comorbid to diseases or disorders such as Parkinson's disease (Chaudhuri & Behan, 2004), depression (Demyttenaere, De Fruyt, & Stahl, 2005), and burnout (Bakker, Demerouti, & Sanz-Vergel, 2014). In the workplace, mental fatigue has been found to be one of the most frequent causes for work accidents (Baker, Olson, & Morisseau, 1994; McCormick et al., 2012). Yet, despite the mundane nature of mental fatigue and its relevance to work performance and safety, the exact psychological mechanisms that are involved remain relatively unknown. One fundamental question is: Why do people get fatigued at all? Or, more specifically, what is the exact adaptive value of fatigue? And how does fatigue affect cognition and task performance in such a dramatic way?

Some researchers have argued that the core of fatigue is a motivational stance driving someone to withdraw further effort investment (e.g., Hockey, 1997). In this view, fatigue may not necessarily reflect the manifestation of reduced cognitive resources, but is rather seen as psychophysiological state that protects an organism from overexertion and depletion. Others have characterized fatigue mainly by its cognitive effects that make it more difficult to maintain task focus and to uphold cognitive performance (Boksem, Meijman, & Lorist, 2005; Lorist et al., 2000; van der Linden, Frese, & Meijman, 2003). For example, when fatigued, one has a higher probability of being distracted or making errors. However, it seems unlikely that certain cognitive processes can no longer be deployed, because under specific circumstances people are able to uphold performance for several hours even when highly fatigued (Hockey, 1997). In this light, and in line with perspectives from other scholars (e.g., Boksem & Tops, 2008; Inzlicht, Schmeichel, & Macrae, 2014), one central point made in this dissertation is that fatigue is the result of an interplay between cognitive and motivational processes. To date, this interplay between cognition and motivation has been one of the most difficult things to grasp. Therefore, the focus of this doctoral dissertation is to find out what types of motivational processes are involved in fatigue and through what (psychophysiological) mechanisms they influence cognition. Before presenting the research aims for this doctoral dissertation, I will give a general overview of the relevant literature to this point.

WHAT IS MENTAL FATIGUE?

Fatigue is a very common phenomenon that everybody will experience from time to time. If you would ask someone what fatigue means, you could get diverse answers like tiredness, drowsiness, exhaustion, and lack of energy. Researchers have had great difficulty defining the exact characteristics of fatigue. Some definitions of fatigue are more focused on the experience of fatigue, whereas others consider performance or physiological indicators (cf. Phillips, 2015). On top of the multiple facets that make up fatigue, there is also a distinction between the common acute version of mental fatigue and a more incidental and clinical chronic version of fatigue. Chronic fatigue is not necessarily related to exertion of effort and is one of the core symptoms of many psychological disorders (e.g., depression; see Demyttenaere et al., 2005). The difference with acute fatigue, apart from the previous exertion of effort, is that acute fatigue is related to a specific task and is temporary. Taking a break, or switching to another activity, can be enough to temporarily relieve the feeling of fatigue and restore cognitive performance. The ability to easily induce and relieve acute fatigue has led to many lab studies that focus on fatigue and its effects on performance (e.g., Boksem et al., 2005; Lorist et al., 2000; van der Linden, Frese, & Meijman, 2003). In these studies, fatigue is often induced by letting participants work on a demanding cognitive task for an extended amount of time.

Recent experimental studies showed that fatigue coincides with a reluctance for further effort (cf. van der Linden, 2011). On the behavioral level, fatigue is related to general disengagement and low vigor, in contrast to the possibility of exploiting the benefits of a certain task, or exploring the environment for rewarding activities (Boksem, Meijman, & Lorist, 2006; van der Linden, Frese, & Sonnentag, 2003). In addition, several studies have shown that fatigue mainly impacts top-down cognitive control processes, such as overseeing and regulating attention and behavior (e.g., Lorist et al., 2000; Lorist, Boksem, & Ridderinkhof, 2005; van der Linden & Eling, 2006; van der Linden, Frese, & Meijman, 2003), as they generally require the subjective experience of investing high amounts of effort (Dehaene, Kerszberg, & Changeux, 1998). Bottom-up cognitive processes such as visual identification, on the other hand, requiring lower amounts effort, are relatively unaffected by fatigue. Boksem and Tops (2008) proposed that feelings of fatigue lead to abandoning behavior when the energetical costs exceed the perceived benefits of continued performance. It is thus widely accepted that, generally speaking, fatigue negatively impacts task engagement when mental effort is required.

TASK ENGAGEMENT (COST AND REWARD)

In earlier years of fatigue research, fatigue has mainly been interpreted as the result of a loss in energetic resources after excessive work and thus was used as a performance indicator (Griffith, Kerr, Mayo, & Topal, 1950; Ryan, 1947). With this interpretation of fatigue in mind, the concept of 'mental energy' served as the basis for motivation and action. According to this classical view, people are less able to initiate or sustain behavior effectively when this energy is lacking. As a result, performance decreases. More recently, this approach has been challenged by findings of recovered effective behavior when people are externally motivated, even though they were previously too fatigued to continue (Boksem et al., 2006; Hockey, 2011). This has led to a new interpretation of mental fatigue as a 'stop emotion', signaling us to discontinue working long before our actual ability to work runs out (Meijman, 2000; van der Linden, 2011). In line with this idea, Hockey (2011) suggested that fatigue is an adaptive state signaling a conflict when deciding between what is being done and what else might be done. This underpins the influence of self-control and motivation in the experience of mental fatigue.

Recently, Inzlicht, Schmeichel and Macrae (2014) have emphasized that problems with maintaining task engagement (e.g., in a fatigued state) are often the product of evolutionary pressures that motivate organisms to balance their desires for exploitation versus exploration behavior. This desire for exploitation versus exploration derives from a trade-off between the expected costs and rewards of a task (Aston-Jones & Cohen, 2005; Cohen, McClure, & Yu, 2007). When the cost/reward trade-off is favorable, exploitation of the task rewards by engaging in the task is stimulated. That is, even though asserting cognitive control is aversive, the task provides enough intrinsic (e.g., pleasure, excitement) and/or extrinsic (e.g., monetary benefits) rewards to make it worth the effort. However, when the trade-off becomes unfavorable, the person will tend to disengage from the task. Instead of exploiting the task rewards, it becomes more likely that one starts to explore the environment to find potentially more rewarding tasks. This increases the probability of failures in self-control and task-related behavior that are often observed during mental fatigue.

The role of cost/reward tradeoffs of engagement has also been emphasized in several previous fatigue studies (e.g., Boksem & Tops, 2008). This indicates that mental fatigue is likely to occur when the costs of engaging in a task exceed the predicted rewards. In line with this notion, increasing the rewards of task engagement under fatigue may cause shifts in motivation that could drive attention back to task-related cues. Such an effect has been confirmed in a previous study by Boksem and colleagues (2006). They showed that after two hours of cognitive performance, fatigued participants could partly restore their performance when they would receive a monetary reward. This effect was accompanied by an increase in the error related negativity event related potential. Boksem and coworkers (2006) considered these findings supportive for the notion that dopaminergic reward systems play a role in fatigue-related decline of performance. However, in this doctoral dissertation, I will argue that another psychophysiological system, the locus-coeruleus norepinephrine system (LC-NE), may also play an important role during fatigue, because of its importance in regulating task engagement.

THE LOCUS COERULEUS NOREPINEPHRINE SYSTEM

The locus coeruleus (LC) is a neuromodulatory nucleus in the brainstem which is responsible for almost all of the norepinephrine (NE) that is released in the brain. It has widespread projections throughout the forebrain. In their seminal article, Aston-Jones and Cohen (2005) delineated their ideas about the role the LC-NE system plays in task engagement and performance, based on results from primarily animal research. Specifically, in their Adaptive Gain Theory, Aston-Jones and Cohen distinguish between baseline and stimulus-evoked release of NE. By combining measures of baseline and stimulus-evoked NE release, they formulated two operating output modes for the LC-NE system that are related to areas below an inverted U curve (see Figure 1.1): the *phasic* and the *tonic* mode. The phasic mode is characterized by intermediate baseline levels of NE and strong stimulus-evoked bursts of NE release. This output mode of the LC-NE system supports high task engagement, meaning that attention is focused to task-relevant stimuli in order to optimize task performance (Minzenberg, Watrous, Yoon, Ursu, & Carter, 2008). In the tonic mode, both baseline and stimulus-evoked levels of NE are high. Such levels imply that the LC-NE system no longer predominantly responds to task-relevant stimuli but also to task-irrelevant stimuli (Cohen et al., 2007). Consequently, one gets distracted more easily and performance on the task at hand deteriorates. The tonic LC-NE output mode is therefore associated with reduced task engagement and increased attention to task-irrelevant stimuli (i.e., distraction).

The phasic and tonic modes are assumed to serve two different forms of adaptive behavior. The phasic mode is presumed to support exploitation of the task at hand in order to optimize task rewards. In contrast, the tonic mode supports exploration of the environment in order to find potentially more rewarding tasks (Cohen et al., 2007). Given the presumed role of the LC-NE system as described by Aston-Jones and Cohen, the model also leaves space for a third output mode that is characterized by low baseline and low stimulus-evoked levels of NE. In this third potential mode, which the authors did not fully develop in their article, the lower levels of NE lead to diminished attention, disengagement from the task at hand, and low vigor in general (Aston-Jones & Cohen, 2005). These effects of diminished NE are very similar to the effects that are typically observed when people are in a state of mental fatigue (Boksem et al., 2006; van der Linden, Frese, & Sonnentag, 2003). Therefore, it would be relevant to test whether the LC-NE system is related to mental fatigue and it behavioral effects. In the studies of this thesis the relation between the LC-NE system and fatigue will be explored. Below I will first describe how I plan to measure LC-NE activity, and relate it to the effects of mental fatigue. Then, I will present the specific research aims I had at the start of this research project.

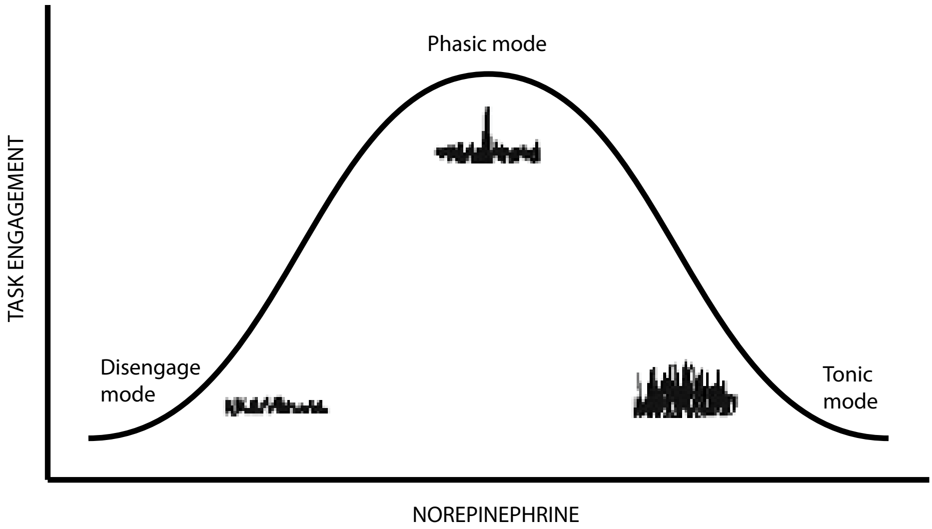


Figure 1.1. The output modes of the LC-NE system.

PSYCHOPHYSIOLOGICAL TESTS OF ENGAGEMENT DURING FATIGUE

Although the theory on the LC-NE system is largely based on data from animal studies, it may also apply to human cognition and behavior. To date, however, there have been very few studies that explicitly observed the LC-NE system in humans. One of the most important reasons for this lack of previous studies, is that the LC is a very small nucleus in the brainstem that lies far from the outside of the skull. Therefore, it is (to date) very costly and invasive to directly measure LC activity in humans (i.e., placing electrodes deep in the brain) and the imaging alternatives (e.g., fMRI) remain too imprecise to scan the small LC nucleus.

While it is hard to measure LC-NE activity directly, there are options to measure its known manifestations. The most influential psychophysiological indicators of the LC-NE system are pupil dynamics and the P3 event-related potential (ERP). Specific arguments in favor of a link between these markers and the LC-NE system can be derived from several studies. For example, Rajkowski and coworkers (2004) simultaneously assessed pupil diameter and directly measured LC-NE activity in an animal study. They found that phasic pupil dilations almost perfectly mirrored stimulus-evoked LC-NE activity and baseline pupil diameter corresponded to baseline LC-NE activity. In addition, Gilzenrat and colleagues (2010) conducted a series of human studies and showed that LC activity could be indexed via pupillometry and that level of task engagement was reliably predicted by pupil diameter. Regarding the P3, Nieuwenhuis and coworkers (2011) wrote a review on a possible link between this EEG-component and the LC-NE system. The P3 is a well-known ERP consisting of a positive shift in EEG-activity following the presentation of stimuli that are novel (P3a) or motivationally relevant (P3b; Polich & Kok, 1995; Polich, 2007). Although the P3 is among the most widely used ERPs, its neurological source is still debated. In this context, Nieuwenhuis et al. (2005) systematically compared properties of P3 and LC-NE and concluded that "The P3 may provide a window into the functioning of the LC-NE system in humans" (p. 526). Supported by the results of these studies, I will measure pupil diameter, pupil dilation, and the P3 amplitude as indicators of LC-NE activity during the studies of this doctoral dissertation.

In the studies included in this thesis, I assume that mental fatigue involves changes in costs/reward tradeoffs of task engagement. Precisely which rewards and costs are involved is not a major theme in this dissertation. The main point is that due to fatigue-related changes in cost/reward tradeoffs, the LC-NE system may change its output mode. I expect that with increasing fatigue, the LC-NE system will shift from the phasic output mode that supports high task engagement and performance, towards a mode that either supports distractibility (i.e., the tonic mode), or general disengagement. This would be reflected by a decrease in phasic activity to task-relevant stimuli (i.e., decreased P3 amplitude/pupil dilations), and a) relatively high baseline activity in the case of distractibility, or b) relatively low baseline activity in the case of general disengagement. In this dissertation, such psychophysiological effects will be studied and systematically related to changes in subjective states, such as fatigue and engagement, and behavior, such as task focus and performance.

Showing that indicators of LC-NE system activity are related to the cognitive effects of fatigue would contribute to a refinement of the neurocognitive model of fatigue. The multi-method approach (e.g., the simultaneous use of pupillometry, ERPs, subjective measures, behavioral measures) is a strong asset to achieve this aim, because it allows firmer conclusions than would be possible with any single-method approach. I recognize that a complete neurocognitive model of task engagement under fatigue will be complex and involve different brain systems and neurotransmitters as well. For example, the LC-NE systems are strongly influenced by sites that are often associated with dopaminergic modulation, such as the ACC and OFC (Aston-Jones & Cohen, 2005). However, there is no reason that this complexity should prevent me to focus on the role of a specific mechanism and its psychophysiological markers in this thesis.

RESEARCH AIMS

From the reasoning in the above, fatigue appears to be the result of an interplay between cognitive and motivational processes. Yet to date, truly understanding this interplay remains to be a major scientific challenge. Therefore, the central aim of this doctoral dissertation is to find how motivation is involved in fatigue and through what (psychophysiological) mechanisms it influences cognition and performance. With this aim in mind, the amount of task engagement during fatigue, deriving from motivational cost/reward tradeoffs, is one of the key concepts that is investigated. Based on the multifaceted nature of fatigue, mental fatigue is examined using multiple indicators of task engagement within a well-established fatigue paradigm. Specifically, fatigue-related effects on motivation, cognition and performance are investigated by using a set of subjective, behavioral and psychophysiological measures of task engagement. This way, it becomes clear on what levels task (dis)engagement and fatigue are related. By directly linking these three types of measures (i.e., subjective, behavioral and psychophysiological measures), this dissertation makes an innovative contribution to the mental fatigue research field. It could provide a deeper understanding of mental fatigue, its effects on performance, and its psychophysiological origins. Additionally, this thesis may also contribute to general knowledge about the fundamental processes that underlie task engagement and expand knowledge on the output modes of the LC-NE system. Because mental fatigue is such a common phenomenon and has such a strong impact on productivity and safety, it could also have important practical implications, such as the refinement of countermeasures to prevent accidents and errors. For example, it may be useful in developing detection systems that can monitor the level of fatigue in operators and provide tools to overcome its negative effects on safety and performance.

I will now provide a general outline of the chapters in this doctoral dissertation and the studies I have conducted in cooperation with my colleagues at the Erasmus University Rotterdam. In Chapter 2 and 3, the foundations for a psychophysiological framework for mental fatigue are established. Utilizing an experimental time-on-task design, it will be tested whether mental fatigue is related to task disengagement. Participants in these experiments continuously work on an n-back task for an extended period (i.e., about 2 hours). The n-back task is known to require high levels of task engagement and sufficient levels of voluntary attentional control (Chen, Mitra, & Schlaghecken, 2008; Cohen et al., 1997; Watter, Geffen, & Geffen, 2001). We expect that during a two-hour continuous performance task, subjective fatigue increases and task engagement decreases with increasing time-on-task. During such a demanding task a decrease in engagement should also be accompanied by compromised task performance. In order to investigate the involvement of the LC-NE system, we also measure multiple indicators of LC-NE activity. In Chapter 2 we test P3 amplitude and baseline pupil diameter and in Chapter 3 we add stimulus-evoked pupil dilation as an alternative measure of stimulus-evoked LC-NE activity. The time-on-task effects of all measures will be compared directly using a multilevel correlational analysis.

Chapter 4 builds on the foundations that are built in the previous two chapters. While there is now substantial empirical evidence for the involvement of motivational cost/reward trade-offs in mental fatigue, it is less clear what attentional disengagement during mental fatigue actually entails. For example, an important question that remains open, is whether being fatigued after engaging in a task for a considerable amount of time implies that one directs attention to other, and potentially more rewarding tasks. Are fatigued individuals likely to pay less attention to task-related stimuli, and explore the environment for other, more interesting stimuli? Or do they still try to stay focused on the task, but do so in a less effective way? While the answers to these questions have important implications for designing fatigue prevention interventions, so far, fatigue studies have mainly been focused on cognitive indicators of engagement that are measured during controlled tasks that offer a very limited amount of interesting alternative stimuli to direct attention to. In Chapter 4, we will induce mental fatigue while also introducing alternative stimuli to the experimental environment. Specifically, we present images of faces on the far sides of the screen during parts of the experiment. It has been widely acknowledged that faces are inherently rewarding to look at, even when they are not task-relevant, because they have an adaptive role and potentially contain important social information (M. H. Johnson, 2005; Schmidt & Cohn, 2001). Because the face stimuli constitute an alternative rewarding stimulus to the environment, eye-tracking can be used to observe the focus of attention with increasing time-on-task and mental fatigue. This allows us to not only observe a potential decrease of attentional control as has been done in chapters 2 and 3, but also to observe shifts in attention (measured with eye movements) between the different stimuli. This will allow for a more precise insight in disengagement of attention during mental fatigue and might answer the question of whether performance decrements during fatigue are caused by an inability to efficiently process the task, or a distraction from the task and exploration of alternative stimuli.

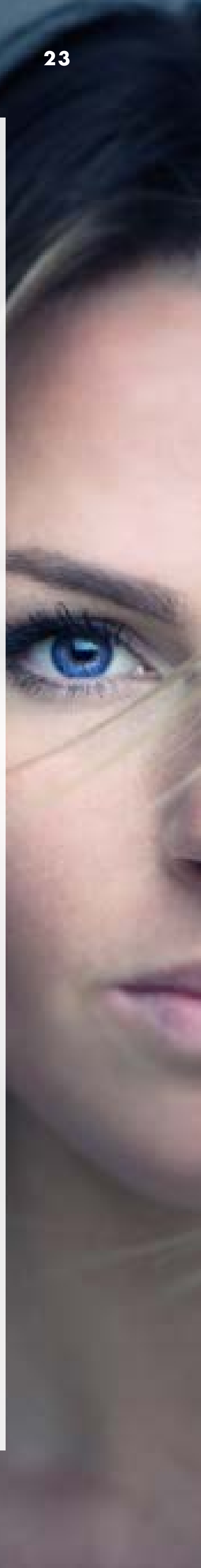
A second important aim of the studies in Chapter 2, 3 and 4 is to test the influence of motivation during mental fatigue and its effects on cognition and performance. The presumed influence of cost/reward tradeoffs makes us expect that task engagement can be restored after periods of fatigue and disengagement, as long as the rewards for task engagement are sufficiently increased. While the more traditional resource approach would expect that rest is needed to replenish energy levels, we expect that increasing motivation to engage will restore levels of task engagement and task performance. To test this, we include a manipulation, in which we increase the rewards for engaging in the task after participants had already worked on the demanding task for two hours. This manipulation, to some extent, resembles the one used by Boksem et al. (2006). Specifically, we will tell participants that the remaining time that is left on the task will depend on the quality of their performance during the last series of trials. Research has shown that after working on the task for two hours, this manipulation provides a strong motivation to re-engage in the task and optimize performance in order to be permitted to stop. We then examine in what way such a reward manipulation affects task engagement, the P3 amplitude and pupil diameter in Chapter 2, pupil dilation in Chapter 3, and task-focused gaze in Chapter 4. We hypothesize that an increase in task rewards will coincide with an increase in P3 amplitude, pupil diameter and dilation, and task focused gaze, thus suggesting re-engagement in the task.

Although chapters 2 through 4 focus on various subjective and cognitive indicators of task engagement, they do not include direct measures of mental effort. However, mental effort could be one of the key components in task disengagement during mental fatigue. That is, when individuals become fatigued they disengage from the task, because the costs and benefits of the task are no longer in balance. As such, it can be expected that lower task engagement during mental fatigue, as indicated by subjective (e.g., analogue scales) and psychophysiological (e.g., pupil dilation) measurements, is also accompanied by a reduction in mental effort. Therefore, in Chapter 5, we report a fatigue study in which we combine subjective, performance, and pupil diameter measures with a psychophysiological measure that is known to reflect mental effort. Specifically, we will use the cardiovascular measure of heart-rate variability in the low frequency domain (i.e., sometimes called the .10Hz domain, measure range: .04–.15 Hz), which has repeatedly been linked to performance on cognitively demanding tasks (Aasman, Mulder, & Mulder, 1987; Meijman & Mulder, 1998; Mulder, 1980). These previous studies have shown that reduced heart-rate variability in the low frequency domain is observed when individuals are engaged in attending demanding mental operations (i.e., investing mental effort). When mental effort is indeed reduced during mental fatigue, this would further support that motivationally induced disengagement is an important mechanism to explain the effects of mental fatigue on task performance.

In Chapter 6, we will test whether the presumed psychophysiological system of mental fatigue, described in the first chapters of this thesis, is stable across different populations. Because to this point we have only tested healthy university students, the proposed system may not be universal. Therefore in Chapter 6, we specifically test a population with a mild form of depression. Because second only to the depressed mood itself, tiredness, low energy, and listlessness are the most common symptoms to be associated with depression (Demyttenaere et al., 2005; Stahl, 2002), examining this specific population will test the robustness of the findings in the previous chapters. De Lecea, Carter and Adamantidis (2012) have suggested that changes in arousal states and thresholds are at the core of most neuropsychiatric disorders, including depression which is correlated to structural hypo-arousal. Chaudhuri and Behan (2004) describe that fatigue and cognitive disengagement in depression often result from a loss of interest and motivation. These authors also argue that even with usual levels of motivation, motor control, and sensory input, premature fatigue may arise because of unpleasant ambient conditions, dysautonomia, and underlying endocrine disturbances. Based on these findings, the question arises whether individuals with mild depressive symptoms (i.e., dysphoria) diverge from their non-depressive counterparts in their susceptibility to the effects of mental fatigue (i.e., earlier onset, more severe effects on performance). In this chapter, we will specifically address this question by comparing both groups while they are working on a cognitive task for an extended period of time. Finally, in Chapter 7 I will integrate and discuss the findings and contributions of this the studies in this thesis.

CHAPTER 2

A multifaceted investigation of the link between mental fatigue and task disengagement



ABSTRACT

Mental fatigue is often characterized by reduced motivation for effortful activity and impaired task performance. We used subjective, behavioral (performance), and psychophysiological (P3, pupil diameter) measures during an n-back task to investigate the link between mental fatigue and task disengagement. After two hours we manipulated the rewards to examine a possible re-engagement effect. Analyses showed that, with increasing fatigue and time-on-task, performance, P3 amplitude, and pupil diameter decreased. After increasing the rewards, all measures reverted to higher levels. Multilevel analysis revealed positive correlations between the used measures with time-on-task. We interpret these results as support for a strong link between task disengagement and mental fatigue.

Keywords. Fatigue; Motivation; P3; Pupil diameter; Task engagement

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INTRODUCTION

Sustained performance on cognitively demanding tasks often leads to mental fatigue, which is a complex state characterized by a reluctance for further effort and changes in mood, motivation, and information processing (Meijman, 1997; van der Linden, Frese, & Meijman, 2003). Levels of mental fatigue may fluctuate due to normal everyday activities (e.g., as a consequence of daily job demands), but may also be chronic and comorbid to diseases or disorders such as Parkinson's disease (Chaudhuri & Behan, 2004), depression (Demyttenaere et al., 2005), and burnout (Maslach, Schaufeli, & Leiter, 2001). In the workplace, mental fatigue has been found to be one of the most frequent causes for work accidents (Baker et al., 1994; McCormick et al., 2012). Despite the mundane nature of mental fatigue, the exact psychological mechanisms that are involved remain relatively unknown. For example, although it appears that cognitive control is sensitive to fatigue, there is an ongoing investigation to determine the exact cognitive processes that are compromised. The most difficult part of fatigue to grasp scientifically may be the interplay between cognition and motivation. Some researchers have referred to fatigue as a stop-emotion that serves to prevent exhaustion by exerting too many resources into a task (cf. van der Linden, 2011). As a consequence, people often tend to disengage from the task at hand when they are getting fatigued. This disengagement is characterized by impairments in motivation (e.g., lower effort invested in the task), cognition (e.g., diminished attention and task focus), and effective behavior (e.g., decreased task performance; Boksem & Tops, 2008; Hockey, 1997).

Based on the multifaceted nature of fatigue, the central aim of the present study is to examine mental fatigue using multiple indicators of task (dis) engagement within a well-established fatigue paradigm. Specifically, we will investigate fatigue-related effects on motivation, cognition, and performance by using a set of subjective, behavioral and psychophysiological measures of task engagement. This way, we assess on what levels task (dis)engagement and fatigue are related. By directly linking these three types of measures (i.e., subjective, behavioral, and psychophysiological) we make an innovative contribution to the mental fatigue research field.

FATIGUE AND ENGAGEMENT

As mentioned earlier, fatigue is often observed as a reluctance for further effort. On the behavioral level, fatigue is related to a general disengagement and low vigor in contrast to the possibility of exploiting the benefits of a certain task, or exploring the environment for rewarding activities (Boksem et al., 2006; van der Linden, Frese, & Sonnentag, 2003). Several studies have shown that fatigue mainly impacts top-down cognitive control processes (e.g., Lorist et al., 2000; Lorist, Boksem, & Ridderinkhof, 2005; van der Linden & Eling, 2006; van der Linden, Frese, & Meijman, 2003), as they generally require the subjective experience of investing high effort (Dehaene et al., 1998). Bottom-up cognitive processes, on the other hand, requiring less effort, are relatively unaffected by fatigue. Boksem and Tops (2008) propose that feelings of fatigue lead to abandoning behavior when the energy cost exceeds the perceived benefits of continued performance. Therefore, it is widely accepted that, generally speaking, fatigue negatively impacts task engagement when mental effort is required.

To date, only few studies have been conducted on the psychophysiology of mental fatigue (e.g., Boksem et al., 2006; Faber, Maurits, & Lorist, 2012; Lorist, 2008). In the present study, we will use two measures that have often been considered as indicators of task engagement. However, these measures, the parietal P3 event-related potential (ERP) and pupil diameter, have not yet been thoroughly tested within a typical fatigue design[1]. The P3 is one of the most heavily investigated ERPs and consists of a frontal P3a component that has been related to focal/stimulus-driven attention and novelty detection, and a parietal P3b component that has been related to focused attention related to subsequent working memory activation and salience detection (Polich, 2007). Begleiter, Porjesz, Chou, and Aunon (1983) proposed that the parietal P3 component may index motivational properties of a stimulus. Later, it was found that the effect of motivational significance on the P3 amplitude is also modulated by the amount of attention that is paid to the stimulus (R. Johnson, 1993). Combining the sensitivity to both motivational and attentional aspects of a task has led researchers to link the P3 to task engagement (e.g., Murphy, Robertson, Balsters, & O'connell, 2011).

1 We know of two studies. (Boksem et al., 2006) briefly mention the P3 but mainly focus on response-locked potentials (Ne/ERN) and (Massar et al., 2010) measure the more frontal P3a component which is functionally different from the parietal P3b that we measure.

The other psychophysiological measure we use, the diameter of the pupil, has for many years been considered as an index of psychophysiological arousal or neural gain. Classic work of Beatty and Kahneman has already showed that the pupil is sensitive to momentary load and effort during mental tasks (Beatty, 1982; Kahneman & Beatty, 1966; Kahneman, 1973). In recent years, however, these statements have been nuanced by specifically relating the pupil diameter to control states of engagement (i.e., exploration vs. exploitation). For example, Gilzenrat and colleagues (2010) and Jepma & Nieuwenhuis (2011) have conducted multiple experiments to relate pupil diameter to task engagement. They observed that task engagement and exploitation behavior were related to an intermediate pupil diameter. On the other hand, disengagement from the task in the form of distraction and explorative behavior was related to increased pupil diameter. This relation was described as the classic Yerkes-Dodson curve (Yerkes & Dodson, 1908), in which intermediate arousal leads to optimal engagement and performance (see Figure 2.1). Low and high arousal, on the contrary, lead to disengagement and impaired task performance. With regard to our study, the low arousal (and corresponding small pupil) state is especially interesting because the behavioral consequence (i.e., general disengagement and impaired performance) seems to strongly overlap with the behavioral consequence of fatigue.

In an experimental time-on-task design, we tested the hypothesis that mental fatigue is related to task disengagement, reduced P3 amplitude, and pupil diameter. Participants continuously worked on an n-back task for an extended time (2 hours). The n-back task is known to require high levels of task engagement and sufficient levels of voluntary attentional control (Chen et al., 2008; Cohen et al., 1997; Watter et al., 2001). We expected that, during a two-hour continuous performance task, subjective fatigue increases and task engagement decreases with increasing time-on-task. On such a demanding task a decrease in engagement should be accompanied by compromised task performance. Moreover, we predicted, that parallel to the increase of fatigue and the decrease of reported task engagement, there will be decreases in both the pupil diameter and the P3 amplitude. The combination and direct comparison of subjective measures of fatigue, measures of task performance, and physiological measures of the P3 and pupil diameter is an informative and innovative way to examine the relation between mental fatigue and task disengagement.

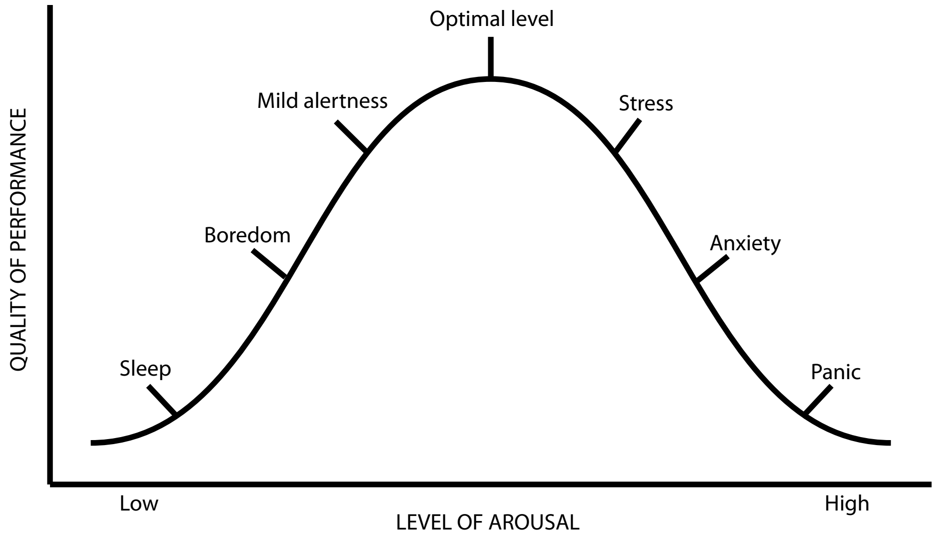


Figure 2.1. The classic Yerkes-Dodson law describes low levels of performance for low and high levels of arousal, and high levels of performance for intermediate levels of arousal.

REVERSIBILITY OF MENTAL FATIGUE EFFECTS

Previous studies have shown that task engagement mainly depends on the expected value of engaging in a task. This expected value is based on a tradeoff between the expected costs and rewards of a task (Aston-Jones & Cohen, 2005; Cohen et al., 2007). When the cost/reward tradeoff is favorable, it stimulates exploitation of the task rewards by engaging in the task. That is, the motivation and corresponding attentional focus that is typical for task engagement occurs when executing the task provides enough intrinsic (e.g., pleasure, excitement) and/or extrinsic (e.g., monetary benefits) rewards to make it worth the effort. However, when the tradeoff becomes unfavorable, one tends to disengage from the task. The exploitation behavior then makes place for exploration behavior that is manifested in the tendency to explore the environment, in pursuit of more rewarding tasks. This subsequently increases the probability of failures in task-related behavior (e.g., failing to respond to important task-related cues).

The role of cost/reward tradeoffs of engagement have also been emphasized in several previous fatigue studies (Boksem & Tops, 2008) indicating that mental fatigue is likely to occur when the costs of engaging in a task exceed the predicted rewards. In line with this notion, increasing the rewards of task engagement under fatigue may cause shifts in motivation that may drive attention back to task-related cues. This effect has been confirmed in a previous study by Boksem and colleagues (2006) who showed that, after two hours of cognitive performance, fatigued participants could partly restore their performance when they received a monetary reward. This effect was accompanied by an increase in the error-related negativity ERP. Boksem and coworkers (2006) considered such findings supportive of the notion that dopaminergic reward systems play a role in fatigue-related decline of performance.

In the present study, we focus on the responsiveness of the P3 amplitude and pupil diameter as measures of task engagement in response to increasing rewards during mental fatigue. We expect that a change in the task rewards may positively influence the cost/reward tradeoff and lead to task re-engagement. To test this, we included a manipulation in which we increased the rewards for engaging in the task after participants had already worked on the demanding task for two hours. This manipulation, to some extent, resembles the one used by Boksem et al. (2006). Specifically, we told participants that the remaining time that was left on the task would depend on the quality of their performance during the last series of trials. After working on the task for two hours this manipulation provided a strong motivation to re-engage in the task and optimize performance to be permitted to stop. We then examine in what way such a reward manipulation affects task engagement, the P3 amplitude, and pupil diameter. We hypothesize that an increase in task rewards concurs with an increase in P3 amplitude and pupil diameter, suggesting re-engagement in the task.

METHOD

PARTICIPANTS

Twenty undergraduate students (3 males, 17 females), between the ages of 17 and 24 (*M* = 19.9 years, *SD* = 2.0) participated in the study and received study credits. All participants were well rested and in good health as measured by self-report. The participants reported to have slept seven or more hours and were asked to withhold the intake of caffeine and alcohol during the 24 hours before the experiment. All participants had normal or corrected-to-normal vision. Written informed consent was obtained prior to the study.

STIMULI AND DATA ACQUISITION

Participants were seated in a comfortable chair in a dimly lit, and sound attenuated room facing an eye-tracking screen at a distance of approximately 65 cm. During the whole experiment, pupil diameter and electroencephalogram (EEG) were measured continuously. The participants performed a visual letter n-back task in 1-back, 2-back and 3-back variants. Participants were asked to decide whether the letter presented on the screen was a target or non-target stimulus. In the n-back task a stimulus is a target when the presented letter is the same as the letter presented n letters before. Accordingly, they responded on the corresponding button in the armrest of the chair. The stimuli were presented in the center of the screen and consisted of the letters B, C, D, E, G, J, P, T, V, and W in the font Palatino Linotype point size 40. In the Dutch language, these letters are phonologically similar in order to prevent sound-related retrieval strategies. The letters were presented randomly with a target rate of 25%. The n-back task has been used successfully in previous experiments to induce mental fatigue (Massar, Wester, Volkerts, & Kenemans, 2010). It is a cognitively demanding task that requires the sustained engagement of working memory and attention in order to uphold adequate levels of performance (Watter et al., 2001).

PROCEDURE

Before the experiment, participants filled out questionnaires about their general health, current level of fatigue, and task motivation (see description of these measures below). After the calibration of the eye-tracking device, participants were instructed on the n-back task (see below). Participants practiced on each variant of the task until they reached a minimum of 70% accuracy. The experimental task was divided in seven time-on-task blocks. Each block consisted of 63 trials of the 1-back task, followed by 63 trials of the 2-back task, followed by 63 trials of the 3-back task and lasted for about 18 minutes (depending on random intervals). There was no rest between tasks. The n-back stimuli were displayed for 500ms with an inter-stimulus interval randomized at 5 to 5.5 seconds. The length of this interval was long enough to ensure that the pupil diameter returned to baseline levels (Beatty, 1982; Stern, Ray, & Quigley, 2000).

After each block, the participants had to indicate their current level of fatigue and task engagement. The participants had only limited time to do this, to make sure they would not rest. After they completed six blocks of 18 minutes, we introduced our reward manipulation. We told them that the remaining time of the experiment would depend on their performance relative to their performance on the previous blocks. We explained that if they performed better the remaining time could be as short as about five minutes. However, we also told them that if they performed similar or worse the remaining time could run up to about forty minutes (i.e., it could range from somewhere between 5 and 40 minutes depending on their performance). We assumed that, after about two hours of continuous performance, this provides a strong incentive to optimize performance. In reality, the length of this last block was the same as the first six blocks. After the experimental task, the participants were asked to fill in questionnaires about their levels of fatigue.

MEASURES AND DATA PROCESSING

Subjective measures. Subjective fatigue was measured before, during, and after the task in order to monitor its temporal progression. Before and after the task, participants filled in the Rating Scale Mental Effort (RSME; Zijlstra, 1993), which consists of seven vertical scales assessing different aspects of mental fatigue (e.g., difficulty keeping attention on the task, difficulty exerting further effort in the task). The scales have numerical (0 to 150) and verbal ("not at all" to "extremely") anchors. After each time-on-task block during the experiment, the participants were asked, "How tired do you feel?". They had to reply by moving a slider from 0 to 100, with increments of five. The slider had no anchors, but the extreme ends were labeled with "very much" and "not at all". Due to missing data at certain blocks, two participants were excluded for the analysis of the subjective fatigue and one participant was excluded for the analysis of the subjective engagement.

After each time-on-task block, we also measured task engagement by asking, "How engaged are you in the task?" The participants had to reply by moving a slider from 0 to 100, with increments of five. The slider had no anchors except for the extremes "very much" and "not at all". Because task engagement was measured multiple times during the experiment, the temporal progression of subjective engagement in the task could also be monitored.

Behavioral measures. The most relevant behavioral measure of performance on the n-back task was accuracy. We operationalized accuracy by calculating the d-prime for each time-on-task interval. As described by signal detection theory, the d-prime was calculated as an indication of accuracy (Wickens, 2001). While accuracy was the most important focus for the participant during the task, we wanted to make sure accuracy effects were not clouded by accuracy/speed tradeoffs. Therefore, we also examined reaction times (RTs).

Physiological measures. Pupil diameter was recorded continuously during the entire length of the experimental task with a Tobii Eyetracker 2150 with a sample rate of 50 Hz. For two female participants the eye-tracking data were not saved due to a technical problem. We excluded these participants from the analysis of the eye-tracking data but included their data in the other analyses. The recordings were exported to Brain Vision Analyzer (Brain Products, Gilching, Germany). Artifacts and blinks were detected by the eye-tracker and removed by using a linear interpolation algorithm. To measure baseline pupil diameter, we averaged the pupil diameter in the 500 milliseconds before stimulus onset. During this period, participants saw a black screen so there was no interference from pupillary light reflexes of the eye to the environmental lighting during the baseline recording. Baseline pupil diameter for each condition and time-on-task interval was then exported to SPSS for further analysis.

For the recording of the EEG, we used a BioSemi Active-Two with Ag/AgCl active electrodes at 32+2 scalp sites (International 10-20 system). There were six additional electrodes attached. Two electrodes were placed on the left and right mastoids as reference. To allow correction for ocular movement artifacts, we placed two electrodes next to the outer side of the eyes for horizontal electrooculogram (HEOG) and two above and below the left eye for vertical electrooculogram (VEOG). Online signals were recorded with a sample rate of 512 Hz and 24-bit A/D conversion. Extensive research of the P3 shows the distinction between the P3a and P3b potential. The P3a is linked to novelty detection and best seen at the Cz and Fz electrodes, while the P3b is linked to salience processing and is best seen at the Pz electrode (Polich, 2007). Because we were interested in the latter we analyzed the EEG signal at the Pz electrode. Reviewing the voltage maps confirmed that the amplitude of the P3 was indeed largest at Pz. The EEG data were analyzed in Brain Vision Analyzer (Brain Products). The ERPs were averaged offline after rejection of out of range artifacts and eye movements, using the Gratton and Coles Method (Gratton, Coles, & Donchin, 1983), were removed. Segments with amplitudes higher than 200 μV and lower than -200 μV (0.122% of the data) and voltage steps above 50 μV/ms (0.004% of the data) were removed. The data were also inspected on low activity (below 0.1 μV) and filtered (low cutoff at 0.1 Hz and high cutoff at 40 Hz). After Baseline correction for the 200 ms before the stimulus onset, we aggregated the data per condition and measured the positive peak between 300 and 450 milliseconds after the onset of the stimulus. Trials in which performance errors occurred were excluded. The mean P3 peak activity for each condition and time-on-task interval was then exported to SPSS for further analysis.

STATISTICAL ANALYSIS

The subjective, behavioral, and psychophysiological data were exported to SPSS and statistically analyzed using repeated measures analysis of variance (ANOVA). First, main and interaction effects of time-on-task and task difficulty were tested. Then, significant effects were further qualified by examining changes from block 1 through 6, in which the fatigue manipulation occurred and changes from block

6 to 7, in which the reward/motivation manipulation occurred.

In addition to the repeated measures ANOVA, we also analyzed the data using a multilevel approach with Mplus statistical software (Muthén & Muthén, 1998). The multilevel method takes into account that in some designs measures may not be fully independent from each other, but are nested on various levels. Repeated measures data can be treated as multilevel data, because the repeated measures (i.e., the time-on-task blocks) are nested within individuals. The multilevel analyses take this information into account when calculating associations between variables, because it partitions the variance to each level. Using this multilevel method, we calculated the associations between the various outcome measures (i.e., pupil diameter, P3, subjective measures, performance) on the individual level with the nested structure of the data taken into account (i.e., blocks are nested within persons). We used a two-level model with time-on-task block at the first level (Level 1; $N = 126$), and individuals at the second level (Level 2; $N = 18$). In this operationalization, a high correlation between the outcome variables, implies that a change in one variable corresponds with a similar change in another variable within individuals, taking into account that each individual has been measured during multiple blocks. For more information about multilevel analysis, see Snijders and Bosker (1999).

RESULTS

SUBJECTIVE MEASURES

Pre- and post-task analysis of the RSME confirmed that our fatigue manipulation was successful as participants reported significantly higher levels of subjective fatigue after the experiment than before, $t(19) = -9.5$, $p < .001$. In a repeated measures analysis of the fatigue measure after each block, we found that with increasing time-on-task, participants felt more fatigued from block 1 through 6, $F(2.4,33.2) = 28.13$, $p < .001$, $\eta_p^2 = .67$. After the reward manipulation, subjective mental fatigue significantly decreased from block 6 to 7, $F(1,17) = 7.52$, $p < .05$, $\eta_p^2 = .96$.

Subjective task engagement significantly decreased with increasing time-on-task from block 1 through 6, $F(2.8,47.1) = 28.23$, $p < .001$, $\eta_p^2 = .62$. After the reward manipulation from block 6 to 7, however, there was a significant increase in subjective engagement, $F(1,18) = 18.16$, $p < .001$, $\eta_p^2 = .50$. The latter finding shows that this manipulation effectively increased subjective task engagement during block 7 (see Figure 2.2).

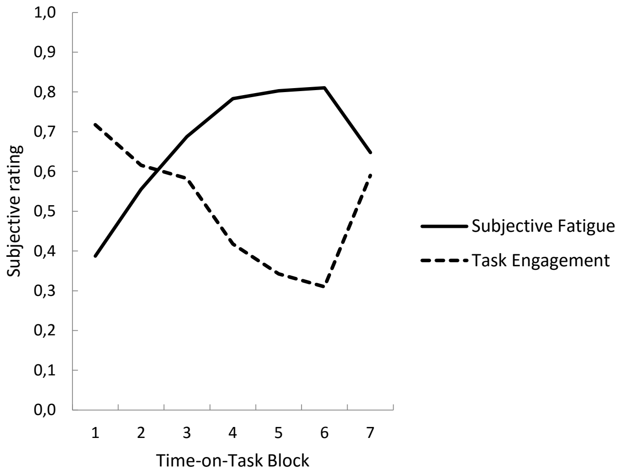


Figure 2.2. Subjective fatigue and engagement ratings with time-on-task. Responses are given ranging from 0 to 1 with 0,05 increments.

2

BEHAVIORAL MEASURES

Repeated measures analysis showed significant main effects for time-on-task, $F(3.3,61.8) = 4.6$, $p < .001$, $\eta_p^2 = .20$, and task difficulty, $F(1.3,23.9) = 16.7$, $p < .001$, $\eta_p^2 = .47$, on d-prime. The main effects were further qualified by a significant interaction between task difficulty and time-on-task from block 1 through 6, $F(5.6,107) = 4.6$, $p < .001$, $\eta_p^2 = .20$. The interaction revealed that the 1-back and 2-back tasks showed a significant decline in d-prime from block 1 to 6 (1-back, ($F(4,75.8) = 6.5$, $p < .001$, $\eta_p^2 = .26$; 2-back, $F(2.5,48.2) = 3.3$, $p < .05$, $\eta_p^2 = .15$), whereas there was no such change in performance on the 3-back task ($\eta_p^2 = .08$; see Figure 2.3). After the reward manipulation, performance significantly increased from block 6 to 7 on all tasks, $F(1,19) = 17$, $p = .001$,$\eta_p^2 = .47$; 1-back, $F(1,19) = 28.8$, $p < .001$, $\eta_p^2 = .60$; 2-back, $F(1,19) = 4.3$, $p = .05$, $\eta_p^2 = .19$; 3-back, $F(1,19) = 4.8$, $p < .05$, $\eta_p^2 = .20$. Note that these results are in line with the results on the subjective measures and indicate a relation between mental fatigue and task engagement on the one hand and task performance on the other hand.

There were no significant time-on-task changes in RTs for the 1-back (η_p^2= .05) and 2-back ($\eta_p^2 = .03$) task. These results show that the decrease in d-prime in the 1-back and 2-back tasks were not due to decreased reaction times, so there was no sign of a speed/accuracy tradeoff with increasing time-on-task (Wickelgren, 1977). However, participants displayed significantly shorter reaction times with increasing time-on-task on the 3-back task, $F(3,57.6) = 3.18$, $p < .05$, $\eta_p^2 = .14$. This indicates that performance on the 3-back task became more efficient over time. It is likely that the difficult 3-back task is more prone to learning effects during this two and a half hour experiment, whereas the 1-back and 2-back tasks reached maximum performance levels relatively early.

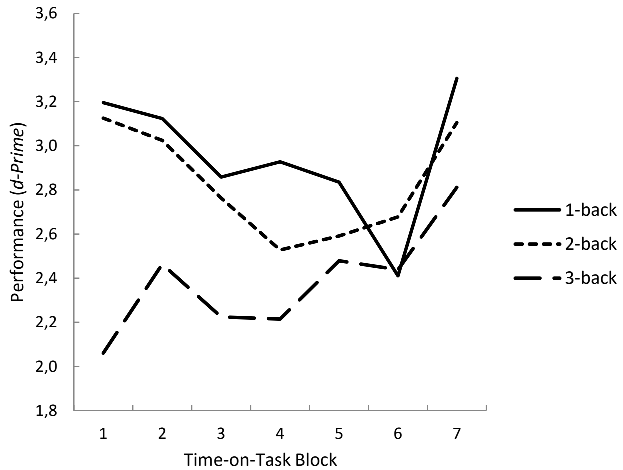


Figure 2.3. Performance on the n-back task with time-on-task for each difficulty level.

PHYSIOLOGICAL MEASURES

Pupil Diameter. As hypothesized, with increasing time-on-task, baseline pupil diameter significantly decreased from block 1 through 6, $F(2.5,42.2) = 4.7$, $p < .01$, $\eta_p^2 = .22$, and significantly increased again after the manipulation from block 6 to 7, $F(1,17) = 10.6$, $p < .01$, $\eta_p^2 = .38$ (see Figure 2.4). The baseline diameter also displayed a strong task difficulty main effect, $F(1.9,32.6) = 10.8$, $p < .001$, $\eta_p^2 = .39$, in which the diameter was significantly larger at more difficult tasks. In Figure 2.4, it can be observed that the initial diameter on block one is much lower for lower-difficulty levels of the n-back task. This lower initial value also results in a time-on-task curve that is less steeply declining. This is also reflected in the significant interaction effect between time-on-task and task difficulty, $F(5.4,92.2) = 2.8$, $p < .05$, $\eta_p^2 = .14$. A subsequent analysis also tested the time-on-task effects for each task individually. The results were in line with the observation that the more difficult the task, the stronger the time-on-task effect (1-back: *ns*, $\eta_p^2 = .09$; 2-back: $F(3,59.2) = 4.0$, $p < .05$, $\eta_p^2 = .17$; 3-back: $F(3.2,64.1) = 7.6$, $p < .01$, $\eta_p^2 = .27$).

P3 Amplitude. We confirmed that the P3b was largest at electrode Pz. The voltage maps in Figure 2.5 show the localization of the P3 ERP during each time-on-task block. The P3b amplitude showed a strong significant main effect for time-on-task, $F(3.3,63) = 4.8$, $p < .01$, $\eta_p^2 = .20$. Figure 2.6 shows the P3 with

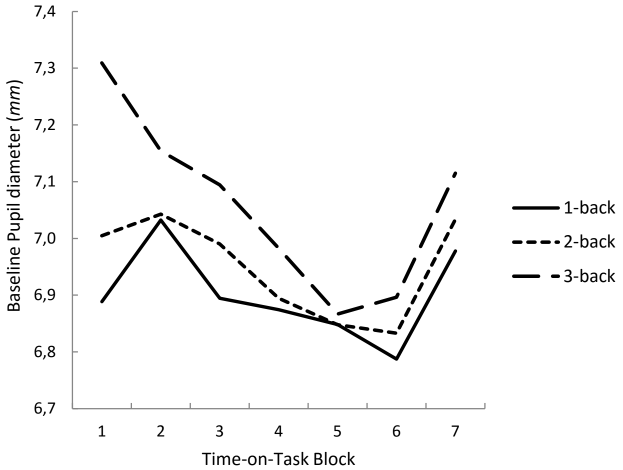


Figure 2.4. Baseline pupil diameter with time-on-task during the 1-back, 2-back, and 3-back task.

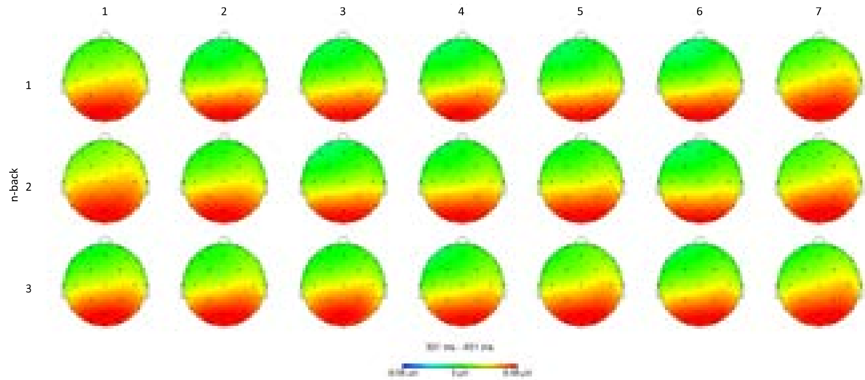


Figure 2.5. Localization of the P3 amplitudes depict a clear maximum at the parietal electrodes.

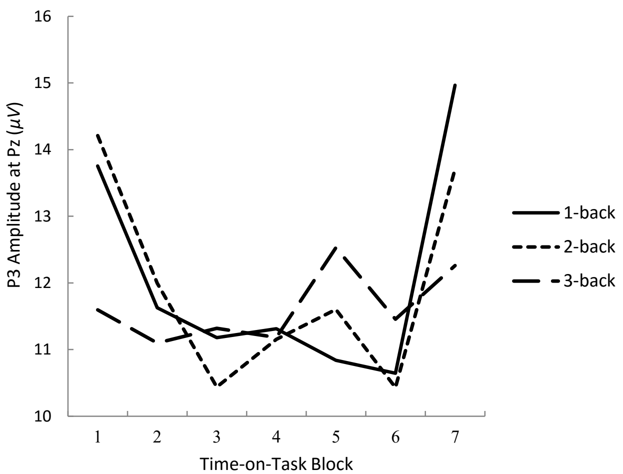


Figure 2.6. P3 amplitude with time-on-task during the 1-back, 2-back, and 3-back task.

increasing time-on-task for the different n-back tasks. Subsequent analysis revealed that the 1-back and 2-back task showed a significant decrease in P3 amplitude from block 1 through 6 (1-back: $F(3.8,72) = 3.3$, $p < .05$, $\eta_p^2 = .15$; 2-back: $F(3.4,64) = 4.4$, $p < .01$, $\eta_p^2 = .19$). The 3-back task did not show a significant change in P3 on this interval ($\eta_p^2 = .03$). This divergent progression of the 3-back task was expressed in a significant interaction effect between task difficulty and time-on-task, $F(26.8,139.3) = 2.9$, $p < .01$, $\eta_p^2 = .13$. Similar to the subjective and behavioral data, the P3 amplitude showed a reverse in pattern after the manipulation and increased significantly from block 6 to 7, $F(1,19) = 26.2$, $p < .001$, $\eta_p^2 = .58$, as was expected in the case of a re-engagement effect. Raw P3 ERPs are displayed in Figure 2.7. By looking at the mean amplitudes, the steepest decrease can be observed during the first hour on the task, whereas the decrease of the pupil diameter seems more gradual over the whole experiment.

Figure 2.7a. Average P3 amplitudes for each time-on-task block during the 1-back task at electrode Pz.

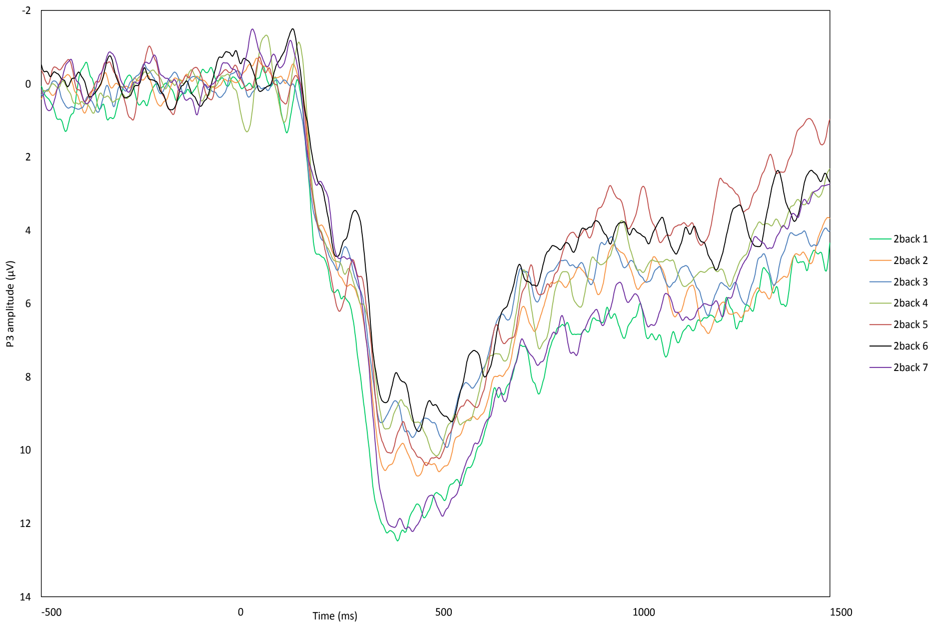


Figure 2.7b. Average P3 amplitudes for each time-on-task block during the 2-back task at electrode Pz.

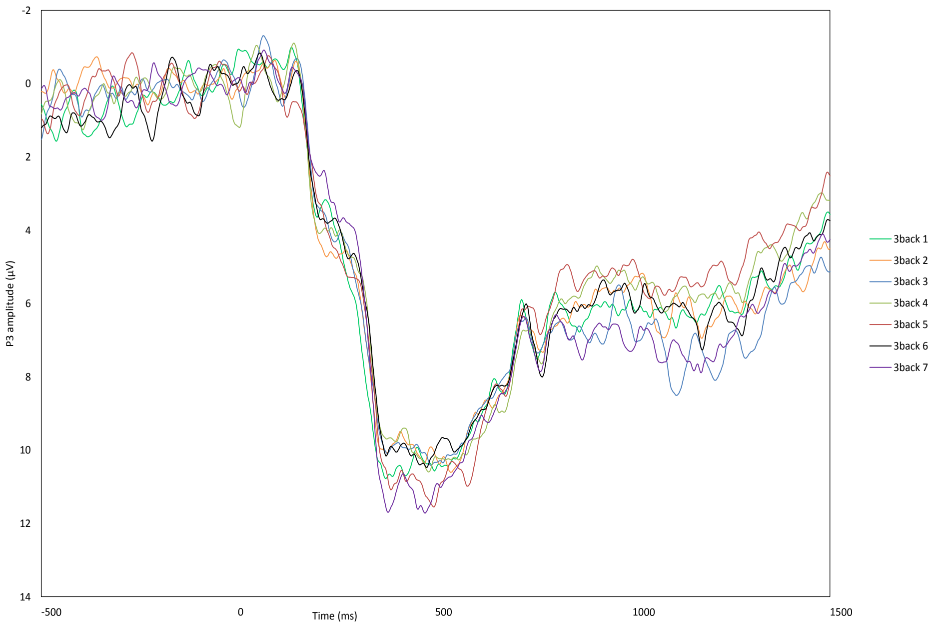


Figure 2.7c. Average P3 amplitudes for each time-on-task block during the 3-back task at electrode Pz.

MULTILEVEL ANALYSIS OF THE SUBJECTIVE, PERFORMANCE, AND PHYSIOLOGICAL MEASURES

In line with our predictions, we found all measures to change congruently with increasing time-on-task. That is, during the first six blocks subjective fatigue increased and performance, baseline diameter, and the P3 amplitude decreased. These findings were obtained using analyses of variance, which is an approach adopted in the majority of studies in the field of behavioral and psychophysiological sciences. However, this method does not provide direct insight into the association between the different measures we used in the present study. Therefore, we also tested the associations between measures using multilevel analysis with Mplus statistical software (Muthén & Muthén, 1998). Using the multilevel approach, we were able to correlate the various measures within individuals while taking the nested structure (i.e., time-on-task blocks are nested within individuals) of the data into account. The use of multilevel analyses is justified when there is sufficient variance explained at two or more levels of analysis. The intraclass correlations (ICC), displayed in Table 2.1, indicated that there indeed was sufficient variance explained on both levels for each observed variable. Table 2.1 also shows the correlations for each pair of observed variables.

We found strong correlations between the p3 amplitude, d-prime, and both subjective measures. This statistically confirms that, in general, a change in one type of measure (e.g., p3 amplitude) was accompanied by a change in another measure (e.g., d-prime), underlining the link between these variables regardless of when this change took place. We also found correlations between baseline pupil diameter and both of the subjective measures. This correlation increased in strength with higher task difficulty. The correlations between the baseline pupil diameter with d-prime and p3 did not reach significant levels.

The multilevel findings are important because they directly support the relatedness of the p3 amplitude, performance on the task, and subjective levels of fatigue and engagement. Our findings also suggest that the baseline (baseline pupil diameter) and stimulus-evoked effects (p3 amplitude) both moved in the hypothesized direction (i.e., declined over time), but their time trajectories differed, leading to non-significant correlation.

Table 2.1a. Multi-level Correlations Between Measures on the 1-back Task

	ICC	1	2	3	4
1. Subjective Fatigue	.29	—	—	—	—
2. Subjective Task Engagement	.42	-.70 ***	—	—	—
3. Performance	.25	-.41 ***	.49 ***	—	—
4. P3 Amplitude	.54	-.28 ***	.31 **	.25 *	—
5. Baseline Pupil Diameter	.89	-.24	.35 ***	.32 *	.11

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

Table 2.1b. Multi-level Correlations Between Measures on the 2-back Task

	ICC	1	2	3	4
1. Subjective Fatigue	.29	—	—	—	—
2. Subjective Task Engagement	.42	-.70 ***	—	—	—
3. Performance	.22	-.41 ***	.48 ***	—	—
4. P3 Amplitude	.41	-.27 **	.35 ***	.36 **	—
5. Baseline Pupil Diameter	.86	-.28 *	.33 **	.05	.12

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

Table 2.1c. Multi-level Correlations Between Measures on the 3-back Task

	ICC	1	2	3	4
1. Subjective Fatigue	.30	—	—	—	—
2. Subjective Task Engagement	.42	-.69 ***	—	—	—
3. Performance	.47	.02	.07	—	—
4. P3 Amplitude	.64	.05	-.09	.33 **	—
5. Baseline Pupil Diameter	.84	-.61 ***	.51 ***	.11	.06

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

DISCUSSION

The results of the present study confirm the link between mental fatigue, task disengagement, and impaired performance on cognitively demanding tasks. An important asset of the study was that we simultaneously measured subjective, behavioral, and physiological responses and directly tested the association between these measures. We found that with increasing time-on-task, subjective mental fatigue increased and the participants' task engagement, as measured by P3 and baseline pupil diameter, decreased. At the behavioral level, this disengagement was accompanied by a decline in cognitive performance. We also found that the detrimental effects of fatigue on the subjective, physiological, and performance measures could be reversed by increasing the task rewards. Increasing the rewards led to task re-engagement in spite of previous signs of fatigue. Importantly, this re-engagement was accompanied by increased pupil diameter and P3 amplitude. The pattern of results in the first six time-on-task blocks suggests that motivation decreased to a point where resources were no longer fully invested. An explanation could be that disengagement occurs to preserve resources for the possibility of encountering more rewarding tasks in the future. By increasing the motivation for engagement (i.e., increasing the task rewards), it becomes worthwhile to reengage in the task to prevent cognitive failures and keep up task performance.

TASK DISENGAGEMENT AND MENTAL FATIGUE

It has been argued that compromised cognitive performance under fatigue might be related to unfavorable tradeoffs between the cost and rewards of task engagement (Boksem & Tops, 2008). Moreover, based on various psychophysiological markers, it has been suggested that the dopamine pathways that are involved in the evaluation of reward information also play an important role in the effects of mental fatigue (e.g., Lorist et al., 2009). Examples of psychophysiological indicators that were used involve the Error-related Negativity (ERN) and the novelty P3a. In the present study, however, we used a different set of psychophysiological indicators (i.e., pupil diameter and P3b), which have received considerably less attention within the mental fatigue context. These measures seem promising, because there are numerous studies that relate the pupil diameter and the P3 ERP on the one hand, and several attentional and motivational processes that modulate task engagement on the other (e.g., Gilzenrat et al., 2010; Murphy et al., 2011). Based on the present study, we suggest that the time-on-task trajectories of these physiological measures are possibly related to the time-on-task trajectories of fatigue and cognitive performance. This is a novel way to measure the role task disengagement plays in the effects of mental fatigue, and creates opportunities for the use of the P3 and pupil diameter as measures in future fatigue research.

The results of this study also show the flexibility of the P3 and pupil diameter during periods of mental fatigue, and their responsiveness to contingencies in the environment. After we increased the rewards, the P3 amplitude and pupil diameter returned to values that compare to those seen at the start of the experiment, even though the participants had already been engaged in the task for two hours and reported high subjective levels of fatigue. Previous studies have shown that, under the right circumstances (i.e., when the rewards are high), participants are able to uphold task performance for a long time, even under high levels of mental fatigue (Boksem et al., 2006; Eccles & Wigfield, 2002; Tops & Boksem, 2010). The effects observed in our reward manipulation confirm this, and show that the P3 and pupil diameter follow the same trajectory as task performance, suggesting re-engagement in the task. This specific finding may have broader impact in other fields of research such as self-control. For example, our results seem to overlap with recent findings suggesting that it is unlikely that self-control resources are fundamentally depleted as stated by classic "ego depletion" theory (Baumeister, Bratslavsky, Muraven, & Tice, 1998). Instead, based on our findings, we favor the explanation by Inzlicht and Schmeichel (2012), in which shifts in motivation and attention play an important role in task disengagement. In the present study, disengagement could be caused by diminished predicted rewards (i.e., the task becomes less interesting, but still requires the same level of attention invested). Most importantly, the present findings contradict the theory of depleted resources, because increased motivation leads to re-engagement and restored performance on a demanding task. We believe that this is an important contribution to the literature.

UNDERLYING PHYSIOLOGICAL SYSTEM

While the present findings provide additional information about the cognitive, motivational, and subjective processes involved in fatigue, they also allow us to further speculate about the involvement of an underlying neuropsychological system. Given that both the P3 and pupil diameter measures were affected by the time-on-task manipulation, there is an interesting possibility that the Locus-Coeruleus Norepinephrine (LC-NE) system plays a role in the effects of fatigue. Although there is still much debate about the system underlying the P3 and pupil diameter, an increasing amount of recent studies have described that these psychophysiological markers reflect activity of the Locus Coeruleus (e.g., Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014; Murphy et al., 2011; Nieuwenhuis, Aston-Jones, & Cohen, 2005). The Locus Coeruleus (LC) is a nucleus in the brainstem responsible for the release of cortical norepinephrine (NE) with ascending connections to large parts of the cortex. Nieuwenhuis and colleagues (2005; 2011) provided an extensive overview of intracranial, pharmacological, and lesion studies with primates suggesting that the P3 may reflect a correlate of stimulus-evoked LC-NE activity. The exact neural pathways that connect the activity of the LC with the pupil and the P3 measures are still under debate and may well be different parallel processes (Nieuwenhuis, De Geus, & Aston-Jones, 2011). To date, there have been relatively few studies that have empirically tested this and have exclusively focused on humans. An early attempt to this comes in the form of a study by Murphy and colleagues (2014), which shows that pupil diameter covaries with blood oxygen level dependent (BOLD) activity in the human LC.

The possible involvement of the LC-NE system in task engagement is supported by strong projections to the LC from the orbitofrontal and anterior cingulate cortices (Aston-Jones et al., 2002; Rajkowski, Lu, Zhu, Cohen, & Aston-Jones, 2000), which are known to be important in the evaluation of the rewards and costs of a task and interact with the dopamine system (Gottfried, O'Doherty, & Dolan, 2003; Holroyd & Yeung, 2012; McClure, York, & Montague, 2004; O'Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001; Yeung, Holroyd, & Cohen, 2005). When the cost/reward tradeoff of a task is favorable, the LC-NE system stimulates exploitation of the rewards by engaging in the task. This enhances cognitive performance and maximizes the benefits of the task. However, when the tradeoff becomes unfavorable, the LC-NE system stimulates disengagement from the task. This is manifested in the tendency to explore the environment for more rewarding tasks and subsequently increases the probability of failures in task-related behavior (e.g., failing to respond to important task-related cues). Aston-Jones and Cohen state that "descending regulation of LC suggests a mechanism for volitional control of waking in the face of fatigue" (Aston-Jones & Cohen, 2005, p. 431). Taking into account that the debate about the extent to which the P3 and pupil diameter are related to the LC-NE system is still ongoing, there is an apparent theoretical and promising psychophysiological explanation of the link between the LC-NE system and task engagement. Therefore, it seems relevant to further explore the possible influence of the LC-NE system on the link between mental fatigue and task engagement.

LIMITATIONS

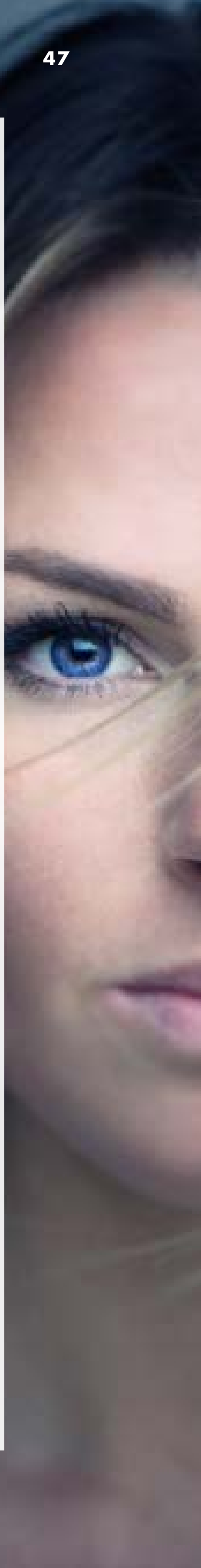
While most of our findings were in line with our hypotheses, a few results remain more open for interpretation. For example, we found that, in contrast to the relatively easier 1-back and 2-back tasks, the performance on the 3-back task did not show a decrease in performance over time, but remained more or less stable. Note, however, that in the 3-back task the level of performance at the start of the task was already much lower. This indicated that the task was more difficult than the other two variants and increases the probability that the observed pattern in performance over time not only reflected a fatigue effect, but also a learning curve. Actually, such a blending of learning and fatigue effects is quite common in the time-on-task studies that use demanding tasks and has been identified in several other studies (Faber et al., 2012; van der Linden, Frese, & Meijman, 2003). In our study, the increase in performance on the 3-back task could also be caused by a learning effect, and may mask the decreased performance due to mental fatigue. This idea is supported by the finding that after the motivational manipulation, performance levels on the 3-back task were even higher than in the beginning of the experiment. In contrast, on the 1-back and 2-back versions of the task, performance went back to levels obtained at the beginning of the experiment. Thus, with the effects of fatigue diminished by the manipulation, possible learning effects became apparent. It should also be noted that the order of the 1-, 2- and 3-back tasks was fixed within each of the seven time-on-task blocks. Because the tasks alternated relatively often, this should not have a major influence on the general time-on-task effects, but careful interpretation of the task difficulty effects is advised. In a study focused mainly on the task difficulty effect, it may be better to counterbalance the tasks within blocks.

CONCLUDING REMARKS

The present study provides evidence for the involvement of the P3 ERP and pupil diameter in the process of task engagement that coincides with mental fatigue. With a multifaceted approach, we revealed a relation between subjective (i.e., subjective fatigue and engagement), behavioral (i.e., task performance), and physiological measures (i.e., P3 and pupil diameter) of fatigue and task engagement. These findings may help to refine knowledge about neurocognitive mechanisms of fatigue. We also speculated that the LC-NE system may play a role as one of the underlying systems that supports task engagement and disengagement. As such, the present study may also contribute to insight into the ways of dealing with the health and safety issues commonly associated with fatigue. For example, they may be helpful in the development of psychopharmacological interventions that target fatigue symptoms in patient groups. The addition of norepinephrine agents to the predominantly used selective serotonin reuptake inhibitors (SSRIs) may have the potential to further ameliorate fatigue effects in patients with Parkinson's disease, depression, and burnout symptoms (Stahl, 2002). In addition to health-related issues, knowing which neurocognitive systems drive the tendency to reduce task engagement after sustained performance may also be relevant for developing a workplace environment that prevents mental fatigue or at least minimizes its negative consequences. After all, human factors, and specifically mental fatigue, remain the most important reason for errors and accidents in the workplace (Baker et al., 1994; McCormick et al., 2012).

CHAPTER 3

The window of my eyes: Task disengagement and mental fatigue covary with pupil dynamics



ABSTRACT

Although mental fatigue is a complex, multi-facetted state that involves changes in motivation, cognition, and mood, one of its main characteristics is reduced task engagement. Despite its relevance for performance and safety, knowledge about the underlying neurocognitive processes in mental fatigue is still limited. Inspired by the idea that central norepinephrine plays an important role in regulating task engagement, we test a set of predictions that have been derived from recent studies that relate pupil dynamics to the levels of norepinephrine in the brain. Participants worked on a 2-back task for two hours while we used pupil measures to further explore the link between task engagement and the effects of mental fatigue. We hypothesized that baseline pupil diameter and stimulus-evoked pupil dilations decrease with increasing fatigue. Also, because previous studies have shown that the effects of fatigue are reversible by increasing the task rewards, we hypothesized that increasing the task rewards after two hours on the task, would restore these pupil measures to pre-fatigue levels. While we did not find a decrease in baseline pupil diameter, we found that increasing mental fatigue coincided with diminished stimulus-evoked pupil dilation. Also, we confirmed that when sufficient rewards were presented to a fatigued individual, the pupil dilations could be restored. This supports the view that motivational factors are important in predicting engagement versus disengagement during fatigue.

Keywords. Mental fatigue; Motivation; Pupil dynamics; Resource depletion; Self-control; Task engagement

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INTRODUCTION

Mental fatigue has a profound impact on human information processing and performance. Fatigue also negatively impacts workplace performance and is considered one of the most important human factors leading to errors and accidents (Baker et al., 1994; McCormick et al., 2012). As such, insight into the building blocks of mental fatigue and its consequences has theoretical as well as practical relevance. Although mental fatigue is a complex, multi-facetted state that involves changes in motivation, cognition, and mood, one of its main characteristics is reduced task engagement (Boksem & Tops, 2008; van der Linden, 2011). When one is engaged in a task, effortful control is used to focus on relevant task features, and to avoid interference of irrelevant information. During such momentary states of task engagement, relevant cognitive systems are used to optimize task performance (Aston-Jones & Cohen, 2005; Beal, Weiss, Barros, & MacDermid, 2005). However in case of fatigue, task engagement is often reduced, since voluntary control of cognition is highly sensitive to fatigue (Lorist et al., 2000, 2005; van der Linden, Frese, & Meijman, 2003). For example, in several experimental studies, fatigued participants displayed difficulties to overrule automatic response tendencies (Csathó, van der Linden, Darnai, & Hopstaken, 2013; van der Linden & Eling, 2006). Recent studies have also shown that the motivational potential of a task has an important influence on whether individuals stay engaged in the task during fatigue (Boksem et al., 2006; Hopstaken, van der Linden, Bakker, & Kompier, 2015a).

Despite its relevance for performance and safety, knowledge about the underlying neurocognitive processes in mental fatigue is still limited. In the present study, we conduct a psychophysiological study on mental fatigue that is inspired by an idea that has recently been proposed in the literature. Namely, that central norepinephrine (NE), released from the locus coeruleus plays an important role in the cognitive effects of fatigue. The Locus Coeruleus (LC) is a nucleus in the brainstem that is responsible for the release of cortical norepinephrine and has ascending connections to large parts of the cortex. It is assumed to play a role in various regulatory processes on cognition (Berridge & Waterhouse, 2003). The exact regulatory processes of the LC-NE system in humans are hard to grasp because they involve interactions with various systems and are also very difficult to measure in-vivo. Therefore, the aim of the present study is not to directly test the involvement of the LC-NE system in fatigue. Instead, we test a set of predictions that have been derived from recent theory about the LC-NE system.

Several recent studies (e.g., Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014) provide empirical evidence that the LC-NE system regulates task engagement, which is correlated to changes in pupil dynamics. In a recent imaging study, Murphy and colleagues (2014) propose that LC-NE activity is partly reflected in baseline pupil diameter and pupil dilations to task-relevant stimuli. Because measuring pupil dynamics is far less invasive, we now have the opportunity to link presumed psychophysiological indicators of cortical norepinephrine and task engagement to mental fatigue in humans. We will use an innovative approach to measure pupil dynamics within an established mental fatigue paradigm, to see whether changes in pupil dynamics are indeed related to changes in task engagement during fatigue. Below we will first elaborate on the LC-NE system and how it may be involved in mental fatigue effects. Subsequently, we will develop the predictions regarding pupil dynamics, subjective states, and task performance during fatigue.

THE LOCUS-COERULEUS NOREPINEPHRINE SYSTEM

Aston-Jones and Cohen (2005) describe the role the LC-NE system plays in task engagement and performance based on results from primarily animal research. Specifically, in their Adaptive Gain Theory, Aston-Jones and Cohen distinguish between baseline and stimulus-evoked release of NE. By combining measures of baseline and stimulus-evoked NE release, they formulated two operating output modes for the LC-NE system that are related to areas below an inverted U curve (see Figure 3.1): the phasic and the tonic mode. The phasic mode is characterized by intermediate baseline levels of NE and strong stimulus-evoked bursts of NE release. This output mode of the LC-NE system supports high task engagement, in which attention is focused to task-relevant stimuli in order to optimize task performance (Minzenberg et al., 2008). In the tonic mode, both baseline and stimulus-evoked levels of NE are high. This implies that the LC-NE system no longer predominantly responds to task-relevant stimuli but also to task-irrelevant stimuli (Cohen et al., 2007). Consequently, one gets distracted more easily and performance on the task at hand deteriorates. The tonic LC-NE output mode is therefore associated with reduced task engagement and increased attention to task-irrelevant stimuli (i.e., distraction). The phasic and tonic modes are assumed to serve two different forms of adaptive behavior. The phasic mode is presumed to support exploitation of the task at hand in order to optimize task rewards. In contrast, the tonic mode supports exploration of the environment in order to find potentially more rewarding tasks (Cohen et al., 2007). The model also leaves space for a third output mode that is characterized by low baseline and low stimulus-evoked levels of NE. In this mode, the diminished levels of NE lead to diminished attention, disengagement from the task at hand, and low vigor in general (Aston-Jones & Cohen, 2005). These behavioral effects are similar to the effects that are typically observed when people are in a state of mental fatigue (Boksem et al., 2006; van der Linden, Frese, & Sonnentag, 2003). Therefore, it would be relevant to test whether presumed indicators of LC-NE activity are related to mental fatigue and its behavioral effects. Pupil dynamics offer such an opportunity as the literature suggests that the baseline diameter and the stimulus-evoked dilation of the pupil covary with activity of the LC-NE system (Murphy et al., 2014).

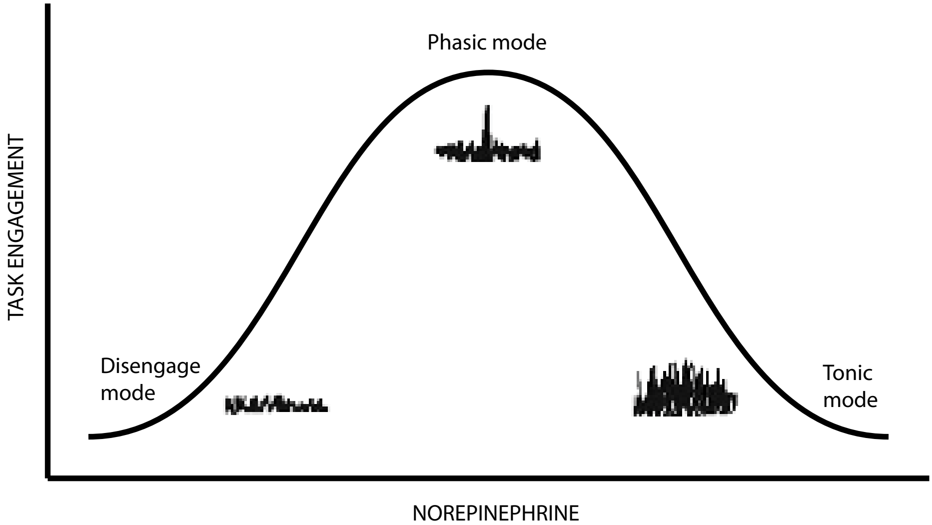

Figure 3.1. The output modes of the LC-NE system.

PUPIL DYNAMICS AND MENTAL FATIGUE

For many years, pupil diameter has been acknowledged as an index of psychophysiological arousal or neural gain and the dilatory response has been linked to the occurrence of task-relevant events. Classic work of Beatty and Kahneman (Beatty, 1982; Kahneman & Beatty, 1966; Kahneman, 1973) has shown that the pupil is sensitive to momentary load and effort during mental tasks. In recent years, this notion has been extended by specifically relating the pupil diameter to task engagement and disengagement. For example, multiple experiments have been conducted that successfully relate pupil diameter to task engagement and observed that task engagement and exploitation behavior were related to an intermediate pupil diameter and large stimulus-evoked dilations (e.g., Gilzenrat et al., 2010; Jepma & Nieuwenhuis, 2011). In contrast, task disengagement in the form of distraction and explorative behavior was related to increased pupil diameter, which consequently also lead to lowered relative stimulus-evoked dilations. These findings correspond with the phasic and tonic output mode of the LC-NE model described by Aston-Jones and Cohen (2005).

With the present study, we contribute to the literature by using pupil dynamics measures to further explore the link between task engagement and the effects of mental fatigue. In this study, small pupil diameter and lowered stimulus-evoked pupil dilations are especially interesting because they are often related to disengagement and impaired performance, which strongly overlaps with the behavioral consequences of fatigue. Therefore, we hypothesize that baseline pupil diameter and stimulus-evoked pupil dilations will decrease with increasing fatigue. We have successfully linked decreases in baseline pupil diameter to increasing mental fatigue in a previous study (Hopstaken et al., 2015a), and the addition of the stimulus-evoked pupil dilation measure allows us to further explore the influence of task disengagement during mental fatigue.

Hypothesis 1: *Increases of mental fatigue coincide with decreases of (a) pupil diameter and decreases of (b) stimulus-evoked pupil dilation.*

Hypothesis 2: *Measures of pupil diameter and stimulus-evoked pupil dilation covary with measures of subjective fatigue, subjective engagement, and task performance*

TASK DISENGAGEMENT: DEPLETED RESOURCE OR MOTIVATIONAL SHIFT?

A frequently debated, yet unsolved issue in the fatigue literature is whether fatigue-related decrements in performance are caused by depleted cognitive resources or reduced motivation for effort (e.g., Boksem et al., 2006; Hopstaken et al., 2015a). Recently, scholars have devoted an increasing amount of attention to the central role of motivational factors in effortful control of task engagement. For example, Kurzban and colleagues (2013) proposed that effort and self-control depend on the mental representation of the costs and benefits of the activity at hand. From a range of possible activities, one will often pursue the one that is most rewarding. Because cognitive systems, like attention, can only be deployed for a limited number of simultaneous tasks they depend on motivation to pursue the next-best task to which these systems may be used. These so-called opportunity costs are experienced as effort and result in reduced task engagement and performance.

Another related model of self-control comes from Inzlicht et al. (2012; 2014), who challenge the classical resource depletion model of Baumeister and colleagues (1998). The resource depletion model states that there is an inner capacity for self-control that relies on limited internal resources. When engaging in effortful control of behavior depletes this capacity, further efforts of self-control are prone to failure. Instead, Inzlicht and colleagues propose that exerting self-control can temporarily shift motivation and attention to undermine or enhance self-control on a subsequent task. This suggests that the exertion of effort and task engagement does not simply lead to a depletion of resources, but entails a more dynamic system driven by cost/reward calculations. When these cost/reward calculations become suboptimal, less effortful or more rewarding alternatives are often preferred over sustained task engagement (Engle-Friedman et al., 2003; Hockey, 2011; Libedinsky et al., 2013). Using this approach, previous studies (e.g., Boksem et al., 2006; Hopstaken et al., 2015a) have shown that the cognitive and behavioral effects of mental fatigue are reversible by increasing the task rewards to restore balance in the cost/reward tradeoff. Hopstaken and colleagues (2015a) showed that two hours of continuous performance led to the expected increase in fatigue and decrease in task performance. However, increasing rewards after these two hours of continuous performance still made participants re-engage in the task. While the latter study exemplifies the role of motivational factors in effortful control and fatigue, the amount of empirical evidence for a motivational approach of fatigue and self-control remains limited. Therefore, we try to extend these findings by examining whether pupil dynamics correlate with the subjective and behavioral re-engagement that we hypothesize when rewards are presented to fatigued individuals.

Hypothesis 3: *When sufficient rewards are presented to a fatigued individual, (a) pupil diameter and (b) stimulus-evoked pupil dilation are (partially) restored to pre-fatigue levels.*

METHOD

PARTICIPANTS

Thirty-three undergraduate students (15 males, 18 females), between the age of 18 and 37 (M = 21.2 years, SD = 3.7) participated in the study and received study credits. All participants were well-rested and in good health as measured by self-reports. The participants reported to have slept seven or more hours and were asked to withhold the intake of caffeine and alcohol during the 24 hours before the experiment. All participants had normal or corrected to normal vision. Written informed consent was obtained prior to the study.

STIMULI AND DATA ACQUISITION

Participants were seated in a dimly lit, and sound attenuated room facing an eye-tracking screen at a distance of approximately 65 cm. During the whole experiment, pupil diameter was measured continuously. The participants performed a visual letter 2-back task in which they had to decide whether the letter presented on the screen was a target or non-target stimulus. In the 2-back task a stimulus is a target when the presented letter is the same as the letter presented two letters before. Accordingly, participants responded by pressing the corresponding button on the keyboard. The stimuli were presented in the center of the screen and consisted of the letters B, C, D, E, G, J, P, T, V, and W in the font Palatino Linotype point size 40. In the Dutch language, these letters are phonologically similar in order to prevent sound-related retrieval strategies. The letters were presented randomly with a target rate of 25%. The n-back task has been used successfully in previous experiments to induce fatigue (Massar et al., 2010). It is a cognitively demanding task that requires the sustained engagement of working memory and attention in order to uphold adequate levels of performance (Watter et al., 2001).

PROCEDURE

Before the experiment, participants filled out questionnaires about their general health, current level of fatigue and task motivation (see description of these measures below). After the calibration of the eye-tracking device, participants were instructed on the n-back task. Participants practiced on each variant of the task until they reached a minimum of 70% accuracy. The experimental task was divided in seven time-on-task blocks. Each block consisted of 183 trials of the 2-back task and lasted for about 18 minutes (depending on random intervals). The n-back stimuli were displayed for 500ms with an inter-stimulus interval randomized at 5 to 5,5 seconds. The length of this interval was long enough to ensure that the pupil diameter returned to baseline levels (Beatty, 1982; Stern et al., 2000).

After each block, the participants had to indicate their current level of fatigue and task engagement. After they completed six blocks of 18 minutes, we introduced our reward manipulation. We told participants that the remaining time of the experiment would depend on their performance relative to their performance on the previous blocks. We explained that the remaining time could range from 5 to 40 minutes, depending on their performance. The better the performance, the shorter the remaining time on the task. Previous studies have shown that after two hours of continuous performance, this provides a strong incentive to optimize performance (Esterman, Reagan, Liu, Turner, & DeGutis, 2014; Hopstaken et al., 2015a). In reality the length of this last block was the same as the first six blocks. The participants had only limited time to answer the questions (i.e., ten seconds) between blocks and to read the instructions before the last block (i.e., fifteen seconds) to prevent them from resting. After the experimental task, the participants were asked to fill in questionnaires about their levels of fatigue and were debriefed.

MEASURES AND DATA PROCESSING

Subjective measures. Subjective fatigue was measured before, during and after the task in order to monitor the temporal progression of fatigue. Before and after the task, participants filled in the Rating Scale Mental Effort (RSME; Zijlstra, 1993) which consists of seven vertical scales assessing different aspects of fatigue (e.g., difficulty to keep attention on the task, difficulty to exert further effort in the task). The scales have numerical (0 to 150) and verbal ("not at all" to "extremely") anchors. Also, to measure time-on-task effects, after each time-on-task block during the experiment the participants were asked "how tired do you feel?". They had to reply by moving a slider from 0 to 100, with increments of five. The slider had no anchors, but the extreme ends were labeled with "not at all" and "very much".

After each time-on-task block, we also measured task engagement by asking "How engaged are you in the task?" The participants had to reply by moving a slider from 0 to 100, with increments of five. The slider had no anchors except for the extremes "not at all" and "very much". Because task engagement was measured multiple times during the experiment, the temporal progression of subjective engagement in the task could also be monitored.

Behavioral measures. The most relevant behavioral measure of performance on the n-back task was accuracy. We instructed the participants that the goal was to answer as much items correctly as possible, and to answer as soon as they knew the correct answer. As described by signal detection theory, the d-prime was calculated as an indication of accuracy (Wickens, 2001). While accuracy was the most important focus for the participant during the task, we wanted to make sure accuracy effects were not clouded by accuracy/speed tradeoffs. Therefore, we also examined reaction times (RTs).

Physiological measures. Pupil diameter was recorded continuously during the entire length of the experimental task with a Tobii Eyetracker 2150 with a sample rate of 50 Hz. The recordings were exported to Brain Vision Analyzer (Brain Products). Artifacts and blinks were detected by the eye-tracker and removed by using a linear interpolation algorithm. Trials that did not contain fixation at the screen were removed from the analysis. To measure baseline pupil diameter, we averaged the pupil diameter in the 500 milliseconds before stimulus onset. During this period, the participants saw a fixation cross with the same level luminosity as the letters, so there was no interference from eye reflexes to the environmental lightning. Baseline pupil diameter for each condition and time-on-task interval was then exported to SPSS for further analysis.

The stimulus-evoked pupil data was analyzed in Brain Vision Analyzer (Brain Products) the same way as we did with the baseline pupil diameter. After Baseline correction for the 200 ms before the stimulus onset we measured the positive peak within the first 1500 milliseconds after the onset of the stimulus. Trials in which performance errors occurred were excluded. The mean pupil dilation peak activity for each time-on-task interval was then exported to SPSS for further analysis.

STATISTICAL ANALYSIS

The subjective, behavioral and psychophysiological data were exported to SPSS and statistically analyzed using repeated measures analysis of variance (ANOVA). First, main effects of time-on-task were tested. Then, significant effects were further qualified by examining changes from block 1 to 6, in which the fatigue manipulation occurred and changes from block 6 to 7, in which the reward/motivation manipulation occurred.

Beside the repeated measures ANOVA, we also analyzed the data using a multilevel approach with Mplus statistical software (Muthen & Muthen, 1998-2014). Repeated measures data can be treated as multilevel data, with the repeated measures nested within individuals. We calculated the correlation between the various outcome measures with the nested structure of the data taken into account (i.e., blocks nested within persons). We used a two-level model with time-on-task block at the first level (Level 1; $N = 231$), and individuals at the second level (Level 2; $N = 33$). In this operationalization a high correlation between dependent variables, means that a change in one variable corresponds with a similar change in another variable for each time-on-task block within individuals (cf. Snijders & Bosker, 1999).

3

RESULTS

SUBJECTIVE MEASURES

To test whether our fatigue manipulation was successful, we analyzed the pre and post task RSME scores. Compared to the beginning of the experiment, we found significantly higher fatigue scores after the experiment, $t(32) = -12.69$, $p < .001$, indicating that the manipulation was successful. The subjective fatigue ratings after each time-on-task block also significantly increased from block 1 through 6, $F(2.2,68.8) = 27.36$, $p < .001$, $\eta_p^2 = .46$, while the subjective rating of task engagement decreased during this period, $F(2.5,76.2) = 37.03$, $p < .001$, $\eta_p^2 = .54$. After the reward manipulation in block 7 we found these measures to change back towards their initial values (fatigue: $F(1,32) = 7.06$, $p < .05$, $\eta_p^2 = .18$; engagement: $F(1,31) = 24.27$, $p < .001$, $\eta_p^2 = .44$). The progression of the subjective measures after each block are displayed in Figure 3.2.

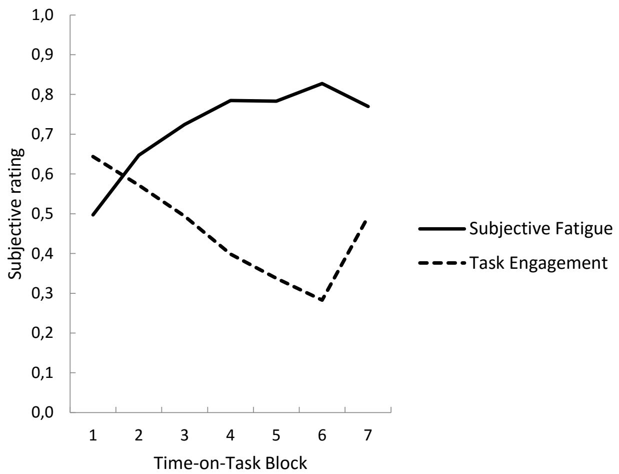

Figure 3.2. Subjective fatigue and task engagement ratings with time-on-task.

BEHAVIORAL MEASURES

During the first two blocks of the experiment, performance increased as d-prime increased and RTs decreased significantly (d-prime: $F(1,32) = 6.45$, $p < .05$, $\eta_p^2 = .17$; RT: $F(1,32) = 13.37$, $p = .001$, $\eta_p^2 = .30$). The observation that task performance increases during the start of the experiment is commonly found. This can be seen as a traditional learning effect. As can be seen in Figure 3.3, from block two until six, performance decreases. This is confirmed by a significant decrease in d-prime, $F(2.3,75.0) = 10.30$, $p < .001$, $\eta_p^2 = .24$. RTs are also decreased during this interval, $F(1.9,62.8) = 7.00$, $p < .01$, $\eta_p^2 = .18$, suggesting a partial trade-off between speed and accuracy with increasing time on task. After our reward manipulation in block 7, performance significantly increased again as d-prime increased, $F(1,32) = 35.58$, $p < .001$, $\eta_p^2 = .53$, while the RTs remained stable, $F(1,32) = 1.19$, $p = .28$ (*ns*), $\eta_p^2 = .04$. These results are in line with the results on the subjective measures and indicate a relation between mental fatigue and task engagement on the one hand and task performance on the other hand. The mean d-prime, hit rate and false alarm rate during each block of the experiment are reported in Table 3.1.

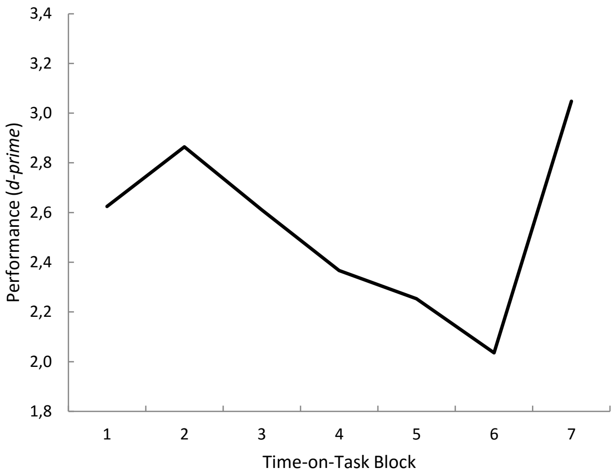

Figure 3.3. Performance on the 2-back task with time-on-task.

Table 3.1. Means of the Performance Indicators for Each of the Time-on-Task Blocks of the Experiment.

Block	Hit Rate	False Alarm Rate	d-prime
1	.83	.08	2.6
2	.86	.06	2.9
3	.79	.06	2.6
4	.73	.07	2.4
5	.71	.08	2.3
6	.68	.09	2.0
7	.88	.04	3.0

PHYSIOLOGICAL MEASURES

In contrast to our hypothesis, the baseline pupil diameter showed no significant changes during the first six blocks of the experiment, $F(3.2,100.9) = 1.86$, $p = .14$ (*ns*), $\eta_p^2 = .06$. However, as can be seen in Figure 3.4, after our reward manipulation the pupil diameter showed a significant increase which is in line with our second hypothesis, $F(1,32) = 4.53$, $p < .05$, $\eta_p^2 = .12$. In Figure 3.5, it can be observed that during the first six blocks of the experiments, the stimulus-evoked pupil dilation significantly decreased in line with Hypothesis 1, $F(2.7,86.1) = 9.12$, $p < .001$, $\eta_p^2 = .22$, and increased again after the reward manipulation in block 7 in line with Hypothesis 2, $F(1,32) = 14.06$, $p = .001$, $\eta_p^2 = .31$. The progression of the mean pupil dilation during each of the time-on-task blocks can be observed in Figure 3.6.

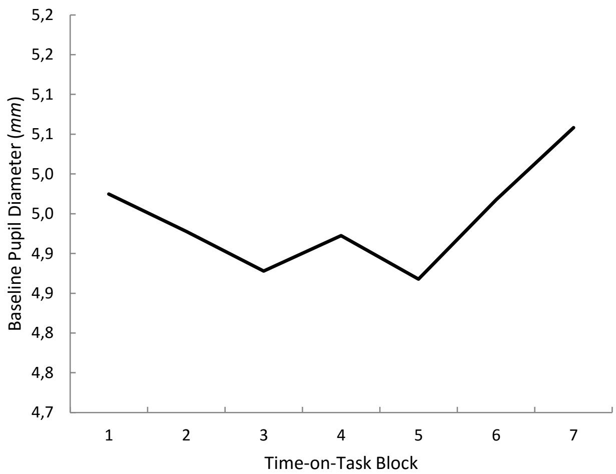

Figure 3.4. Baseline pupil diameter with time-on-task.

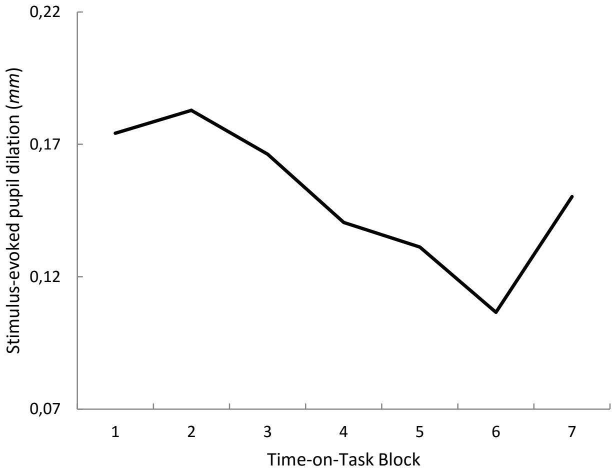

Figure 3.5. Stimulus-evoked pupil dilation with time-on-task.

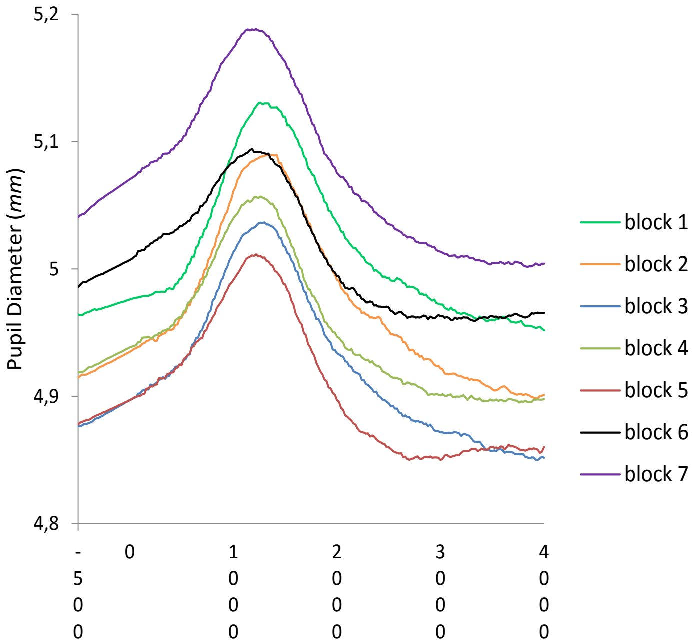

Figure 3.6. Average pupil diameter during each time-on-task block of the experiment.

3

Table 3.2. Multi-level Correlations Between Measures on the 2-back Task

	ICC	1	2	3	4
1. Subjective Fatigue	.53	–	–	–	–
2. Subjective Task Engagement	.49	-.56 ***	–	–	–
3. Performance	.54	-.24 **	.49 ***	–	–
4. Stimulus-evoked Pupil Dilation	.76	-.33 **	.42 ***	.32 ***	–
5. Baseline Pupil Diameter	.96	.08	-.04	.04	-.14 *

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

3

MULTILEVEL ANALYSIS

In line with our predictions, we found that the majority of the measures changed congruently with increasing time-on-task. The results presented above were obtained using analysis of variance, which is an approach adopted in the majority of studies in the field of behavioral and psychophysiological sciences. However, this method does not provide direct insight into the association between the different measures in the present study. Therefore, we also tested the associations between measures using multilevel analysis using Mplus (Muthén & Muthén, 1998-2014). Such an analysis, takes the nested structure of the data into account (i.e., blocks nested within persons). Using this multilevel approach, we were able to correlate the time-on-task trajectories of the different measures within individuals. In this way, we could directly compare measures within individuals while taking the nested structure (i.e., time-on-task blocks are nested within individuals) of the data into account. Multilevel analyses are preferred when there is sufficient variance explained at two or more levels of analysis. The intraclass correlation (ICC), displayed in Table 3.2, indicated that there indeed was sufficient variance explained on both levels for each observed variable. Table 3.2 also shows the correlations for the each pair of observed variables.

These multilevel findings are important because they directly support the relatedness of the measures. We found strong multilevel correlations between the stimulus-evoked pupil dilation, d-prime, and both subjective measures (see Table 3.2). This statistically confirms that within individuals, a change in one type of measure over time (e.g., stimulus-evoked pupil dilation) was accompanied with a change in another measure (e.g., d-prime), underlining the link between these variables. Another interesting observation is that the correlations of subjective engagement with performance and pupil dilation are even higher than the correlations between subjective fatigue and these measures. The correlations of the baseline pupil diameter with the other measures were found to be small and non-significant.

DISCUSSION

The central aim of this study was to investigate whether pupil dynamics can be linked to the emergence and effects of mental fatigue. This would provide a noninvasive and objective way to the relate task engagement to the effects of mental fatigue. We hypothesized that pupil dynamics may reflect task engagement, based on the literature about the involvement of the LC-NE system in task engagement. While we did not find a decrease in baseline pupil diameter, the results are in line with our hypothesis that increasing mental fatigue coincides with diminished stimulus-evoked pupil dilation. Also, we confirmed that when sufficient rewards are presented to a fatigued individual, the pupil dilation could be restored. This supports the view that motivational factors are important in predicting engagement versus disengagement during fatigue. In what follows, we will discuss the main contributions of the study.

PUPIL DYNAMICS AND FATIGUE

A major contribution of the present study is that it expands previous studies that link mental fatigue to task disengagement (e.g., Boksem & Tops, 2008; Hopstaken et al., 2015a). By measuring the stimulus-evoked pupil dilation we have an objective indicator of task engagement that reveals strong time-on-task effects. Furthermore, our multilevel analysis of the data shows that these time-on-task effects of pupil dilation correlate strongly with subjective measures of fatigue and engagement, and cognitive performance. Because previous studies have shown that the dilation of the pupil is related to cortical levels of norepinephrine (Gilzenrat et al., 2010; Murphy et al., 2014, 2011), this suggests that the LC-NE system may also play a role in the emergence and effects of fatigue.

In contrast with a previous study (Hopstaken et al., 2015a), we did not find a hypothesized decrease in baseline pupil diameter during the first blocks of the experiment. We predicted, based on the LC-NE theory of Aston-Jones and Cohen (2005), that the shift from task engagement to task disengagement would be accompanied by a shift from large stimulus-evoked pupil dilations and an intermediate baseline pupil diameter to small stimulus-evoked pupil dilations and baseline diameter. While this indicates that there is a larger range for the effect at the stimulus-evoked level (i.e., from high to low suggests a larger possibility for change than from intermediate to low), we still expected to see a change in the baseline pupil diameter as well. In the present study this was not the case. Because there are also no increases in both of these measures we have no reason to suspect that the observed disengagement was cause by distraction and exploration behavior, as would be predicted by the tonic mode of the LC-NE model. A more plausible explanation for the absence of the pupil diameter effect could be that, because baseline pupil diameter is often related to the amount of experienced physiological arousal (e.g., Beatty, 1982), participants were only mildly aroused at the start of the study. Compared to the previous study (Hopstaken et al., 2015a), where we did find the decreased pupil diameter effect with increasing time-on-task, the present study had a much less arousing lab environment (i.e., without EEG setup). This could have resulted in a 'floor effect' for initial levels of arousal, and would imply that there was only a limited range for decrease. The clear increase in pupil diameter after we presented participants with rewards, which can be seen as arousing, supports this explanation.

A couple of strengths of the study should be highlighted. For example, when it comes to predictions based on the LC-NE system, most studies focus on the phasic and tonic mode of the system. A third possible output mode that leads to disengagement receives far less attention[2]. A strong point of our present study, is that it explored a mode of the system that is characterized by low NE levels at the stimulus-evoked level. Based on this mode, we tested the prediction that the emergence of mental fatigue covaries with lowered task-evoked pupil dilations. By taking the nested structure of the data into account (i.e., the inclusion of a multilevel analysis), we get insight in the relatedness of several fatigue related measures. In our study, we showed that task-evoked pupil dilations do not only coincide with decreased performance, but also with a change in subjective experience of fatigue and engagement in the task. We think that this type of analysis, that is more common within other disciplines (e.g., organizational psychology), is particularly useful in the field of psychophysiological research. The present paper could serve as a useful example of this.

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2 Some studies (e.g., Murphy et al., 2011; Smallwood et al., 2011) have reported time-on-task effects of presumed indicators of NE activity, but most of these studies where not specifically suited to draw conclusions with regard to the effect of mental fatigue (i.e., because of the experimental design or relatively short time-on-task).

Another strength of our study is that it used pupil dilation as a measure of task engagement on a visual task. Because the pupil is very sensitive to ambient and stimulus-emitted light, it is hard to create conditions that control for all sorts of disruption. Because of this, many studies that focus on pupil dynamics (especially stimulus-evoked dilations) use auditory stimulation (e.g., Gilzenrat et al., 2010; Murphy et al., 2011). While this may not be a major concern in some experimental paradigms, most experiments on mental fatigue and self-control rely on visual stimuli. Also, using a visual task increases the ecological validity because in practice, fatigue usually derives from tasks that have visual components (e.g., fatigue during driving or surgery). With the present study, we show that a robust effect can be observed using a visual paradigm.

THE COST/REWARD TRADEOFF FOR ENGAGEMENT

The role that subjective experience plays in time-on-task studies when it comes to task disengagement and task performance has recently received much attention. In many recent articles on self-control and mental effort there is increasing attention for the role of motivational aspects of the task (Inzlicht et al., 2014; Inzlicht & Schmeichel, 2012), but empirical evidence for this approach is still scarce. The present experiment contributes to this literature, because it shows that the manipulation of the rewards of a task has a strong effect on task engagement and performance when individuals are fatigued. This contradicts Baumeister et al.'s (1998) popular theory that assumes depletion of a limited resource for self-control. We found support for our hypothesis that increasing the rewards of a task, after two hours of continuous performance high levels of fatigue, resulted in restored task performance and stimulus-evoked pupil dilation (i.e., levels that are similar to or higher than at the start of the experiment). This strongly suggests that, even after two hours of continuous performance, resources may not be depleted. We favor the explanation of these results in terms of cost/reward tradeoffs (Kurzban et al., 2013). With increasing time-on-task, the rewards of the experimental task stay the same or may even decrease (i.e., because the task becomes less challenging or interesting), while the opportunity cost of not engaging in other possible activities increases. This results in an imbalance between the costs and rewards of the task and eventually leads to disengagement. Because there are no clear alternative tasks to engage in that are rewarding, the most rewarding alternative is to conserve energy for the moment that a more rewarding activity presents itself. When sufficient rewards are presented in the last part of the experiment, the imbalance between costs and rewards is restored and participants reengage in the task.

The opportunity cost account (Kurzban et al., 2013) does not only present an interesting explanation for the results of the present study, it also reveals a limitation. While design of the experiment is very well suited to observe a possible disengagement effect from the task with increasing fatigue, the question remains what would happen if alternative tasks where presented to the task environment. While not the main focus of this study, we think there is an interesting opportunity to look into the possibility that while the task related stimuli become less rewarding and lead to disengagement, other stimuli may still draw attention and engagement if they are perceived to be rewarding.

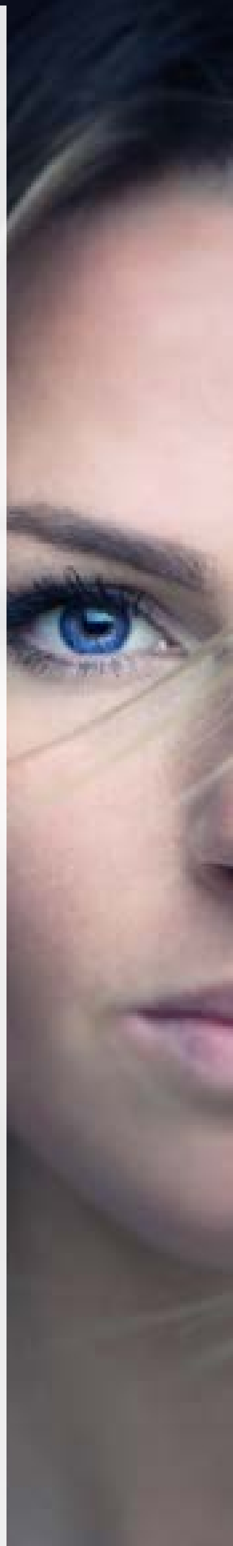
Another interesting, however not hypothesized, finding to note is that the correlation between subjective engagement and indicators of task engagement and performance is stronger than the correlation between subjective fatigue and indicators of task engagement and performance. This is also in line with the motivational approach that task engagement is more dependent on subjective feelings of effort and engagement, than subjective feelings of fatigue and low vigor. These results overlap with findings in the field of organizational psychology that employee work engagement is a stronger predictor of work performance than chronic fatigue/burnout (Bakker & Bal, 2010; Crawford, Lepine, & Rich, 2010; Taris, 2006).

CONCLUSION

Recent studies have shown that many cognitive problems that derive from mental fatigue coincide with task disengagement. Based on predictions the LC-NE system makes about disengagement, we measured pupil dynamics, which were linked to levels of cortical NE, during a task that invoked fatigue. In our study, increases in fatigue coincided with decreased stimulus-evoked pupil dilation, task performance, and subjective engagement. This confirms the strong link between the effects of fatigue and task engagement. Other recent studies underpin the importance of motivational aspects in task engagement and effortful control of attention (Hopstaken et al., 2015a; Inzlicht et al., 2014). In the present study, we confirm that increasing rewards can motivate participants to reengage in activities for which they were heretofore too fatigued. This contradicts traditional limited resource approaches to explain effortful self-control, and confirms the explanation that cost/reward tradeoffs motivate whether or not we engage in certain activities.

CHAPTER 4

Shifts in attention during mental fatigue: Evidence from subjective, behavioral, physiological, and eye-tracking data



ABSTRACT

There is an increasing amount of evidence that during mental fatigue, shifts in motivation drive performance rather than reductions in finite mental energy. So far, studies that investigated such an approach have mainly focused on cognitive indicators of task engagement that were measured during controlled tasks, offering limited to no alternative stimuli. Therefore it remained unclear whether during fatigue, attention is diverted to stimuli that are unrelated to the task, or whether fatigued individuals still focused on the task but were unable to use their cognitive resources efficiently. With a combination of subjective, EEG, pupil, eye-tracking, and performance measures the present study investigated the influence of mental fatigue on a cognitive task which also contained alternative task-unrelated stimuli. With increasing time-on-task, task engagement and performance decreased, but there was no significant decrease in gaze towards the task-related stimuli. After increasing the task rewards, irrelevant rewarding stimuli were largely ignored, and task engagement and performance were restored, even though participants still reported to be highly fatigued. Overall, these findings support an explanation of less efficient processing of the task that is influenced by motivational cost/reward tradeoffs, rather than a depletion of a finite mental energy resource.

Keywords: Attention; Mental Fatigue; Motivation; Self-control; Task Engagement

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INTRODUCTION

For many years, scholars have tried to explain the phenomenon of mental fatigue. During the early years, fatigue has mainly been interpreted as the result of a loss in energetic resources after excessive work and been used as a performance indicator (Griffith et al., 1950; Ryan, 1947). With this interpretation of fatigue in mind, the concept of 'mental energy' served as a requirement for motivation and action. According to this classical view, when energy is lacking people are less able to initiate or sustain behavior effectively. As a result, performance decreases. More recently, this approach has been challenged by findings of recovered effective behavior when people are externally motivated, even though they were previously too fatigued to continue (Boksem et al., 2006; Hockey, 2013; Hopstaken et al., 2015a). This has led to a new interpretation of mental fatigue as a stop emotion, signaling us to stop working long before our actual ability to work runs out (van der Linden, 2011). In line with this idea, Hockey (2013) suggested that fatigue is an adaptive state signaling a conflict in deciding between what is being done and what else might be done. This underpins the influence of self-control and motivation in the experience of mental fatigue.

Inzlicht, Schmeichel and Macrae (2014) have emphasized that problems with maintaining task engagement (e.g., in a fatigued state) are often the product of evolutionary pressures that motivate organisms to balance their desires for exploitation of the task at hand versus exploration of the environment. This desire for exploitation versus exploration derives from a trade-off between the expected costs and rewards of a task (Aston-Jones & Cohen, 2005; Cohen et al., 2007). When the cost/reward trade-off is favorable, exploitation of the task rewards by engaging into the task is stimulated. In that case, even though asserting cognitive control is aversive, the task provides enough intrinsic (e.g., pleasure, excitement) and/or extrinsic (e.g., monetary benefits) rewards to make it worth the effort. However, when the trade-off becomes unfavorable, the person will tend to disengage from the task. Instead of exploiting the task rewards, it becomes more likely that one starts to explore the environment to find potentially more rewarding tasks. This increases the probability of failures in self-control and task-related behavior that are often observed during mental fatigue (van der Linden, Frese, & Meijman, 2003). Both the fatigue and the self-control literature explain the link between motivational cost/reward trade-offs (Boksem & Tops, 2008) and the effects of diminished performance via the process of attentional disengagement (Hopstaken et al., 2015a; Inzlicht et al., 2014).

While there is substantial empirical evidence for the involvement of motivational cost/reward trade-offs in mental fatigue (Boksem et al., 2006; Boksem & Tops, 2008; Hopstaken et al., 2015a), it is less clear what attentional disengagement during mental fatigue actually entails. For example, an important question that remains open is whether fatigued individuals who have been engaging in a task for a considerable amount of time direct their attention to other, and potentially more rewarding, tasks. In other words, are they exploring the environment for other, more interesting, stimuli? The alternative is that they still try to stay focused on the task, but do so in a less effective way. While the answers to this question has important implications for designing fatigue prevention interventions, so far, fatigue studies have mainly been focused on cognitive indicators of engagement that are measured during controlled tasks, which offer only limited or no alternative stimuli to direct attention to. In these studies, it is often observed that when participants become fatigued, (neuro) physiological indicators suggest task disengagement, which is associated with compromised task performance (Boksem et al., 2005; Hopstaken et al., 2015a; Inzlicht & Gutsell, 2007). Nevertheless, it remains unclear whether attention is diverted to stimuli that are not related to the task, or whether fatigued individuals still focused on the task but were unable to use their cognitive resources efficiently.

Schmeichel and colleagues (2010) pointed out that fatigued participants working under conditions that required high levels of attentional control were more effective in correctly identifying reward-relevant visual symbols (i.e., dollar signs), than participants who worked on tasks that required lower levels of control. For reward-irrelevant symbols (i.e., percent signs), however, this difference was absent. The authors explained this difference by suggesting that fatigued individuals are more sensitive to detect alternative rewarding stimuli that signal a potentially desired distraction from the task that they were already working on for an extended time. In other words, fatigued individuals would have a tendency to explore the environment for more rewarding activities. In addition to these observations, the opportunity cost model of Kurzban and colleagues (2013) does not only suggests exploration of the environment when the cost/reward trade-off becomes unfavorable, but also describes that the presence of competing tasks can be considered as costs themselves. When there are more, and especially more rewarding, competing tasks, more control of attention is needed to stay focused on the task at hand. This underpins the relevance of the question whether fatigued individuals disengage from a task to explore other options, or still focus on the task stimuli but do so less effectively.

The absence of competing and potentially rewarding stimuli in most previous studies may have restricted participants in the possibility to explore, by only allowing focus on either the task stimuli or other areas of the lab room that did not contain any rewarding stimuli. Such a design would be limited, given the results of Schmeichel et al. (2010) that suggest that fatigue could possibly lead to increased attention towards unrelated, but rewarding alternative stimuli. Therefore, the goal of the present study is to create a more comprehensive understanding of attentional disengagement during mental fatigue, by introducing alternative rewarding stimuli to the relatively isolated task environment that traditional mental fatigue experiments tend to have. Similarly to previous studies, we use physiological measures to access cognitive disengagement, but we also include eye tracking techniques to investigate in detail how participants divide their gaze over the different stimuli with increasing levels of mental fatigue. Additionally, we manipulate task motivation in order to test how increased external rewards for engaging in the task affect the direction of participants' gaze. Through the utilization of eye-tracking measures, our aim is to provide a more precise and comprehensive understanding of attentional disengagement during mental fatigue.

MENTAL FATIGUE AND SHIFTS IN ATTENTION

Continuously working on a demanding cognitive task for an hour or more has repeatedly been found to induce mental fatigue and to result in decreased task performance (Boksem et al., 2006; Hopstaken et al., 2015a; Lorist, 2008). In the present study, we will induce mental fatigue using such a time-on-task paradigm and introduce alternative stimuli to the experimental environment. Specifically, we present images of faces on the far sides of the screen during parts of the experiment. It has been widely acknowledged that faces are inherently rewarding to look at even when they are not task-relevant, because they have an evolutionary adaptive role and potentially contain important social information (M. H. Johnson, 2005; Schmidt & Cohn, 2001). Because the face stimuli constitute alternative rewarding stimuli to the environment, eye-tracking can be used to observe the focus of gaze with increasing time-on-task and mental fatigue.

Alongside eye-tracking, we also monitor subjective ratings of fatigue and engagement, physiological indicators of engagement (i.e., P3 amplitude and baseline pupil diameter), and task performance. The combination of these measures allows us to observe the amount of task disengagement with increasing time-on-task, as has been done in previous studies (e.g., Hopstaken et al., 2015a; Murphy, Robertson, Balsters, & O'connell, 2011), but also to observe the direction of the participants gaze, which presents information about possible shifts in attention. This will result in a more precise insight in disengagement of attention during mental fatigue and may answer the question whether performance decrements during fatigue are caused by a less efficient processing of the task, or distraction from the task and exploration of alternative stimuli. An increase in gaze position towards the alternative stimuli would point towards the exploration explanation. In this case general engagement, or the ability to process information, is not necessarily compromised, but rather redirected towards other stimuli. When gaze is still prominently directed towards the task-related stimuli, this would imply that while participants are still focusing their eyes on the task but the processing of the stimuli they look at may be less efficient. The first research aim of this study is to investigate whether engagement is redirected during mental fatigue, or participants are still attending the task-related stimuli but process them less efficiently.

The second aim of the present study is to investigate the flexibility of the mechanisms that direct disengagement during mental fatigue. We examine whether increasing motivation for task engagement can reverse the effects of mental fatigue. To test this, we have included a manipulation in which the rewards for engagement are increased after the participants have already worked on the task for 90 minutes. Following the exploration explanation, we would expect that increasing the rewards of the task would redirect engagement towards it. Following the less efficient processing explanation, there are still two distinct possible explanations. First, fatigue could be associated with depleted energy resources. In this case, the increase of motivation is expected to lead to no, or only very minor, improvements of performance. Specifically, if resources are depleted it would take recuperation (e.g., resting or doing something different) in order to replenish these resources. The second explanation, is that fatigue effects are related to more flexible motivational mechanisms. In this case, we expect that performance may show strong improvements or even go back to initial levels after the motivational manipulation. Only this latter explanation predicts that increasing the benefits of task engagement will result in reengagement in the task. Therefore, we also expect that there could be an increase in the subjective and physiological indicators of task engagement, and possibly the amount of time gaze is directed towards the task, in order to maximize the newly established benefits of the task that are introduced by the manipulation.

METHOD

PARTICIPANTS

Forty-seven undergraduate students (15 males, 32 females), between the age of 18 and 25 (*M* = 20.5 years, *SD* = 1.8) participated for study credits. All participants were well-rested and in good health as measured by self-report. The participants reported to have slept seven or more hours and were asked to withhold the intake of caffeine and alcohol during the 24 hours before the experiment. All participants had normal or corrected to normal vision. Written informed consent was obtained prior to the study.

STIMULI AND DATA ACQUISITION

Participants were seated in a comfortable chair in a dimly lit, and sound attenuated room facing an eye-tracking screen at a distance of approximately 65 cm. During the experiment, pupil diameter, gaze position, and EEG were measured continuously. Participants performed a visual letter 2-back task. They were asked to decide whether the letter presented on the screen was a target or non-target stimulus. In the 2-back task a stimulus is a target when the presented letter is the same as the letter presented two letters before. Accordingly, they responded on the corresponding button at the keyboard in front of them. The stimuli were presented in the center of the screen and consisted of the letters B, C, D, E, G, J, P, T, V, and W in the font Palatino Linotype point size 60. In the Dutch language these letters are phonologically similar in order to prevent sound-related retrieval strategies. The letters were presented randomly with a target rate of 25%. The 2-back task has been used successfully in previous experiments to induce mental fatigue (Hopstaken et al., 2015a; Massar et al., 2010). It is a cognitively demanding task that requires the sustained engagement of working memory and attention in order to uphold adequate levels of performance (Watter et al., 2001).

Pictures of human faces were presented on both sides of the screen alongside the letters of the 2-back task as alternative task-unrelated distractor stimuli in some parts of the experiment (see procedure). These face stimuli where greyscale photos with a size of 256x384 pixels, selected from the Face Recognition Technology (FERET) program database. FERET is a large database of facial images developed by the National Institute of Standards and Technology (NIST) for testing face recognition algorithms and other research purposes. The database consists of 9,457 photos containing 1,199 unique individuals. 732 unique individuals with neutral expression were selected for the present study. Half of the images selected were male and different ethnicities were selected and randomly presented during the task in order to minimize potential gender and cultural biases.

PROCEDURE

Before the experiment, participants filled out questionnaires about their general health, current level of fatigue and task motivation (see below). After the calibration of the eye-tracking device, participants were instructed on the 2-back task. Participants practiced until they reached a minimum of 70% accuracy. The experimental task was divided in seven time-on-task blocks. Each block consisted of 139 trials 2-back task and lasted for about 15 minutes (depending on random intervals). The 2-back stimuli were displayed for 500ms with an inter-stimulus interval randomized at 5 to 5,5 seconds. The length of this interval was long enough to ensure that the pupil diameter returned to baseline levels (Beatty, 1982; Stern et al., 2000). We displayed the face images at the far left and right side of the screen during the 500ms the 2-back stimuli were presented. We alternated blocks that contained the face stimuli with blocks that contained only task-related stimuli. To counterbalance conditions, participants were randomly assigned to version 1 or version 2. In version 1 faces were presented in block 2, 4, 6 and in version 2 faces were presented in block 1, 3, 5. After each block, participants had to indicate their current level of fatigue and task engagement. The participants only had limited time to respond, to make sure they would not rest.

4

Reward manipulation. After participants completed six blocks, a reward manipulation was introduced. We told them that the remaining time of the experiment would depend on their performance relative to their performance on the previous blocks. We explained that if they would perform better than the previous blocks, the remaining time could be as short as about five minutes. However, we also told them that if they performed similar or worse the remaining time could run up to about forty minutes (i.e., it could range from somewhere between 5 and 40 minutes depending on their performance). Previous studies point out that after about 90 minutes of continuous performance, such a manipulation provides a strong incentive to optimize performance (Esterman et al., 2014; Hopstaken et al., 2015a). In reality the length of this last block was the same as the first six blocks (i.e., 15 minutes) for each participant. During this last block, face stimuli were shown in each of the two versions of the experiment. Doing so, we were able to investigate the effect of the manipulation on task-related attention, relative to the attentional pull that the face stimuli may have.

After the experimental task, the participants were asked to fill in questionnaires about their level of fatigue and were debriefed.

MEASURES AND DATA PROCESSING

Subjective measures. Subjective fatigue was measured before, during and after the task in order to monitor its temporal progression. Before and after the task participants filled in the Rating Scale Mental Effort (RSME; Zijlstra, 1993) which consists of seven vertical scales assessing different aspects of mental fatigue (e.g., difficulty to keep attention on the task, difficulty to exert further effort in the task). The scales have numerical (0 to 150) and verbal ("not at all" to "extremely") anchors.

To measure subjective experience of fatigue during the experiment, participants were asked "how tired do you feel?" after each time-on-task block. They had to reply by moving a slider from 0 to 100, with increments of five. The slider had no anchors, but the extreme ends were labeled with "very much" and "not at all". Immediately after this question, we also asked "How engaged were you in the task?" after each time-on-task block, to investigate subjective engagement during the experiment. The participants again had to reply by moving a slider from 0 to 100, with increments of five. The slider had no anchors except for the extremes "very much" and "not at all".

Behavioral measures. The most relevant behavioral measure of performance on the n-back task was accuracy. As described by signal detection theory, the d-prime was calculated as an indication of accuracy (substracting the standardized false alarm rate from the standardized hit rate; Wickens, 2001). While accuracy was the most important focus for the participant during the task, we wanted to make sure accuracy effects were not clouded by accuracy/speed trade-offs. Therefore, we also examined reaction times (RTs).

Area of interest, pupil and EEG measures. Pupil diameter and gaze position were recorded continuously during the entire length of the experimental task with a SMI RED250 eyetracker with a sample rate of 60 Hz. For the recording of the EEG we used a BioSemi Active-Two with Ag/AgCl active electrodes at 32+2 scalp sites (International 10-20 system). There were six additional electrodes attached. Two electrodes were placed on the left and right mastoids as reference electrodes. To allow for correction of ocular movement artifacts we placed two electrodes next to the outer side of the eyes for horizontal electrooculogram (HEOG) and two above and below the left eye for vertical electrooculogram (VEOG). Online signals were recorded with a sample rate of 512 Hz and 24-bit A/D conversion. Because of technical problems, movement artefacts, and/or calibration errors some of the eye-tracking and EEG data failed to record correctly for the entire 90 minutes of the experiment. We excluded these data from the analysis of that specific source. Because of this, we used 37 participants in the EEG analysis and 35 participants in the eye-tracking and pupil diameter analysis.

Information about gaze position was obtained by defining and comparing gaze towards task-related areas, two face-stimulus areas and the rest of the remaining areas containing a black background. The task-related stimulus (the 2-back letter) was positioned in the center of the screen surrounded by an area of interest of 320x320 pixels. The face images were vertically centered and positioned at the far left and right side of the screen. They were each surrounded by an area of interest of 380x520 pixels and analyzed as one area (i.e., by adding up the gaze towards each of the two areas). With a screen resolution of 1680x1050 the space between the task and face areas of interest was 300 pixels, ensuring enough discriminability. Relative gaze time towards the task, face, and other areas of the screen during the 500ms the stimuli were displayed was aggregated on the block level and exported to SPSS. We also exported the percentage of missing data during each block as an indication of off-screen gaze or closed eyes.

To measure baseline pupil diameter, we averaged the pupil diameter in the 200 milliseconds before stimulus onset. During this period the participants saw a black screen with a fixation cross. Therefore, there was no interference from pupillary reflexes to the environmental lighting during the baseline recording. Baseline pupil diameter for each time-on-task interval was exported to SPSS for further analysis.

Extensive research of the P3 shows the distinction between the P3a and P3b potential (Polich, 2007). The P3a is linked to novelty detection and best seen at the Cz and Fz electrodes. The P3b is linked to salience processing and is best seen at the Pz electrode. Because we were interested in the latter we analyzed the EEG signal at the Pz electrode. Reviewing the voltage maps confirmed that the amplitude of the P3 was indeed largest at Pz. The EEG data were analyzed in Brain Vision Analyzer (Brain Products). The ERPs were averaged offline after rejection of out of range artifacts and eye movements, using the Gratton and Coles method (Gratton et al., 1983). Segments with amplitudes higher than 200 μV and lower than -200 μV and voltage steps above 50 μV/ms were removed. The data were also inspected on low activity (below 0.1 μV) and filtered (low cutoff at 0.1 Hz and high cutoff at 40 Hz). After Baseline correction for the 200 ms before the stimulus onset we aggregated the data per condition and measured the positive peak between 300 and 450 milliseconds after the onset of the stimulus.

Trials in which performance errors occurred were excluded. The mean P3 peak activity for each time-on-task interval was then exported to SPSS for further analysis.

STATISTICAL ANALYSIS

The subjective, behavioral, gaze and psychophysiological data were exported to SPSS and statistically analyzed using repeated measures analysis of variance (ANOVA). Because each participant did three blocks with face stimuli and three without face stimuli, we used a 3x2 design with time-on-task and the presence or absence of face stimuli as within subject factors. We tested the main and interaction effect of time-on-task (Block 1, 2, 3) and face stimulus (blocks with and without alternative stimulus). Also, we tested the effect of the reward/ motivation manipulation by comparing the last block with face stimuli before the manipulation, with the block after the manipulation (which also contained the face stimuli).

In addition to the repeated measures ANOVA, we analyzed the data using a multilevel approach with Mplus statistical software. A multilevel approach to experimental data has rarely been used in previous fatigue studies, but can be a very useful addition. Specifically, repeated measures data can be treated as multilevel data, with the repeated measures nested within individuals. We calculated the correlation between the various outcome measures on the individual level with the nested structure of the data taken into account (i.e., blocks nested within persons). We used a two-level model with time-on-task block at the first level (Level 1; N = 238), and individuals at the second level (Level 2; N = 34). In this operationalization a high correlation between dependent variables, means that a change in one variable corresponds with a similar change in another variable for each time-on-task block within individuals.

RESULTS

SUBJECTIVE MEASURES

Pre and post task analyses of the RSME confirmed that our fatigue manipulation was successful as participants reported significantly higher levels of subjective fatigue after the experiment than before, $t(46) = -19.8$, $p < .001$. Figure 4.1 shows the progression of subjective fatigue and task engagement during the course of the experiment. This figure shows the effect of time-on-task and the reward manipulation on both of the subjective measures, while also clearly showing the similarity in blocks with and without face stimuli. During the experiment, subjective fatigue increased over time in the blocks before the reward manipulation, $F(2,92) = 71.5$, $p < .001$, $\eta_p^2 = .61$, but decreased after the reward manipulation, $F(1,46) = 15.2$, $p < .001$, $\eta_p^2 = .25$. We neither found a main effect of the face stimuli, $F(1,46) = .06$, *ns*, $\eta_p^2 < .01$, nor a face x time-on-task interaction effect, $F(2,92) = .6$, *ns*, $\eta_p^2 = .01$, on subjective fatigue.

Subjective task engagement significantly decreased with increasing time-on-task before the reward manipulation, $F(2,92) = 49.2$, $p < .001$, $\eta_p^2 = .52$. After the reward manipulation, there was a significant increase, indicating reengagement into the task, $F(1,46) = 15.2$, $p < .001$, $\eta_p^2 = .25$. Similarly to subjective fatigue, we did not find a main effect of the face stimuli, $F(1,46) = 4.0$, *ns*, $\eta_p^2 = .08$, or a face x time-on-task interaction, $F(2,92) = 1.9$, *ns*, $\eta_p^2 = .04$.

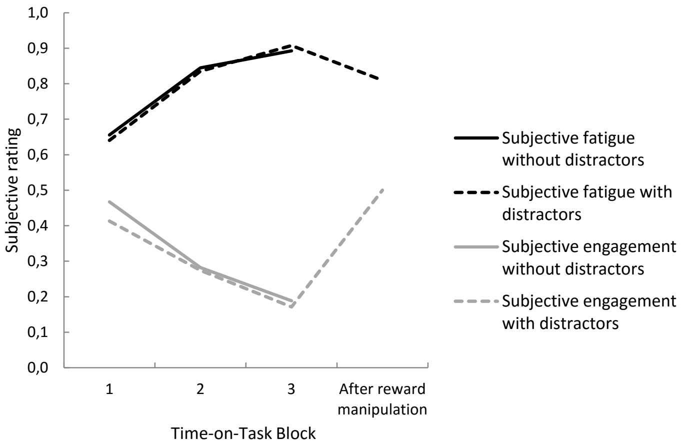

Figure 4.1. Subjective ratings of fatigue and task engagement with increasing time-on-task.

BEHAVIORAL MEASURES

As Figure 4.2 clearly shows, the results of the performance measure were largely in line with the findings on the subjective measures. Specifically, we found that d-prime decreased from the first to the sixth block, $F(2,92) = 22.5$, $p < .001$, $\eta_p^2 = .33$, suggesting that fatigue compromised cognitive performance. After the reward manipulation in block seven d-prime clearly increased again, $F(1,46) = 46.4$, $p < .001$, $\eta_p^2 = .50$. Also similar to the results of the subjective measures, was the absence of a main effect of the face stimuli, $F(1,46) = 1.7$, *ns*, $\eta_p^2 = .04$, and the interaction between time-on-task and the faces, $F(2,92) = .8$, *ns*, $\eta_p^2 < .01$, on task performance. We did find a decrease in RT before the reward manipulation as well, suggesting a (partial) speed/accuracy trade-off, $M_1 = 960$ ms, $M_2 = 884$ ms, $M_3 = 858$ ms, $F(2,92) = 16.3$, $p < .001$, $\eta_p^2 = .26$. However, after the reward manipulation RT did not change significantly, M_{pre} = 845 ms, M_{post} = 848 ms, $F(1,46) = .1$, *ns*, $\eta_p^2 < .01$, while accuracy improved. This indicates that before the reward manipulation participants performed suboptimal even after slowing down their reaction time, which makes it less likely that the results before the manipulation were solely caused by a speed/accuracy trade-off.

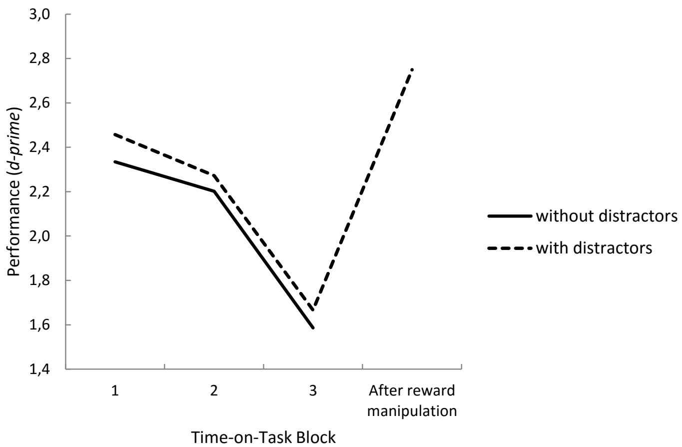

Figure 4.2. Performance with increasing time-on-task.

GAZE DATA

Table 4.1 shows the percentage of the gaze towards each of the areas of interest during each of the time-on-task blocks. Using repeated-measures ANOVA, we found that the percentage of off-screen and missing gaze position significantly increased from block 1 through block 6, $F(2,68) = 10.0$, $p = .001$, $\eta_p^2 = .23$, while the change over time in the other areas did not reach significant levels (*task*: $F(2,68) = 2.4$, $p = .10$, $\eta_p^2 = .07$; *faces*: $F(2,68) = 1.2$, *ns*, $\eta_p^2 = .03$; *rest of screen*: $F(2,68) = 1.2$, *ns*, $\eta_p^2 = .04$). This shows that increased fatigue is not necessarily associated with decreased time focused on the task-related area of the screen or an increase towards the task-unrelated rewarding alternatives (i.e., the faces). After the reward manipulation in the last block, the percentage of off-screen or missing gaze position, $F(1,34) = 15.3$, $p < .001$, $\eta_p^2 = .31$, and gaze towards the faces, $F(1,34) = 18.2$, $p < .001$, $\eta_p^2 = .35$, significantly decreased, while gaze towards the task significantly increased, $F(1,34) = 10.1$, $p < .01$, $\eta_p^2 = .23$. This is in line with the explanation of a flexible motivational system, which predicts that participants reengage in the task after increasing the rewards of the task. The percentage of gaze towards the rest of the screen (which was already very small) remained stable after the reward manipulation, $F(1,34) = .5$, *ns*, $\eta_p^2 = .01$.

We found a significant main effect of the face stimuli for all areas of interest. In blocks that contained face stimuli (versus blocks that did not contain faces), participants looked more at the face areas, $F(1,34) = 7.0$, $p < .05$, $\eta_p^2 = .17$, but surprisingly also looked more at the task related stimuli, $F(1,34) = 5.0$, $p < .05$, $\eta_p^2 = .13$. At the same time, they looked relatively less at the rest of the screen, $F(1,34) = 18.3$, $p < .001$, $\eta_p^2 = .35$, and there were less off-screen and missing gaze positions, $F(1,34) = 4.8$, $p < .05$, $\eta_p^2 = .13$. This means that the presence of the faces seems to influence gaze position, but that it did not lead to decreased time focused on the task-related area of the screen. We did not find any interaction effects between time-on-task and the faces (*task area*: $F(2,68) = .8$, *ns*, $\eta_p^2 = .02$; *face areas*: $F(2,68) = .8$, *ns*, $\eta_p^2 = .02$; *rest of screen areas*: $F(2,68) = .6$, *ns*, $\eta_p^2 = .02$; *off-screen/missing*: $F(2,68) = 1.0$, *ns*, $\eta_p^2 = .03$)

Table 4.1. Percentage of gaze towards each of the areas of interest with time-on-task.

	Block 1	Block 2	Block 3	After Reward manipulation
Area of interest: task *without faces*	70.5	67.2	65.1	–
Area of interest: task *with faces*	73.4	73.9	70.4	78.8
Area of interest: faces *without faces*	.6	.6	.7	–
Area of interest: faces *with faces*	3.5	2.7	4.3	.9
Area of interest: rest *without faces*	22.9	24.0	22.4	–
Area of interest: rest *with faces*	18.5	18.3	15.4	16.3
Off-screen & missing *without faces*	5.9	8.3	11.8	–
Off-screen & missing *with faces*	4.7	5.2	9.9	4.0

PUPIL DIAMETER

As displayed in Figure 4.3, baseline pupil diameter significantly decreased with time on task throughout the first six blocks of the experiment, $F(2,68) = 8.2$, $p < .01$, $\eta_p^2 = .20$, and significantly increased again after the reward manipulation in the last block, $F(1,34) = 13.7$, $p = .001$, $\eta_p^2 = .29$. This is in line with earlier findings that pupil diameter is sensitive to time-on-task fatigue effects (e.g., Hopstaken et al., 2015b). We also found a main effect for the presence of the face stimuli, $F(1,34) = 13.9$, $p = .001$, $\eta_p^2 = .29$. Blocks with the alternative face stimuli had lower baseline pupil diameter than blocks without the face stimuli. However, this effect is likely caused by the fact that the blocks with the alternative stimuli had a higher average screen luminosity, and it is well known that luminance of the screen and surroundings has profound impact on pupil size. Although the baseline pupil diameter was measured during the period before the stimulus onset (i.e., during a black screen) it is possible that the pupils adapted to the brighter stimuli that were displayed throughout the blocks duration. We did not find an interaction effect between time-on-task and the alternative face stimuli, $F(2,68) = .14$, $p = .83$, $\eta_p^2 < .01$.

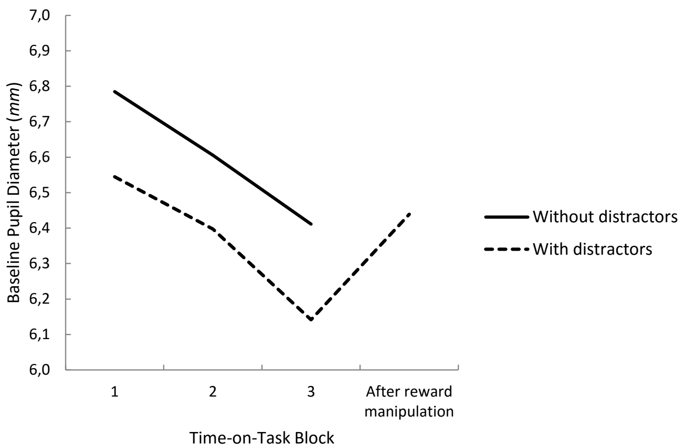

Figure 4.3. Baseline pupil diameter with increasing time-on-task.

P3 AMPLITUDE

We measured P3 amplitudes as a known physiological indicator of task engagement (Hopstaken et al., 2015a; Murphy et al., 2011; Nieuwenhuis et al., 2011). We first confirmed that the P3b was largest at electrode Pz as can be seen in the voltage maps in Figure 4.4, which shows the localization of the P3 ERP during each time-on-task block. The P3b amplitude showed a strong significant main effect for time-on-task, $F(2,72) = 28.6$, $p < .001$, $\eta_p^2 = .44$. Figure 4.5 shows the declining P3 with increasing time-on-task for blocks with and without the presence of face stimuli. Similar to the subjective, behavioral, and pupil data, the P3 amplitude showed a reverse in pattern after the reward manipulation in the last block and increasing significantly as hypothesized, $F(1,36) = 26.5$, $p < .001$, $\eta_p^2 = .42$. Raw P3 ERPs are displayed in Figure 4.6. No main effect of the alternative stimulus was found for the P3 amplitude, $F(1,36) < .01$, $p = 1$, $\eta_p^2 < .01$, and an interaction between time-on-task and the alternative stimulus was also absent, $F(2,72) = .03$, $p = .96$, $\eta_p^2 < .01$.

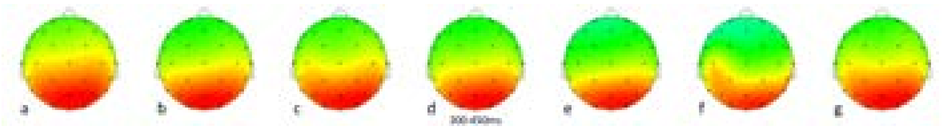

Figure 4.4. EEG voltage maps in the 300-450ms range showing that the P3 is largest at electrode Pz on each of the time-on-task blocks. a, b, and c are blocks 1, 2, and 3 without faces; d, e, and f are blocks 1, 2, and 3 with faces; g is block 7 after the reward manipulation.

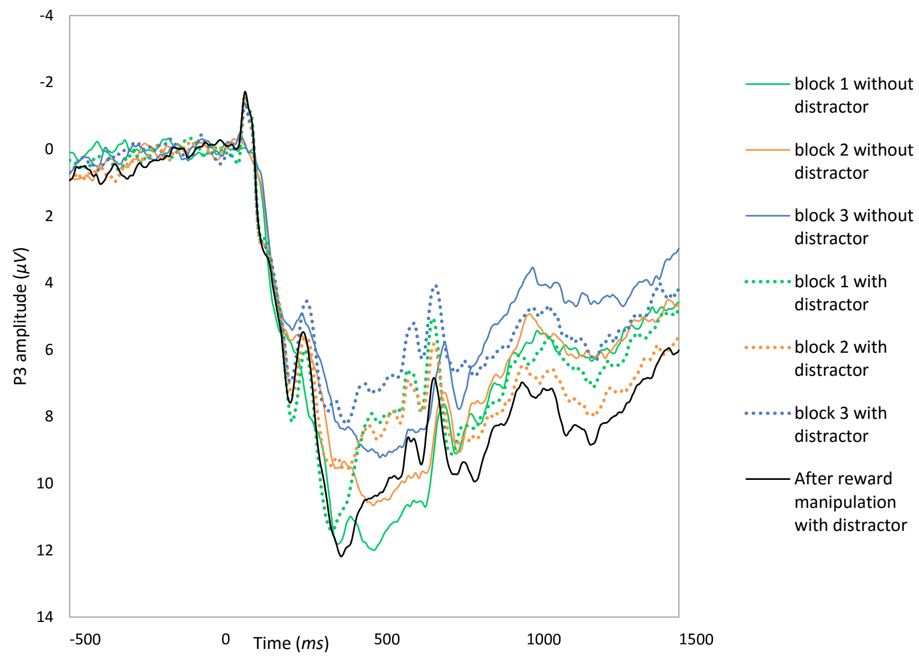

Figure 4.6. Raw P3 amplitudes at electrode Pz.

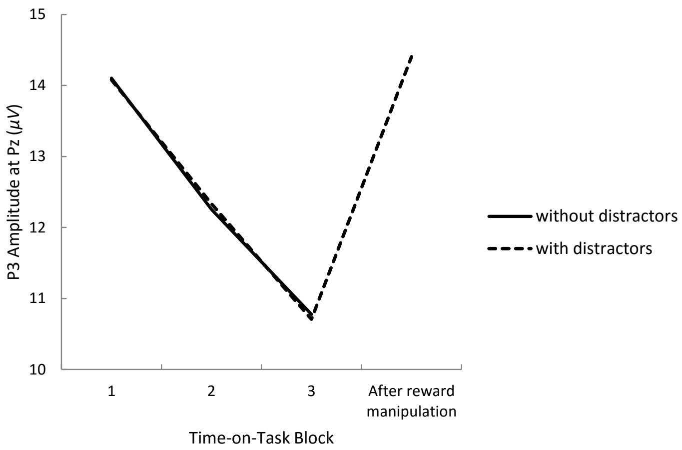

Figure 4.5. P3 amplitude at electrode Pz with increasing time-on-task.

MULTILEVEL ANALYSIS OF THE SUBJECTIVE, PERFORMANCE, AND PHYSIOLOGICAL MEASURES

4

Although the previously reported findings, obtained by analyses of variance, were able to shed light on the progression of mental fatigue effects over time, this method did not provide direct insight into the associations between the various measures used in the present study. Therefore, to address whether shifts in gaze are related to the various measures of disengagement we utilized multilevel analysis with Mplus statistical software (Muthén & Muthén, 1998). Using the multilevel approach, we were able to correlate the different measures we have used in this study and directly compare measures within individuals while taking the nested structure (i.e., time-on-task blocks are nested within individuals) of the data into account. This allows us to directly compare the subjective, performance, and physiological measures of engagement to the measures of gaze position during the different phases of the experiment. The use of multilevel analyses is justified when there is sufficient variance explained at two or more levels of analysis. The intraclass correlations (ICC), which are displayed in table 4.2, indicated that there indeed was sufficient variance explained on both levels for each of the observed variable.

Table 4.2 also shows the correlations for each pair of observed variables. From this table it becomes clear that there are strong correlations between the P3 amplitude, d-prime, pupil diameter, and both subjective measures of fatigue and disengagement. This statistically confirms that a change in one type of measure (e.g., p3 amplitude) was accompanied by a change in another measure (e.g., d-prime), underlining the link between these variables regardless of when this change took place. We found high positive correlations between the percentage of gaze towards the task, several measures of task engagement (i.e., subjective task engagement, P3 amplitude, pupil diameter), and task performance. High negative correlations were found between the amount of gaze towards the faces, off-screen and measures of task engagement and task performance. This indicates that high subjective engagement and physiological engagement are indeed consistently related to attending the task related stimuli. These results also point out that after the task is manipulated to be perceived as more rewarding, and task engagement strongly reappears, gaze towards task-unrelated stimuli (even though they are inherently rewarding and attention-grabbing) is nearly absent.

Table 4.2. Percentage of gaze towards each of the areas of interest with time-on-task.

	ICC	1	2	3	4	5	6	7	8
1. Subjective fatigue	.39	–	–	–	–	–	–	–	–
2 Subjective task engagement	.51	-.47 ***	–	–	–	–	–	–	–
3. d-prime	.36	-.34 ***	.51 ***	–	–	–	–	–	–
4. P3 amplitude	.67	-.38 ***	.51 ***	.44 ***	–	–	–	–	–
5. Baseline pupil diameter	.84	-.34 ***	.35 ***	.38 ***	.24 ***	–	–	–	–
6. AoI task	.73	-.12	.25 ***	.28 *	.29 ***	.18	–	–	–
7. AoI faces	.19	.14 *	-.19 ***	-.12	-.14 **	-.32 ***	-.39 ***	–	–
8. AoI rest screen	.80	-.06	.04	.09	-.05	.29 **	.70 ***	-.11	–
9. AoI offscreen / missing	.61	.21 *	-.38 ***	-.54 ***	-.36 ***	-.48 ***	-.65 ***	.16 **	.06

AoI measures indicate the amount of time a specific area of the screen was attended, * $p < .05$, ** $p < .01$, *** $p < .001$

DISCUSSION

With a combination of subjective, EEG, pupil, eye-tracking, and performance measures the present study tested the influence of mental fatigue on cognitive task performance. The goals of the study where to examine, a) whether task disengagement and decreased task performance where related to explorative shifts in attention versus less efficient processing of the task, and b) whether mental fatigue reflects a depletion of finite energy resources or more likely reflects a motivational mechanism that protects individuals from overspending energy when the benefits are relatively low. During several parts of the experiment, face stimuli were presented as a potentially rewarding alternative to the task-related stimuli. While we found that task disengagement was related to an increase of gaze towards these face stimuli, there was no significant decrease in gaze towards the task-related stimuli with increasing time-on-task. Compared to parts of the experiment without faces, the presence of face stimuli also had no additional negative effect on task performance. Therefore, we cannot conclude that the effect of fatigue on task performance was related to exploration of the task-unrelated stimuli, and the explanation of less efficient processing of the task stimuli seems to provide a better explanation of the results. Additional insight, into the nature of this less efficient processing, was provided by the reward manipulation at the end of the experiment. We found that increasing the rewards for task engagement strongly directed gaze towards task-related stimuli. Although participants still reported to be highly fatigued, irrelevant rewarding stimuli where largely ignored after increasing the task rewards. Subjective and psychophysiological engagement were restored and task performance was even higher than at the start of the experiment. This suggests that participants were able to overcome their subjective state of fatigue and reengage in the task. These results support the view that mental fatigue is a, mostly motivationally driven, protection mechanism which restrains individuals from spending cognitive resources on tasks that are not worth the effort. This directly contradicts the view that fatigue effects are explained by an inability to engage in the task (or explore the alternative stimuli) caused by depleted resources. Direct comparison of the various measures using a multilevel analysis, showed that they were related over the course of the experiment. That is, an increase in subjective fatigue and task disengagement was accompanied by indications of lowered physiological task engagement (i.e., task directed gaze, P3, pupil diameter) and decreased task performance. In what follows, we will discuss the contributions and limitations of the study in more detail.

FATIGUE AND CONTROL OF ATTENTION

Based on the notion that individuals engage in and disengage from a task based on cost/reward trade-offs (Cohen et al., 2007), we predicted that, with increasing time-on-task, attention may shift from task-related toward task-unrated stimuli. Our findings showed however, that the amount of gaze towards the task did not decrease significantly throughout the experiment. Combined with the finding that performance still deteriorated, but was restored after increasing the task rewards, this indicates that with increasing time-on-task, the outcome of the cost/

reward trade-off for task engagement became less favourable and exploiting the task rewards became less attractive. As an alternative to exploitation of the task there are two options, exploration of the environment to find other activities that may have a more positive cost/reward trade-off, or disengaging in general to save resources for the time they may be more useful. These findings contradict Baumeister et al.'s (1998) theory, which assumes a depletion of a limited resource for self-control and is still very popular and often implemented in practice. Baumeister's resource depletion model states that engaging in effortful control of behavior depletes an inner capacity for self-control. Based on the results of this study however, we favor an explanation in terms of a motivational cost/reward tradeoffs (e.g., Inzlicht et al., 2014; Kurzban et al., 2013). With increasing time-on-task, the rewards of the experimental task stay the same or may even decrease (i.e., because the task becomes less challenging or interesting), while the opportunity cost of not engaging in other possible activities increases. This results in an imbalance between the costs and rewards of the task and eventually leads to disengagement. When the motivation to engage in the task becomes too low, fatigue serves as a stop emotion that protects individuals from overspending energy, and conserve it for the moment that a more rewarding activity presents itself (Hockey, 2011; van der Linden, 2011). When sufficient rewards are presented (i.e., after the rewards manipulation), the imbalance between costs and rewards is restored and participants reengage in the task. These eye-tracking data provide additional evidence for motivational disengagement, instead of depletion of resources, to best describe the effect of fatigue on attention and task performance.

In addition to the inclusion of eye-tracking, another strength of the present study is that we were able to observe and directly compare the time-on-task effect of several different measures of task engagement. With multilevel correlation analyses we were able to compare the change in one measure (e.g., subjective task engagement) to another measure (e.g., gaze towards task-related areas of the screen). Because we argue that the task was processed less efficiently with increasing fatigue, especially the combination of gaze data and P3 amplitudes was informative. We found that subjective task engagement, P3 amplitude and gaze toward task related areas of the screen correlated strongly and positively over the course of the experiment. Although gaze towards the task-related areas of the screen did not decrease significantly, P3 amplitudes did, which can be seen as evidence for lowered attention and processing of the observed stimuli. Recently P3 amplitudes have been associated with activity in the locus coeruleus and noradrenergic modulation of the brain (Murphy et al., 2011; Nieuwenhuis et al., 2005; Nieuwenhuis, 2011). Aston-Jones and Cohen (2005) distinguish between baseline and stimulus-evoked release of noradrenaline. By combining measures of baseline and stimulus-evoked noradrenaline release, they formulated two operating output modes for the locus coeruleus that lead to task engagement or explorative disengaged behavior. The present study leaves an interesting possibility for a third output mode that describes mental fatigue and leads to a more general disengaged behavior, without specifically exploring the environment for rewarding activities (cf. Hopstaken, van der Linden, Bakker, & Kompier, 2015b).

RELEVANCE AND LIMITATIONS

Although the present study adds further insight into attention during fatigue, there are also some limitations that should be taken into account. Specifically, although they were attended during the study, the face stimuli that were used as the competing alternative stimulus did not significantly influence task performance. The most important reason to use faces was that they are inherently and universally rewarding and therefore have a high chance of being explored (M. H. Johnson, 2005; Schmidt & Cohn, 2001). The downside of this, with regard to our study, is that recognizing and analyzing faces is such an important aspect of adaptive functioning that it has evolved in a 'special' separate system in the brain. Many researcher have argued that the processing of faces is an automatized process utilizing specific mostly autonomous brain regions and requires very little cognitive resources (Lavie, Ro, & Russell, 2003; Vuilleumier, Armony, Driver, & Dolan, 2003). The automatized nature of observing face stimuli could pose an alternative explanation for the absence of a clear exploration effect and the relatively unaffected task performance. In future studies it would be insightful to see whether other task-unrelated rewarding stimuli, that use more cognitive resources, are more likely to lead to exploration behavior during mental fatigue. Finding the right type distractor may deserve a line of research by itself, because it may be challenging to find a distractor that is universally rewarding (i.e., that possesses as a strong reward in a similar way to everybody). A possibility for such a stimulus might be self-rewarding material, although there are indications that this type of stimulus is also processed relatively automatically (Bargh, 1982).

Another thing that could be seen as a limitation is that we chose to adopt a within-subject design to examine our research aims. An important strength of the within-subjects design that we used is that it minimizes error variance and the influence of individual differences in reward evaluation. Because both the face stimuli and the rewards manipulation have a subjective aspect, we consider it methodologically sounder to evaluate fatigue effects within participants, rather than between participants. While we have no specific reason to expect that a replication of the study with a between-subject design would yield very different results, we encourage scholars to pursue such a replication which would extend our present contribution.

In addition to the theoretical contributions, the present study also presents considerable implications for practical applications. Specifically the observation that, during mental fatigue, information is processed less efficiently, and gaze could be diverted from focusing on task-related stimuli to exploration of the environment, impacts the direction of work safety and work performance interventions. For example, in the sector of transportation and industry fatigue prevention measures are, to large extent, still based on the presumption that fatigue is caused by a loss of energy resources. A common practice in the transportation sector to prevent fatigue related accidents, is to rest 15-20 minutes every couple of hours (European Commision Mobility and Transport, 2006; Federal Motor Carrier Safety Administration, 2014). Based on the results of this study, which points out the danger of disengagement when the cost/rewards trade-off becomes unfavorable, it seems worthwhile to also explore ways to motivate drivers to focus on the road again. This is particularly important, since resting for 15-20 minutes does not necessarily seem to change the costs or rewards for engaging in driving after the break. We think there may be an interesting opportunity for future research to compare the efficiency of such a motivational intervention directly to traditional resting interventions.

CONCLUSION

While there has been an increasing amount of evidence for a more dynamic model of mental fatigue, which is based on shifts in motivation and attention compared to classical models of resource depletion (e.g., Hopstaken et al., 2015a; Inzlicht & Gutsell, 2007), this study is among the first to specifically address these shifts in attention by tracking gaze position during cognitive performance. Although the addition of alternative stimuli did not have a significant additional effect on task performance, the findings support both shifts in motivation and attention during mental fatigue. Opposed to classical resource depletion views, these shifts were explicitly linked a motivationally driven inefficient processing of the task. This opens up possibilities for new interventions aimed at the prevention of fatigue and gives a more elaborate view of what impaired attention during mental fatigue actually entails. The finding that subjective task engagement, gaze at task-related stimuli, P3 amplitudes and task performance correlate highly during the course of the experiment presents a more specific explanation for the often observed impaired task performance during fatigue. Namely, when individuals become fatigued because of sustained task performance, they disengage from the task to protect from overspending costly cognitive resources and save them for times where more rewarding activities present themselves.

CHAPTER 5

Diminished mental effort during mental fatigue: A heart-rate variability and pupillometry study

ABSTRACT

When one gets fatigued after a period of sustained performance, subjectively and objectively measured task engagement, like sustained attention on the task, often decrease significantly resulting in impaired task performance. Although several recent fatigue studies have focused on subjective and cognitive indicators of task engagement, they did not include direct measures of mental effort investment. In the present study we measured mental effort using the cardiovascular measure of heart-rate variability in the low-frequency domain, which has repeatedly been linked to performance on cognitively demanding tasks. Participants (*N* = 92) worked on a 2-back task for one hour to induce mental fatigue. Results showed that alongside the previously established decreases in task engagement (subjective and pupillometry), measures of heart-rate variability in the low-frequency domain increased with time-on-task indicating that fatigued individuals lowered the amount of mental effort they invested into the task. These results support the view that motivation is an important factor in explaining the emergence of mental fatigue effects on task performance. When the motivation to engage in the task becomes too low, fatigue serves as a stop emotion that protects individuals from overspending energy, and conserve it for the moment when a more rewarding activity presents itself.

Keywords: Mental Fatigue; Motivation; Mental Effort; Pupillometry; Self-Control; Task Engagement

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INTRODUCTION

When engaging in demanding tasks for a sustained period (e.g., several hours) one often experiences a sense of acute mental fatigue. This type of fatigue is a complex, multi-faceted state that involves changes in motivation, cognition, and mood (cf. Phillips, 2015). Recent studies have shown, that one of the most important characteristics of mental fatigue is reduced task engagement (Boksem & Tops, 2008; Inzlicht et al., 2014). For example, when one gets fatigued after a period of sustained performance, subjectively and objectively measures of task engagement, like sustained attention on the task, often decrease significantly resulting in impaired task performance (Hopstaken et al., 2015a). It has been acknowledged for many decades, that mental fatigue has a profound impact on workplace performance and is one of the most important human factors leading to errors and accidents (Baker et al., 1994; McCormick et al., 2012). As such, it has great theoretical and practical relevance to get more insight into the fundamental cognitive and motivational processes underlying fatigue.

Initially, it was thought that mental fatigue can be considered as a draining of resources, somewhat analogue to the idea of a battery running low (e.g., Griffith, Kerr, Mayo, & Topal, 1950). However, in recent years, it has become increasingly clear that the effects of fatigue do not simply reflect a reduction of energetic or cognitive resources. Instead, fatigue may also be considered the manifestation of strategic decisions about the level of task engagement (Hopstaken et al., 2015a, 2015b). Inzlicht, Schmeichel and Macrae (2014) have emphasized that problems with maintaining task engagement (e.g., in a fatigued state) are often the product of evolutionary pressures that motivate organisms to balance their desires for exploitation versus exploration behavior. This desire for exploitation versus exploration derives from a trade-off between the expected costs and rewards of a task (Aston-Jones & Cohen, 2005; Cohen et al., 2007). When the cost/reward trade-off is favorable, exploitation of the task rewards by engaging into the task is stimulated. That is, even though asserting cognitive control is aversive, the task provides enough intrinsic (e.g., pleasure, excitement) and/or extrinsic (e.g., monetary benefits) rewards to make it worth the effort. However, when the trade-off becomes unfavorable, the person will tend to disengage from the task. Instead of exploiting the task rewards, it then becomes more likely that one starts to explore the environment to find potentially more rewarding stimuli. This increases the probability of failures in self-control and task-related behavior that are often observed during mental fatigue.

Although several recent fatigue studies have focused on subjective and cognitive indicators of task engagement (e.g., Boksem, Meijman, & Lorist, 2006; Inzlicht & Gutsell, 2007), they did not include direct measures of mental effort. For example, pupil dilation in response to task relevant stimuli was found to be related to levels of task engagement (Hopstaken et al., 2015b). When fatigued, pupil dilations toward task related stimuli tend to become smaller indicating decreased task engagement. It is posited by theories that are based on cost/reward tradeoffs that the performance decrements are mainly motivationally, rather than energetically, driven (Boksem & Tops, 2008; Inzlicht et al., 2014). That is, when individuals get fatigued they disengage from the task, because the costs and benefits of the task are no longer in balance. As such, it can be expected that lower task engagement during mental fatigue, as indicated by subjective (e.g., analogue scales) and psychophysiological (i.e., pupil dilation) measurements, is also accompanied by a reduction in mental effort. As we mentioned, this link has not been explicitly tested before, while objectively measuring the amount of mental effort that is invested during mental fatigue could be helpful to explain whether this is indeed the case. When mental effort is indeed reduced during mental fatigue, this would further support that motivationally induced disengagement is an important mechanism to explain the effects of mental fatigue on performance.

In line with the above, we conducted a fatigue study in which we combined subjective, performance, and pupil diameter measures with a psychophysiological measure that is known to reflect mental effort. Specifically, we will use the cardiovascular measure of heart-rate variability in the low-frequency domain (i.e., sometimes called the .10Hz domain, measure range: .04–.15 Hz) which has repeatedly been linked to performance on cognitively demanding tasks (Aasman et al., 1987; Meijman & Mulder, 1998; Mulder, 1980). These previous studies have shown that reduced heart-rate variability in the low-frequency domain is observed when individuals are engaged in attending demanding mental operations (i.e., investing mental effort).

To test our hypotheses we will induce fatigue using a well-known continuous performance time-on-task paradigm while constantly measuring physiological indicators of task engagement and mental effort. We expect that similar to previous work (e.g., Hopstaken et al., 2015b), increasing mental fatigue will coincide with decreased subjective engagement, pupil dilation, and task performance. Additionally we relate these findings to an objective measure of mental effort (i.e., low-frequency domain heart-rate variability). Based on recent findings that fatigue coincides with task disengagement that is caused by shifts in motivation, we expect that participants will invest less mental effort when they become fatigued. Therefore we also expect that increased mental fatigue will coincide with increased heart-rate variability in the low-frequency domain, which is indicative of a decrease in mental effort.

METHOD

PARTICIPANTS

Ninety-two undergraduate students (18 males, 74 females), between the age of 17 and 37 (M = 20.8 years, SD = 3.1) participated for study credits. All participants were well-rested and in good health as measured by self-reports. The participants were asked to withhold the intake of caffeine and alcohol during the 24 hours before the experiment. All participants had normal or corrected to normal vision. Written informed consent was obtained prior to the study.

STIMULI AND DATA ACQUISITION

During the experiment, pupil diameter and electrocardiogram (ECG) were measured continuously. Participants performed a visual letter 2-back task. They were asked to decide whether the letter presented on the screen was a target or non-target stimulus. In the 2-back task, a stimulus is a target when the presented letter is the same as the letter presented two letters before. Accordingly, they responded on the corresponding button at the keyboard in front of them. The stimuli were presented in the center of the screen and consisted of the letters B, C, D, E, G, J, P, T, V, and W in the font Palatino Linotype 60. In the Dutch language these letters are phonologically similar in order to prevent sound-related retrieval strategies. The letters were presented randomly with a target rate of 25%. The 2-back task has been used successfully in previous experiments to induce mental fatigue (Hopstaken et al., 2015a; Massar et al., 2010). It is a cognitively demanding task that requires the sustained engagement of working memory and attention in order to uphold adequate levels of performance (Watter et al., 2001).

PROCEDURE

Participants were seated in a comfortable chair in a dimly lit, and sound attenuated room facing an eye-tracking screen at a distance of approximately 65 cm. Before the experiment started, participants filled out questionnaires about their general health, current level of fatigue, and task motivation. Three adhesive electrodes were placed for the ECG measurements. The plus on the left side of the frontal lower ribs, the minus on the sternum, and the ground on the right side of the frontal lower ribs. After the calibration of the eye-tracking device, participants were instructed on the 2-back task. Participants practiced until they reached a minimum of 70% accuracy. The experimental task was divided in four time-on-task blocks. Each block consisted of 139 trials 2-back task and lasted for about 15 minutes (depending on random intervals). The 2-back stimuli were displayed for 500ms with an inter-stimulus interval randomized at 5 to 5,5 seconds. The length of this interval was long enough to ensure that the pupil diameter returned to baseline levels (Beatty, 1982; Stern et al., 2000). After each block, participants had to indicate their current level of fatigue and task engagement. The participants only had limited time to respond, to make sure they would not rest.

MEASURES AND DATA PROCESSING

Subjective measures. Subjective fatigue was measured before, during and after the task in order to monitor its temporal progression. To measure subjective experience of fatigue during the experiment, participants were asked "how tired do you feel?" after each time-on-task block. They had to reply by moving a slider from 0 to 100, with increments of five. The slider had no anchors, but the extreme ends were labeled with "very much" and "not at all". Immediately after this question, we also asked "How engaged were you in the task?" after each time-on-task block, to investigate subjective engagement during the experiment. The participants again had to reply by moving a slider from 0 to 100, with increments of five. The slider had no anchors except for the extremes "very much" and "not at all".

Behavioral measures. The most relevant behavioral measure of performance on the n-back task was accuracy. As described by signal detection theory, the d-prime was calculated as an indication of accuracy (Wickens, 2001).

Physiological measures. Pupil diameter and ECG were recorded continuously during the entire length of the experimental task utilizing a SMI RED250 eye tracker with a sample rate of 60 Hz, and a Biopac MP150 with ECG100C module. To measure baseline pupil diameter, we averaged the pupil diameter in the 200 milliseconds before stimulus onset. During this period the participants saw a black screen with a fixation cross. Therefore, there was no interference from pupillary reflexes to the environmental lighting during the baseline recording. To measure pupil dilation we then applied a baseline correction for the 200 ms before the stimulus onset. Then, we measured the positive peak within the first 1500 milliseconds after the onset of the stimulus. Artifacts and blinks were detected by the eye-tracker and corrected by using a linear interpolation algorithm. Trials that did not contain fixation at the screen were removed from the analysis (< 1% of the data). One participant was excluded from the pupil data analyses because of technical problems with the eye-tracker.

To calculate low-frequency HRV we used the Biopac AcqKnowledge software. We first applied a digital band pass filter to the ECG between 0.5 and 35 Hz. The signal was then transformed to RR intervals using the QRS detector with a minimum BPM of 40, a maximum of 200, and a R wave threshold of 50. All RR intervals were automatically and visually scanned on artifacts. Pieces of the ECG that contained artifacts were removed from the analysis, leaving a minimum of 5 minutes of clean data per time-on-task block to continue. Shorter parts of clean data were dropped from the analysis, leading to missing data of one or more blocks in eleven participants. Low-frequency HRV was then calculated using the 0.04-0.15 Hz range. The mean pupil diameter, dilation and low-frequency HRV for each time-on-task interval were then exported to SPSS for further analysis. The subjective, behavioral, gaze and psychophysiological data were statistically analyzed using repeated measures analysis of variance (ANOVA).

RESULTS

5

SUBJECTIVE MEASURES

To address our research questions we first looked at the time-on-task effects of subjective fatigue and subjective task engagement. Table 5.1 contains the means and standard deviations for each of the time-on-task blocks. In accordance with our hypothesis, subjective fatigue increased, $F(3,273) = 160.2$, $p < .001$, $\eta_p^2 = .64$, and subjective engagement decreased, $F(3,273) = 21.5$, $p < .001$, $\eta_p^2 = .19$, significantly with increasing time on task.

PHYSIOLOGICAL MEASURES

Alongside the subjective measures, we also collected physiological measures during the experimental task. Our measure of interest for this study was HRV in the low-frequency domain. We predicted that there would be an increase in this measure with increasing time-on-task. In our analysis we indeed found such an increase, $F(3,246) = 47.2$, $p < .001$, $\eta_p^2 = .37$, suggesting decreased mental effort during the task. This decreased mental effort coincides with increases in reported fatigue and decreases in reported engagement.

Earlier studies reported that with increasing time-on-task and task disengagement, baseline pupil diameter and stimulus-evoked pupil dilations decrease. In our study, we replicate these effects of the pupil diameter, $F(3,270) = 30.2$, $p < .001$, $\eta_p^2 = .25$, although the effect of pupil dilation was only marginal, $F(3,270) = 2.4$, $p = .06$, $\eta_p^2 = .03$. We observed that there was no increase or decrease in pupil dilations between the first and second block of the task (see Table 5.1). In time-on-task experiments, such effects are not uncommon and suggest that participants initially became somewhat more engaged, likely because they were getting better at the task, countering initial fatigue effects (e.g., Boksem, Meijman, & Lorist, 2005; Csathó, van der Linden, Darnai, & Hopstaken, 2013; Lorist et al., 2000). Note that the pattern of these findings is similar to the subjective engagement (and task performance; see Table 5.1) results. When we look at the effect of pupil dilation from block two through four however, we do see a steady and significant decrease over time, $F(2,180) = 4.1$, $p = .01$, $\eta_p^2 = .04$, indicating the onset of fatigue effects.

Table 5.1. Means and standard deviations on each time-on-task block of the experiment.

	Block 1	Block 2	Block 3	Block 4
Subjective Engagement	.58 (.26)	.63 (.26)	.54 (.27)	.45 (.30)
Subjective Fatigue	.31 (.23)	.48 (.24)	.65 (.25)	.76 (.22)
Performance (*d-prime*)	2.57 (.90)	2.59 (1.11)	2.30 (1.12)	2.05 (1.48)
Baseline pupil diameter (*mm*)	5.00 (.68)	4.94 (.70)	4.82 (.68)	4.73 (.69)
Pupil dilation (*mm*)	.32 (.09)	.32 (.10)	.31 (.11)	.30 (.11)
Low-frequency HRV (ms^2)	1576 (652)	1683 (600)	1861 (768)	1928 (716)

TASK PERFORMANCE

We quantified performance on the 2-back task as a calculated d-prime accuracy, based on the hit and false alarm rates of the participants. We measured d-prime on each time-on-task blocks during the experiment and noticed a similar pattern as the subjective engagement and pupil dilation measure (see Table 5.1). More specific, we observed that there was no increase or decrease in performance from block one to two, but a fairy steep decrease in performance from block two through four. Overall, this decrease in performance was highly significant in our repeated measures analysis, $F(3,270) = 12.6$, $p < .001$, $\eta_p^2 = .12$. This underpins earlier findings that also report decreased performance with increasing time-on-task and increased fatigue and disengagement (e.g., Boksem et al., 2006; Hopstaken et al., 2015a). In this study, we observed that this decrease in performance coincides with an increase in HRV in the low-frequency domain indicating lowered mental effort with increasing time-on-task.

DISCUSSION

The present study examined the role of mental effort during fatigue-related task disengagement. First, in line with previous studies (e.g., Hopstaken et al., 2015a), we observed that, with increasing time-on-task, subjective mental fatigue increased, while task engagement decreased. Alongside these observations we found that measures of heart-rate variability in the low-frequency domain increased with time-on-task. This indicates that fatigued individuals tended to lower the amount of mental effort they invest into the task. Kurzban, Duckworth, Kable, and Myers (2013) are among the scholars who have proposed that mental effort depends on the mental representation of the costs and benefits of the activity at hand (also see Boksem & Tops, 2008). They argue that from a range of possible activities one will often pursue the one that is the most rewarding. However, when the relative benefits of staying engaged in a task become too low, one will require more mental effort to stay engaged in a task. When the motivation to engage in the task becomes too low, fatigue serves as a *stop emotion* that protects individuals from overspending energy, and conserve it for the moment that a more rewarding activity presents itself (Hockey, 2011; Meijman, 2000; van der Linden, 2011).

The theoretical framework of Kurzban and colleagues (2013) also presents an interesting follow-up question to this study. They argue that individuals always consider the cost/reward tradeoffs relative to the cost/reward tradeoffs of all other possible activities they could engage in. All these competing activities then serve as extra costs of opportunity themselves, because one could also consider to switch tasks and engage in other (possibly more rewarding) activities. Because there were no other rewarding activities available in the present study, mental effort is eventually decreased and energy is conserved for rewarding future events. A question that remains to be tested, however, is what would happen to observed mental effort when other task unrelated stimuli or activities where to be presented in the experimental environment. One would expect that when these stimuli or activities would be rewarding enough, participants would direct their resources towards these potential rewards and mental effort could be increased again. A related question that arises is how flexible the engagement of mental effort is. It has been argued that under the right conditions, even during high levels of fatigue, compensatory effort may be used to overcome such feelings and tendencies in order to uphold task performance (Hockey, 1997, 2011). In such a situation, where individuals are sufficiently motivated, it would be expected that mental effort actually increases during mental fatigue, in order to stay focused on the task and keep up performance. Indeed, some studies have reported that the negative effects of fatigue can be reversed and task performance can be successfully restored by providing additional motivation to engage in the task (Boksem et al., 2006; Hopstaken et al., 2015a). It would be interesting to see whether objective measures of mental effort, such as the HRV we measured in this study, also show such a reversed pattern.

While some questions regarding the flexibility of mental effort during mental fatigue remain open, the findings of this study have important implications for the debate about whether fatigue is a motivational or an energy resource problem. In addition to the replication of previous findings, that fatigue is accompanied by disengagement from the task, we have now provided evidence that this disengagement coincides with reduced mental effort. When individuals would still be motivated to engage in a task, but lack the energy resources, one would expect that before resources are depleted, extra effort is invested to try to uphold task performance. However, this does not seem to be the case in the present study. Therefore, the approach of a more dynamics system that revolves around motivational cost/reward tradeoffs that drive task engagement seems better suited to explain the effect of fatigue on task engagement and performance, than a system that revolves around resource depletion.

CHAPTER 6

Does dysphoria lead to divergent mental fatigue effects on a cognitive task?

ABSTRACT

Tiredness, low energy, and listlessness are common symptoms to be associated with depression. The question remains to what extent these symptoms influence the effects of fatigue on sustained performance tasks, such as impaired task engagement and performance. Based on earlier findings, it was hypothesized that dysphoric (i.e., mildly depressed) individuals, compared to healthy controls, would display earlier fatigue onset and more severe fatigue effects on task engagement and performance during a cognitive task. Sixty-one dysphoric and twenty-one non-dysphoric control participants were compared during one hour of continuous performance on a 2-back task. During the task, subjective fatigue, subjective engagement, objective task performance, baseline pupil diameter, and stimulus-evoked pupil dilation were measured. While we found that the dysphoric group reported relatively higher subjective fatigue than the healthy control group at the start of the experiment, we did not find any other divergent fatigue effects during the experimental task. One explanation for the absence of divergent effects is that dysphoria may not have such a profound impact on available cognitive resources, like attention, as initially thought. Based on the results of the present study, we conclude that dysphoria is not necessarily an increased risk factor for impaired sustained performance on cognitive tasks that may induce mental fatigue.

Keywords: Dysphoria; Depression; Fatigue; Pupillometry; Task Engagement

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INTRODUCTION

Depression has a high prevalence in the United States (Gotlib & Joormann, 2010) and Europe (Ayuso-Mateos et al., 2001) and negatively impacts work and academic performance (Hysenbegasi, Hass, & Rowland, 2005; Lerner et al., 2010). This mood disorder is especially associated with difficulties in concentration (Lyubomirsky, Kasri, & Zehm, 2003), complex problem solving (Lyubomirsky et al., 2003; Lyubomirsky & Nolen-Hoeksema, 1995), and impaired work strategies (Lyubomirsky et al., 2003). Depression is generally known to negatively affect health (Barth, Schumacher, & Herrmann-Lingen, 2004; Knol et al., 2006), personal relationships (Fröjd et al., 2008), and productivity (Doris, Ebmeier, & Shajahan, 1999). In the student population, depression is associated with lower educational performance (Fröjd et al., 2008; Hysenbegasi et al., 2005; Szulecka, Springett, & De Pauw, 1987) and higher drop-out rates from education (Szulecka et al., 1987). Although in many cases depression leads to discontinued work activities, milder depressive symptoms (i.e., dysphoria) often go unnoticed within the working population (Fan et al., 2012). The question remains to what extent these milder symptoms are associated with impaired work performance.

Second only to the depressed mood itself, tiredness, low energy, and listlessness are the most common symptoms to be associated with depression (Demyttenaere et al., 2005; Stahl, 2002). De Lecea, Carter and Adamantidis (2012) have suggested that changes in arousal states and thresholds are at the core of most neuropsychiatric disorders, including depression which is correlated to structural hypo-arousal. Chaudhuri and Behan (2004) describe that fatigue and cognitive disengagement in depression often result from a loss of interest and motivation. These authors also argue that even with usual levels of motivation, motor control, and sensory input, premature fatigue may arise because of unpleasant ambient conditions, dysautonomia, and underlying endocrine disturbances. Based on these findings, the question arises whether individuals with mild depressive symptoms (i.e., dysphoria) diverge from their non-depressive counterparts in their susceptibility to the effects of mental fatigue (i.e., earlier onset, more severe effects on performance). In this study, we will specifically address this question by comparing both groups while they are working on a cognitive task for an extended period of time.

Mental fatigue can occur as a chronic symptom of mental or physical disorders, but can also arise as an adaptive temporary condition resulting from prolonged cognitive effort (e.g., after a demanding workday). Mental fatigue is characterized by a reluctance for further effort and changes in mood motivation and information processing (Meijman, 1997; van der Linden, Frese, & Meijman, 2003). As a consequence, fatigued individuals have a tendency to disengage from the task at hand to prevent exhaustion. This disengagement is accompanied by lowered motivation (e.g., reduced effort), compromised cognition (e.g., diminished attention and task focus), and impaired performance (Boksem & Tops, 2008; Hockey, 1997). Although these detrimental effects of fatigue have now been clearly established in healthy populations (e.g., students, healthy workers), there is a remarkable lack of studies testing how working on cognitively demanding and fatigue-inducing tasks affects individuals with subclinical depression. Yet, as it is known that individuals with dysphoric mood often also report chronic fatigue (Bültmann, Kant, Kasl, Beurskens, & van den Brandt, 2002; Chaudhuri & Behan, 2004; Demyttenaere et al., 2005), it can be hypothesized that, compared to non-dysphoric individuals, they will be more susceptible to fatigue and disengagement while working on such tasks.

In the present study, we compare students with a dysphoric mood and healthy controls on task performance and subjective indices of mental fatigue. Moreover, we also examine the level of task engagement by measuring pupil dynamics. The diameter of the pupil has for many years been considered an index of psychophysiological arousal or neural gain, and the dilatory response has been linked to the occurrence of task-relevant events. Classic work of Beatty and Kahneman showed that the pupil is sensitive to momentary load and effort during mental tasks (Beatty, 1982; Kahneman & Beatty, 1966; Kahneman, 1973). In recent years, this notion has evolved by specifically relating pupil diameter to task engagement and disengagement, based on cost-reward tradeoffs (Gilzenrat et al., 2010; Jepma & Nieuwenhuis, 2011). After working on a demanding task for a prolonged period of time, increasing levels of effort are required to maintain task focus. At some point, the effort no longer aligns with the potential benefits of engaging in the task. It has been argued and shown that the disengagement that results from this unfavorable tradeoff is reflected in decreased baseline pupil diameter and stimulus-evoked dilations toward task-relevant stimuli (Hopstaken et al., 2015b). Based on the established association between dysphoric mood and heightened levels of chronic mental fatigue, we hypothesize that dysphoric individuals have lower average task engagement and display premature onset of mental fatigue effects on task engagement compared to healthy controls.

More specifically,

Hypothesis 1: *Individuals with dysphoric thoughts display higher average subjective fatigue and lower average subjective task engagement, baseline pupil diameter, stimulus-evoked pupil dilations and task performance compared to control individuals without dysphoric thoughts.*

Hypothesis 2: *Individuals with dysphoric thoughts display premature fatigue onset and effects reflected in earlier onset of increasing subjective fatigue and decreasing subjective task engagement, baseline pupil diameter, stimulus-evoked pupil dilations, and task performance compared to control individuals without dysphoric thoughts.*

METHOD

PARTICIPANTS

Sixty-one dysphoric psychology students were compared to a control group of 21 non-dysphoric psychology students. The sample group for this study was part of a larger intervention study at a psychology institute of the university. Therefore, we were unable to perfectly balance the sample size of each of the groups. Although there is a noticeable difference in group size, modern analysis software use techniques that are generally robust to such an inequality of groups. The inclusion criterion was a Beck Depression Inventory – II (BDI-II) (Beck, Steer, & Brown, 1996) score of minimally 10 for the dysphoric group and of maximally 5 for healthy group. We confirmed the statistically significant difference between the groups using an exact Mann-Whitney test for non-normally distributed data ($U = 1239$, $z = 6.79$, $p < .01$, $r = .76$, with a mean rank equal to 11 for the healthy control group and 51 for the dysphoric group). The mean BDI-II score of the dysphoric group was 20.2 (SD = 7.6, range: 10 - 46), which indicates an average depression (Beck et al., 1996) and .7 (SD = 1.1, range: 0 - 3) for the healthy group. The cut-off scores used for the selection are based on other studies comparing dysphoric and healthy students (Owens & Derakshan, 2013; Owens, Koster, & Derakshan, 2013). Information about age, gender, use of medication and medication and therapy history of both groups is reported in Table 6.1. All participants were well-rested and in good health as measured by self-reports. The participants reported to have slept seven or more hours and were asked to withhold the intake of caffeine and alcohol during the 24 hours before the experiment. All participants had normal or corrected to normal vision.

Table 6.1. Demographic Variables.

	Dysphoric group	Healty control group
Gender (% male)	23.7	23.8
Age (M, SD)	20.8 (3.6)	21.4 (4.7)
% Currently in therapy	13.6	0
% History of therapy	35.6	0
% Use of medication for psychopathology	5.1	0

STIMULI AND DATA ACQUISITION

Participants were seated in a dimly lit, and sound attenuated room facing an eye-tracking screen at a distance of approximately 65 cm. During the whole experiment, pupil diameter was measured continuously. The participants performed a visual letter 2-back task. The n-back task has been used successfully in previous experiments to induce fatigue (Hopstaken et al., 2015a; Massar et al., 2010). It is a cognitively demanding task that requires the sustained engagement of working memory and attention in order to uphold adequate levels of performance (Watter et al., 2001).

PROCEDURE

The study was approved by the Medical Ethical Committee of the Erasmus University Rotterdam and registered at ClinicalTrials.gov (ID: NCT02184481). Students subscribed for the study through the psychology website and received credits for participation. All participants provided written informed consent to participate in the study. Participants practiced on the task until they reached a minimum of 70% accuracy. The experimental task lasted one hour and was divided into six time-on-task blocks. Each block consisted of 83 trails of the 2-back task and lasted for about 10 minutes (depending on random intervals). The n-back stimuli were displayed for 500ms with an inter-stimulus interval randomized at 5 to 5,5 seconds. The length of this interval was long enough to ensure that the pupil diameter returned to baseline levels (Beatty, 1982; Stern et al., 2000).

MEASURES AND DATA PROCESSING

Subjective Measures. To measure time-on-task effects, the participants were asked "how tired do you feel?" after the practice trials and each time-on-task block during the experiment. They had to reply by moving a slider from 0 to 100, with increments of five. The slider had no anchors, but the extreme ends were labeled with "not at all" and "very much". After answering this question we also asked "How engaged are you in the task?" before the task continued. Because these questions about subjective task engagement and fatigue were measured multiple times during the experiment, we could monitor the temporal progression with time-on-task. The participants had only limited time to answer the questions (i.e., ten seconds) to prevent them from resting between blocks.

Depression. We used the BDI-II (Beck et al., 1996; Dutch version: Van der Does, 2002) to measure participants' severity of depression symptoms. This self-report questionnaire contains 21 groups of statements about depression symptoms experienced the last two weeks. Adding up the scores of the questions, which range from 0 to 3, results in the total score. The reliability of this widely used questionnaire is good (Evers, Van Vliet-Mulder, & Groot, 2005), with a Cronbach's α of .94 in the present study.

Performance. The most relevant behavioral measure of performance on the n-back task is accuracy. We operationalized accuracy by calculating the d-prime, as described by signal detection theory, for each time on task interval (Wickens, 2001). While accuracy was the most important focus for the participant during the task, we wanted to make sure accuracy effects were not clouded by accuracy/speed tradeoffs. Therefore, we also examined reaction times (RTs).

Physiological measures. Pupil diameter was recorded continuously during the entire length of the experimental task with a Tobii Eyetracker 2150 with a sample rate of 50 Hz. The recordings were exported to Brain Vision Analyzer (Brain Products, Gilching, Germany). Artifacts and blinks were detected by the eye-tracker and removed by using a linear interpolation algorithm. To measure baseline pupil diameter, we averaged the pupil diameter in the 500ms before stimulus onset. During this period, the participants saw a fixation cross with the same luminosity as the letters, so there was no interference from eye reflexes to the environmental lightning. To analyze stimulus-evoked pupil dilation we performed a baseline correction for the 200ms before the stimulus onset. Then, we measured the positive peak within the first 1500ms after the onset of the stimulus. Trials in which performance errors occurred were excluded. The mean baseline pupil diameter and pupil dilation peak for each time-on-task interval were then exported to SPSS for further analysis.

STATISTICAL ANALYSIS

The subjective, performance and pupil data were statistically analyzed using repeated measures ANOVA. Main and interaction effects of time-on-task and group (i.e., Dysphoric vs. Control) were tested over the six time-on-task blocks. To make sure that the effect of medication use did not influence the results and conclusions of the study, we did a parallel analysis that excluded the three participants that used medication. However, these parallel analyses showed that exclusion of these participants did not change the results in any meaningful way. Therefore, we only report the findings of the analyses that included these participants in the results section below.

RESULTS

SUBJECTIVE MEASURES

We analyzed the time-on-task effects for subjective fatigue and engagement during the experiment and found that fatigue significantly increased, $F(6,384) = 109.4$, $p < .01$, $\eta_p^2 = .63$, and engagement significantly decreased, $F(6,384) = 10.8$, $p < .01$, $\eta_p^2 = .15$, with increasing time-on-task. In contrast to our hypotheses, we did not find a significant group (dysphoric vs control), $F(1,64) = 1.3$, $p = .25$, $\eta_p^2 = .02$, and time-on-task x group interaction, $F(6,384) = 1.4$, $p = .24$, $\eta_p^2 = .02$, effect for engagement. We did however, find small group, $F(1,64) = 4.1$, $p < .05$, $\eta_p^2 = .06$, and interaction effect, $F(6,384) = 3.1$, $p < .05$, $\eta_p^2 = .05$, for subjective fatigue. Figure 6.1 shows that the dysphoric group scored higher on subjective fatigue, than the healthy control group, at the start of the experiment, but afterwards both groups scored similar. As can been seen in Table 6.2, which contains the means and standard deviations of all the observed measures during the experiment, the difference between the groups is especially large at the start of the experiment (dysphoric: $M = .39$, $SD = .21$; control: $M = .18$, $SD = .20$) which may explain these significant results.

BEHAVIORAL MEASURES

Analyzing the task performance data from block 1 through 6, we did not find a significant effect of time-on-task, $F(5,320) = 1.9$, $p = .13$, $\eta_p^2 = .03$. Looking at the mean performance at each block it became apparent that performance was relatively stable in the first part of the experiment and started to decline after the third block. The observation that task performance is stable or sometimes even increases during the start of the experiment is commonly found. This can be seen as a learning effect that can mask the effects of the onset of fatigue (Boksem et al., 2005; Lorist et al., 2000, 2005). During the first three blocks of the experiment there was no change in d-prime, $F(2,128) = 1.5$, $p = .24$, $\eta_p^2 = .02$. However, from block three through six, d-prime significantly decreases, $F(3,192) = 3.7$, $p = .01$, $\eta_p^2 = .06$. RTs do not change significantly during the time of the experiment, $F(5,320) = 2.4$, $p = .07$, $\eta_p^2 = .04$, indicating there is no trade-off between speed and accuracy. While we found a main effect for time-on-task, we did not find a significant group effect (block 1 through 3: $F(1,64) = .2$, $p = .69$, $\eta_p^2 < .01$; block 3 through 6: $F(1,64) = .9$, $p = .36$, $\eta_p^2 = .01$) or time-on-task x group interaction effect for d-prime (block 1 through 3: $F(2,128) = .3$, $p = .68$, $\eta_p^2 = .01$; block 3 through 6: $F(3,192) = .5$, $p = .61$, $\eta_p^2 = .01$). We also did not find a significant group, $F(1,64) = 1.5$, $p = .22$, $\eta_p^2 = .02$, and interaction effect, $F(5,320) = .4$, $p = .77$, $\eta_p^2 < .01$, on RTs. These findings are not in line with our hypothesized differences between the dysphoric and control groups.

Table 6.2. Means and standard deviations of the observed variables.

	Pre-training		block 1		block 2		block 3		block 4		block 5		block 6	
	D	C	D	C	D	C	D	C	D	C	D	C	D	C
1	.39	.18	.50	.30	.59	.46	.68	.58	.72	.67	.76	.70	.81	.71
	(.21)	(.20)	(.25)	(.21)	(.24)	(.25)	(.23)	(.28)	(.24)	(.27)	(.23)	(.29)	(.19)	(.32)
2	.48	.43	.53	.58	.48	.58	.42	.51	.38	.48	.33	.43	.27	.39
	(.24)	(.27)	(.27)	(.26)	(.25)	(.28)	(.25)	(.32)	(.25)	(.35)	(.26)	(.34)	(.24)	(.35)
3	–	–	1.80	1.79	2.05	1.85	2.12	1.94	2.20	1.75	2.12	1.72	1.78	1.53
			(1.21)	(1.23)	(1.08)	(1.80)	(1.00)	(1.77)	(1.17)	(1.54)	(1.14)	(1.85)	(1.21)	(1.75)
4	–	–	1156	1039	1117	1003	1085	970	1072	996	1082	959	1035	978
			(353)	(281)	(354)	(285)	(324)	(294)	(305)	(295)	(331)	(277)	(247)	(275)
5	–	–	5.19	4.79	5.06	4.67	4.97	4.69	4.93	4.73	4.94	4.69	4.94	4.73
			(.86)	(.56)	(.80)	(.63)	(.75)	(.67)	(.78)	(.63)	(.80)	(.63)	(.77)	(.65)
6	–	–	.13	.14	.12	.13	.12	.12	.11	.10	.11	.10	.08	.08
			(.08)	(.10)	(.07)	(.10)	(.08)	(.10)	(.07)	(.09)	(.08)	(.08)	(.06)	(.07)

D = Dyspohoric group, C = Healthy control group; 1 = Subjective fatigue, 2 = Subjective task engagement, 3 = d-prime, 4 = RT (*ms*), 5 = Pupil diameter (*mm*), 6 = Pupil dilation (*mm*).

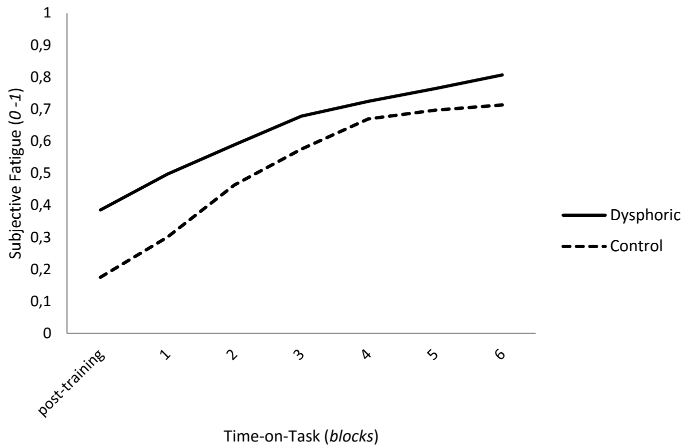

Figure 6.1. Interaction effect of time-on-task and group (dysphoric versus control) on subjective fatigue.

PHYSIOLOGICAL MEASURES

In line with previous studies, we found a decrease in both baseline pupil diameter, $F(5,250) = 4.7, p < .01, \eta_p^2 = .09$, and peak pupil dilation, $F(5,250) = 6.9, p < .01, \eta_p^2 = .12$, with increasing time-on-task. However, in contrast to our hypothesis and in line with most of the previously described analyses of this study, we did not find any significant group (baseline pupil diameter: $F(1,64) = 1.7, p = .19, \eta_p^2 = .03$; Peak pupil dilation: $F(1,64) < .01, p = .93, \eta_p^2 < .01$) or time-on-task x group interaction effects (baseline pupil diameter: $F(5,250) = 2.2, p = .09, \eta_p^2 = .04$; Peak pupil dilation: $F(5,250) = .6, p = .70, \eta_p^2 = .01$).

DISCUSSION

The present study examined whether individuals with dysphoric mood have a higher average, and earlier onset of, the negative effects of fatigue on task engagement and sustained performance during a cognitively demanding task. In line with previous findings of Hopstaken et al. (2015a, 2015b), we found that subjective, performance, and psychophysiological measures of task engagement changed with increasing time-on-task. While we found that the dysphoric group reported relatively higher subjective fatigue than the healthy control group during the early stages of the experiment, we did not find any other divergent fatigue effects during the experimental task. This absence of divergent patterns contradicts our hypotheses, which we based on earlier work that showed that

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dysphoric mood is often associated with difficulties in concentration (Lyubomirsky et al., 2003), complex problem solving (Lyubomirsky et al., 2003; Lyubomirsky & Nolen-Hoeksema, 1995), and impaired work strategies (Lyubomirsky et al., 2003). Therefore, it seems that a dysphoric mood does not necessarily increase the risk of more severe, or earlier, fatigue related decrements in engagement and performance on a cognitive task.

There are several explanations for the absence of divergent fatigue effects in dysphoric versus non-dysphoric students. One explanation is that dysphoria does not have such a profound impact on available cognitive resources, like attention, as initially thought. Although, some studies have suggested that the rumination that is associated with mood disorders uses cognitive resources that may diminish performance (Nolen-Hoeksema, 2000), others have observed that rumination often becomes a more automated bottom up process that has a relatively small load on cognitive resources (Andersen & Limpert, 2001; Bargh & Tota, 1988). In as far as the conclusions from the later studies are correct, it could be an explanation for why dysphoria does not have an additional detrimental effect on performance during mental fatigue. Another explanation for the absence of divergent fatigue effects may be found in sample we used. First of all, our group consisted mainly of relatively young academic students. While evidence for an age-related explanation of dysphoria remains limited, there are studies suggesting that performance decrements are mainly visible in the elderly population (Hayslip, Kennelly, & Maloy, 1990). Yet, there are other studies reporting the exact opposite (Kim, Kim, Kim, Baik, & Yang, 2003).

Also with regard to the present sample, it must be noted that participants were dysphoric students, which indicates that they had a relatively low level of depression. Because few researchers have compared dysphoria and more severe depression directly, it is still an open question whether results obtained with dysphoric samples generalize to clinically depressed participants (Gotlib & Joormann, 2010). However, the use of a dysphoric, instead of a severely depressed subgroup, could also be seen as a strong feature of our study. The dysphoric group we used is much more likely to be part of the student or working population, while individuals with severe episodes of a depressive disorder are more likely to discontinue their study or work activities. Therefore, the impact of fatigue-related decrements in performance could, in practice, have a much larger effect within the dysphoric population. Based on the results from our study, however, we conclude that dysphoric mood is not necessarily an increased risk factor for impaired sustained performance on cognitive tasks that may induce mental fatigue.

CHAPTER 7

Summary and general discussion

INTRODUCTION

The central aim of this dissertation was to examine how motivation influences fatigue and through what psychophysiological mechanisms it influences cognition. With this aim in mind, task disengagement, which is defined as an affective, cognitive, and motivational state of commitment to mobilize effort in order to reach task goals, while ignoring task-unrelated stimuli (adapted from Matthews et al., 2002), was one of the core concepts. Due to the presumed multifaceted nature of fatigue and task engagement, multiple indicators of task engagement were measured within a well-established fatigue paradigm. Specifically, we used a set of subjective, behavioral, and psychophysiological measures of fatigue and task engagement. Utilizing this approach, this dissertation brings forth at least three major contributions that will be discussed in this chapter. First, in part 1 of this chapter, closely following the central aim for the thesis, I will discuss the contribution of the studies towards the formation of a psychophysiological model for mental fatigue, which revolves around the locus-coeruleus norepinephrine neurotransmitter system (LC-NE system). The observed flexibility of this psychophysiological model has pointed out a second contribution of this thesis. Because the negative effects of fatigue appeared to be reversible by manipulating motivation for task engagement, this thesis contains strong evidence against classical resource depletion approaches. This evidence will be discussed in part 2 of this chapter. In part 3, the limitations, implications, and future directions will be discussed. Part 3 also includes a third major contribution of this thesis. While it was not part of the central aims of this research project, the objective measurement of task engagement has shown to be very consistent during all studies in this thesis. This observation has a very important implication for the future of applied science research (e.g., organizational and educational psychology), because there is a dire need for strong objective variables. Within these fields, task engagement can serve both as a predictor and outcome variable. In part 3, I will present examples for future studies. Finally, this chapter will be concluded by a short summary highlighting the most important conclusions.

PART 1: THE PSYCHOPHYSIOLOGY OF MENTAL FATIGUE

The first aim of this dissertation was to gain more insight in the psychophysiological substrates of attention and performance during mental fatigue. To address this aim, the studies were focused on the role of a psychophysiological system that is assumed to play a role in regulating task engagement, the LC-NE system (Aston-Jones & Cohen, 2005). A previous series of studies had already provided initial support that the LC-NE system is involved in decisions about whether to engage in, or disengage from, the task at hand. Most of these previous studies focused on an LC-NE output mode in which high baseline and stimulus-evoked levels of NE lead participants to explore the environment at the expense of reduced task performance (e.g., Cohen, McClure, & Yu, 2007). In the present dissertation, however, it is suggested that especially the often neglected output mode, characterized by low amounts of cortical norepinephrine (NE) at both the baseline and the stimulus-evoked level, may be relevant for fatigue research because this mode has been described to lead to diminished attention, disengagement from the task at hand, and low vigor in general. These effects are very similar to the effects that are typically observed when people are in a state of mental fatigue (Boksem et al., 2006; van der Linden, Frese, & Sonnentag, 2003). In the previous chapters of this thesis, the foundations for a psychophysiological framework for mental fatigue, based on the LC-NE system, have been established.

During the experiments, participants performed a classical time-on-task paradigm to induce fatigue. They worked on a visual letter n-back task in 1-back, 2-back, and/or 3-back variants. The n-back task has been used successfully in previous experiments to induce mental fatigue (Massar et al., 2010). It is a cognitively demanding task that requires the sustained engagement of working memory and attention in order to uphold adequate levels of performance (Watter et al., 2001). The experimental tasks were divided in several time-on-task blocks, without rest between the blocks. During the experiments we measured levels of subjective fatigue and engagement, objective task performance, and various indicators of task engagement and the LC-NE system, such as pupil diameter (Chapter 2 through 6), pupil dilation (Chapter 3, 5, and 6), the P3 event-related potential of the electroencephalogram (Chapter 2 and 4), and gaze direction (Chapter 4). By comparing the progression of all these different measures, we were able to relate task engagement and activity of the LC-NE system to varying levels of mental fatigue. In Figure 7.1, an illustrative model of the role of task engagement and the LC-NE system during mental fatigue is presented. This figure will be used to support the argumentation in this chapter.

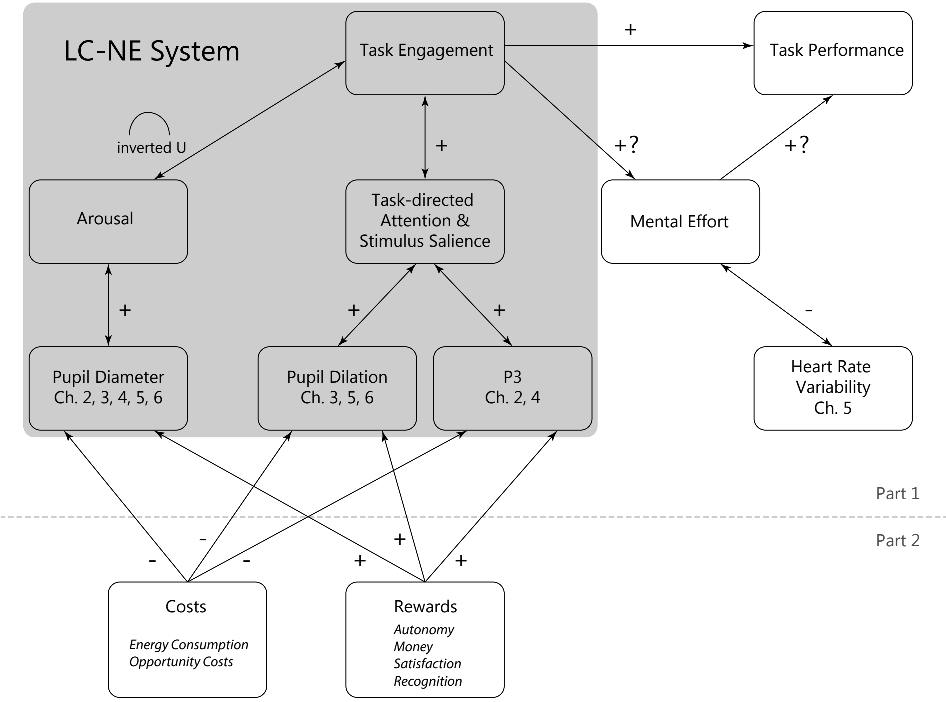

Figure 7.1. An illustrative model of the mechanisms that are described in this thesis. The top part is mainly discussed in part 1 of this chapter and reflects the role of the LC-NE system in task engagement and mental fatigue. The bottom part is mainly discussed in part 2 of this chapter and reflects the influence of motivational tradeoffs between costs and rewards on the LC-NE system during fatigue. Note that this model is meant for illustrative reasons and the arrows do not necessarily reflect causal relations.

THE LC-NE SYSTEM DURING MENTAL FATIGUE

Because task engagement is a broad concept involving affective, cognitive, and motivational components, multiple psychophysiological indicators of task engagement were used to assess LC-NE activity in this dissertation. While all of these measures reflect parts of the broader concept of task engagement, they also reflect different sub-processes of the LC-NE system. Pupil diameter, for example, can be seen as a measure that reflects the amount of physiological arousal (i.e., a baseline level of task engagement; Beatty, 1982), and the P3 is more reflective of the selection of motivationally significant events (i.e., stimulus-evoked levels of task engagement/task-directed attention; Polich, 2007). At the same time, these measures have also been shown to overlap with the baseline (pupil diameter) and stimulus-evoked (P3, pupil dilation) levels of cortical NE released by the locus coeruleus (Murphy et al., 2011; Nieuwenhuis et al., 2005). With regard to our fatigue paradigm, the study in Chapter 2 showed that with increasing time-on-task, there was a pronounced and significant decrease in both pupil diameter and P3 amplitudes with increasing levels of reported fatigue. This may indicate that a generally lowered amount of NE was released. Along with the decreasing task engagement, we also observed a decrease in task performance (i.e., accuracy, measured in d-prime). A very similar pattern was observed in the studies in the following chapters. While a schematic model of these findings is presented in Figure 7.1, Table 7.1 gives a specific overview of the effect that time-on-task had on subjective and objective measures of task engagement during each of the conducted studies.

To support the idea of relatedness of the various measures, several multilevel correlational analyses were conducted to investigate the associations of the different measures over time. The correlations were generally very strong between the P3 amplitude, pupil diameter, pupil dilation, task performance (d-prime), and the subjective measures of fatigue and engagement (with the correlation of subjective fatigue being a negative one) during each of the five separate studies. Therefore, the hypothesized role of the LC-NE system in task engagement and performance during mental fatigue is consistently supported by our findings. Although the support for the involvement of the LC-NE system during fatigue is relatively strong, I must note that because of the correlational nature of the evidence, the suggested links in the model are based on my estimation and not necessarily causal. When inspecting Figure 7.1, it is also noteworthy that this thesis has especially focused on the processes involved in the emergence of task engagement and disengagement during fatigue. All studies investigated a part of the link between the dynamics of the LC-NE system and task engagement during mental fatigue. In each of the chapters, these dynamics eventually led to disengagement when fatigue kicked in and this disengagement was strongly associated with decreased task performance. However, because it was not the main focus of this thesis, the link between task engagement and task performance has only briefly been investigated in chapter 5. Classical fatigue studies have specifically related problems with mental effort to decreased task performance during fatigue (e.g., Meijman, 1997). Therefore, in the study in chapter 5, initial steps were taken to see whether mental effort could serve as a mechanism that connects task disengagement to decreased task performance during mental fatigue. While the results of the study where confirming that mental effort decreased alongside a decreasing task engagement and task performance, more research should be conducted to verify these idea's. I hope that the vision and methods of this study (the first fatigue study in nearly two decades that utilizes the low-frequency domain of hearth-rate variability to index mental effort) may inspire others to further investigate this link in the model.

Table 7.1. The main effects of time-on-task in each chapter

	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6
Subjective fatigue	↗	↗	↗	↗	↗
Subjective engagement	↘	↘	↘	↘	↘
P3 amplitude	↘	–	–	↘	–
Baseline pupil diameter	↘	→	↘	↘	↘
Stimulus-evoked pupil dilation	–	↘	–	↘	↘
Task performance	↘	↘	↘	↘	↘

Main effects of time-on-task on the key variables used in this thesis. Arrows depict an increasing, stable or decreasing effect over time. A hyphen is used when the variable was not measured during the study.

RELIABLE MEASUREMENT OF LC-NE SYSTEM ACTIVITY DURING FATIGUE

In this thesis, we have used several indicators of LC-NE system activity. As can be inferred from Table 7.1, these indicators have shown to be very consistent and reliable in our fatigue paradigm. While all of the measurements are consistent, there are also some concerns one should keep in mind to ensure reliable measurement of these LC-NE indicators. Looking at Table 7.1, in can be noted that slightly deviating from the otherwise very consistent pattern, we did not find the hypothesized decrease in baseline pupil diameter during the first blocks of the experiment in Chapter 3. We predicted, based on the LC-NE theory of Aston-Jones and Cohen (2005), that the shift from task engagement to task disengagement would be accompanied by a shift from large stimulus-evoked pupil dilations and an intermediate baseline pupil diameter to small stimulus-evoked pupil dilations and baseline diameter. While this suggests that there is a larger range for the effect at the stimulus-evoked level (i.e., from high to low levels provides a broader range for change than the baseline levels that are hypothesized to change from intermediate to low levels), we still expected to see a change in the baseline pupil diameter as well. In this particular study, this was not the case. Because there are also no increases we have no reason to suspect that the observed disengagement was caused by distraction and exploration behavior, as would be predicted by the tonic mode of the LC-NE model (Cohen et al., 2007). Another explanation for the absence of the pupil diameter effect along the same line of reasoning is that, because baseline pupil diameter is often related to the amount of experienced physiological arousal (e.g., Beatty, 1982), participants were only mildly aroused at the start of the study. Compared to the studies reported in Chapters 2 and 4, in which we did find the decreased pupil diameter effect with increasing time-on-task, the study in Chapter 3 had a much less arousing lab environment (i.e., without EEG setup, which gives the room more of a laboratory feel). This could have resulted in a 'floor effect' for initial levels of arousal, and would imply that there was only a limited range for decrease. This finding exemplifies how important study design is, when measuring LC-NE activity during mental fatigue. Because of the complex nature of the baseline and stimulus-evoked aspects of the system, it is very important to monitor initial levels of arousal in order to leave enough space for a possible effect with time-on-task.

Another factor that can potentially influence the measurement of the LC-NE via the pupil is ambient light and screen luminosity. Because the pupil is very sensitive to light from any source, it remains difficult to create experimental conditions that control for all sorts of disruption. Because of this, many studies that focus on pupil dynamics (especially stimulus-evoked dilations) have mainly used auditory stimulation instead (e.g., Gilzenrat et al., 2010; Murphy et al., 2011). While this may not be a major concern in some experimental paradigms, most experiments on mental fatigue and self-control rely on visual stimuli. Also, using a visual task increases the ecological validity because in practice, fatigue usually derives from tasks that have visual components (e.g., fatigue during driving or surgery). Due to these advantages of visual tasks, we neutralized all differences in stimulus-emitted and ambient light in chapter 3, 5 and 6. This showed that when carefully controlled for, ambient and screen light do not have to be a major issue when measuring pupil dilation as an indicator during mental fatigue.

One last issue with regard to measuring the activity of the LC-NE system during fatigue that deserves more discussion is whether it is also consistent across different samples. Most of the samples that were used in our studies were very similar (i.e., university students). Although the use of university students is widely accepted and generally tends to generalize to the general population, we tested a very different sample in Chapter 6 to see whether the findings are still robust when extrapolated to other populations. Because tiredness, low energy, and listlessness belong to the most common symptoms (apart from the depressed mood itself) to be associated with depression (Demyttenaere et al., 2005; Stahl,

2002) we were interested to see whether the psychophysiological effects of fatigue diverge in individuals with a mild form of depression. We also directly compared whether individuals with mild depressive symptoms (i.e., dysphoria) diverge from their non-depressive counterparts in their susceptibility to the effects of mental fatigue (i.e., earlier onset, more severe effects on performance). In line with the findings in the previous chapters, we found that subjective, performance, and psychophysiological measures of task engagement (in this case pupil dilation) decreased with increasing time-on-task. While we found that the dysphoric group reported relatively higher subjective fatigue than the healthy control group during the early stages of the experiment, we did not find any other divergent fatigue effects during the experimental task. These results are an example of the robustness of the link between mental fatigue and the LC-NE system. Although the mildly depressed participants reported to be more fatigued than their non-depressive counterparts, they showed a very similar pattern with increasing task-induced fatigue and task disengagement. Therefore, the results of the study reported in Chapter 6 make two main contributions. First, they constitute a replication of the findings in Chapter 2 through Chapter 5 in a different sample showing the consistency of the observed LC-NE system effects. Secondly, we conclude that depressed mood is not necessarily an increased risk factor for impaired sustained performance on cognitive tasks that may induce mental fatigue.

THEORETICAL CONTRIBUTIONS TO THE LC-NE LITERATURE

Summing up, the studies in this thesis present consistent evidence that mental fatigue and decreased task performance coincide with various indicators of LC-NE system activity. The combined results of the studies in this dissertation give a clear indication that fatigue is consistently related to a range of presumed LC-NE system indicators. The question that remains is how these findings can be integrated in existing fatigue and LC-NE theories. The most influential theory on the LC-NE system is the Adaptive Gain Theory by Aston-Jones and Cohen (2005). Most of the recent studies using the LC-NE theory have exclusively focused on comparing the tonic versus phasic output modes of the LC-NE system in order to predict suboptimal task performance (e.g., Cohen et al., 2007). This implies that the majority of these studies mainly looked at the output modes representing the middle and right-side of the Yerkes-Dodson inverted U-curve (see Figure 7.2). The combined results of the studies in this dissertation, however, indicate that increased mental fatigue coincides with decreased baseline and decreased stimulus-evoked levels of NE. Therefore, these studies suggest that there is a third possible output mode of the LC-NE system, which reflects the left side of the Yerkes-Dodson inverted U-curve and concurs with a general disengagement and a decrease in performance on tasks that demand attentional focus. This output mode could be labeled as the disengage mode and complements the well-studied phasic and tonic modes. With the addition of the disengage mode, the full range of the Yerkes-Dodson inverted-U curve is now covered. The phasic mode is associated with exploitation behavior, characterized by task engagement in order to maximize the potential rewards of a task. This mode is optimal for maximizing task performance. The other two modes are related to impaired task performance, but in a different way. The tonic mode is associated with increased exploration behavior, characterized by distraction from the task in order to explore the environment for alternative, and potentially more rewarding, options. Operating in this mode leads to engagement, but there is no clear focus on the task (i.e., task engagement is still impaired) which harms performance. The disengage mode that has emerged from the studies in this thesis, is also characterized by reduced task engagement and declined

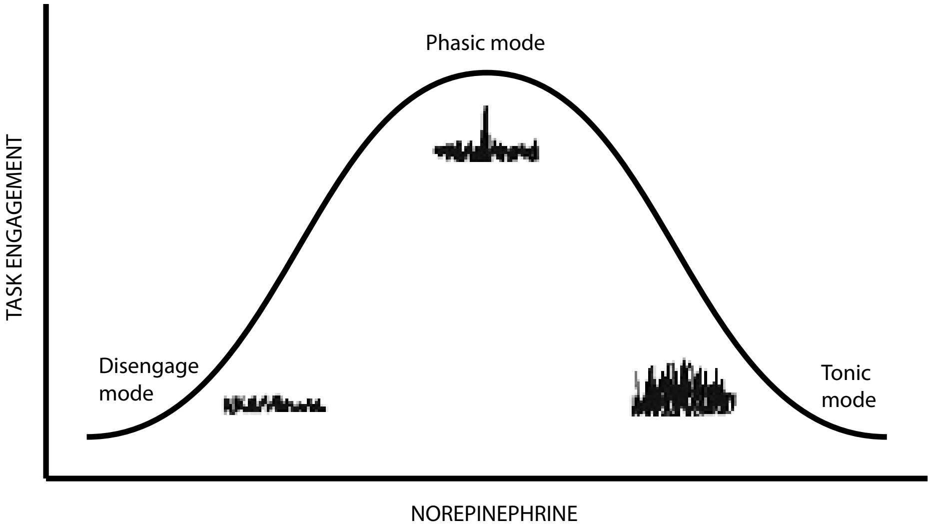

Figure 7.2. This figure displays the suggested output modes of the LC-NE system. The addition of this thesis is the disengage mode on the left side of the curve, which is characterized by low levels of norepinephrine and task engagement. The plots beneath the curve display typical NE release over time. Where the disengage mode and tonic mode have very stable low and high NE release respectively, the phasic mode is much more sensitive to specific task-related stimuli which results in peaks of NE release.

performance. Yet, in contrast to the tonic mode, the disengage mode involves a tendency towards a more general withdrawal from interaction with the environment. Such a tendency fits the presumed functionality of mental fatigue as described in the literature (Meijman, 1997). Specifically, mental fatigue is assumed to be a state protecting against the depletion of cognitive resources (Hockey, 1997, 2011). In situations in which one has already deployed many resources (extended continuous performance) or in an environment that does not provide rewarding alternatives to engage in (boring or isolated environment), it may be useful to conserve energy. This grants time to recuperate and restore resources, or to save them for more rewarding opportunities that may occur in the near future. The conservation of resources may be an important function of the proposed disengage mode of the LC-NE system. In part 2 of this chapter, I will elaborate on this function in more detail. There, I will also discuss what could drive the LC-NE system from one mode to another. When does one start to conserve resources and under what conditions is task engagement stimulated? Later, in part 3 of this chapter, I will discuss how my extension of the LC-NE system impacts the fatigue literature in general, and how future studies can take advantage of these innovations.

PART 2: TASK ENGAGEMENT: A SONG OF COSTS AND REWARDS

The second aim of this dissertation was to get more insight in the role of motivation during fatigue. The line of thought from part 1 of this chapter, which suggests that the LC-NE system plays a role in the cognitive and behavioral effects of mental fatigue, implies that influencing the LC-NE system could possibly reverse the effects of mental fatigue. To be more specific, because we knew that the output mode of the LC-NE system depends on the tradeoff between the costs and rewards of a task (Aston-Jones & Cohen, 2005), we expected that changing the rewards of a task may influence the effects of mental fatigue. It is acknowledged that exerting effort to stay focused while performing a cognitive task in a state of fatigue can be considered as cost in this cost/reward tradeoff (Boksem & Tops, 2008). Consequently, when one is getting fatigued, resistance against further effort will increase and it will become more difficult to remain engaged in the task (van der Linden, 2011). Because the costs increase and the potential rewards of the task remain similar, or may even decrease, the cost-reward tradeoff becomes more unfavorable. This may drive the LC-NE system to operate in the aforementioned disengage mode.

To see whether an increase in the task rewards would positively influence the cost/reward tradeoff and lead to task re-engagement, we included a manipulation in Chapter 2, 3 and 4, in which we increased the rewards for engaging in the demanding task after participants had already worked on it for two hours. In all three chapters, we observed that after we increased the rewards, the P3 amplitude, pupil diameter and pupil dilation returned to values that compare to those at the start of the experiment, even though the participants were already working on the task for two hours and reported high subjective levels of fatigue. These results show the flexibility of task engagement during periods of mental fatigue, and its responsiveness to contingencies in the environment. Alongside the reengagement effects, we also observed that task performance was restored to levels that compared to, or even exceeded, the performance at the start of the experiment. Previous studies have shown that under the right circumstances (i.e., when the rewards are high), participants are able to uphold task performance for a long time, even under high levels of mental fatigue (Boksem et al., 2006; Eccles & Wigfield, 2002; Tops & Boksem, 2010). The results of our studies confirm this effect of motivation. An innovative aspect of our set of studies is that we specifically showed that the presumed indicators of the LC-NE system are sensitive to the motivational manipulation as well. Multilevel analysis of the data pointed out that over the course of the whole experiment, the P3 amplitude and pupil diameter follow a very similar trajectory as subjective task engagement and objective task performance. This underpins the role that task engagement and the LC-NE system play in sustained task performance during fatigue.

THE MYTH OF DEPLETED RESOURCES

Recently, the role that subjective experience plays in task disengagement and task performance during time-on-task studies has received much attention. In many recent articles on self-control and mental effort there is increasing attention for the role of motivational aspects of the task (Inzlicht et al., 2014; Inzlicht & Schmeichel, 2012), but empirical evidence for this approach has remained scarce. Therefore, this doctoral dissertation makes an important contribution to the literature. It shows that the manipulation of task rewards has a strong effect on task engagement and performance when individuals are fatigued. I argue that this has strong implications for classical resource depletion theories that, to date, remain very influential.

Probably the most well-known and influential resource depletion theory is Baumeister's ego depletion theory (Baumeister et al., 1998). In their early work, Baumeister and colleagues tested participants' performance on a difficult or frustrating task. Half of the participants had to resist a certain temptation before they conducted the performance test. For example, in one experiment this group had to resist the temptation to eat chocolate and force themselves to eat radishes. Baumeister and colleagues showed, that participants who had to resist temptation first, gave up much quicker on the subsequent difficult or frustrating task. They concluded that, both forms of self-control drew from the same limited resource, and that exerting self-control for a period of time depletes this resource. With a reference to Sigmund Freud's *ego*, which suppresses the urges and desires of the *id*, this process was dubbed *ego depletion*. Ego depletion has been further conceptualized in the past twenty years as a depletion of a limited resource for self-control caused by engagement of effortful control (Baumeister, Muraven, & Tice, 2000). When this capacity is depleted, ego depletion predicts that further efforts of self-control are prone to failure. During mental fatigue, failures in self-control are often seen as the main reason for impaired performance during demanding tasks (cf. Hockey, 2013). In the context of mental fatigue, this resource depletion approach views the brain as a muscle that can be exhausted after repeated investment of mental effort. Just like muscle fatigue, this approach argues that mental fatigue impairs sustained performance and rest is needed to replenish it.

Other common analogies for ego depletion are that *one's batteries are running low*, or *the tank is empty*. Staying with this analogy, the resource depletion theory would predict that if the participants in this dissertation were a car, they would get fatigued with increasing exertion of effort and time on task. This would then not only lead to the tank running empty (i.e., increased fatigue and decreased disengagement), but also the headlights of the car would get faded, and the steering wheel would become less responsive (i.e., decreased P3 amplitude). Probably the blinkers would also stop working, because the battery would not get charged anymore (i.e., decreased pupil diameter and dilation). So far, this analogy seems to work fine. In this conceptualization, it seems very hard for the car to perform like it is supposed to perform. Driving a car like this could potentially lead to dangerous situations and accidents. However, the problem with this analogy is that the only way to get the car's performance up again, would be to stop the car, fill the tank, and charge the battery. The studies in this dissertation however, have shown that motivation can be used to restore performance, without stopping and refilling the tank. We found that increasing the rewards for task engagement redirected attention significantly towards task-related stimuli, and completely restored task performance. This suggests that participants were able to overcome their psychophysiological and subjective state and reengage in the task. Therefore, while from the ego depletion point of view, fatigued participants are seen as a car with trouble (i.e., empty tank, broken headlights etc.), it seems much more likely that participants are the drivers who are operating the car instead. Following this change of view, a more precise analogy would be that the car's tank and battery are actually not completely empty. The problem is not the car that cannot drive anymore, but that the driver doesn't want to drive it anymore. The participants, who are already metaphorically driving for several hours, may decide to lower the speed to conserve gas and switch to a less demanding driving style. In their head, the radio is continuously playing a song about costs and rewards. And when the costs and rewards get out of balance to much, the driver may get disengaged from the other cars and the road and the danger of accidents increases.

From these analogies, it becomes clear that ego depletion is not able to explain the effects of mental fatigue on behavior and task performance. We favor an explanation of the effect of fatigue in terms of cost/reward tradeoffs. An interesting theory that can be used to explain the costs and rewards of engaging in a task is the opportunity cost model of Kurzban and colleagues (2013). These scholars also adopt the view that effort and self-control depend on the mental representation of the costs and benefits of the activity at hand. From a range of possible activities, one will often pursue the one that is most rewarding. Because cognitive systems, like attention, can only be deployed for a limited number of simultaneous tasks, Kurzban and colleagues propose engagement depends on the level of motivation to pursue the next-best task to which these systems may be used. These so-called opportunity costs are experienced as effort and result in reduced task engagement and performance. For example, while you could be relatively motivated to focus on your work, there could be other activities on your mind that you are even more motivated for. Therefore, you could experience high levels of effort to stay engaged in a relatively rewarding activity, when there are more rewarding alternatives. In our studies, the rewards of a task could be stable or may even decrease with increasing time-on-task (i.e., because the task becomes less challenging or interesting), while the opportunity cost of not engaging in other possible activities increases. This results in an imbalance between the costs and rewards of the task that eventually leads to disengagement. When the motivation to engage in the task becomes too low, and there are no immediate alternative tasks to engage in, fatigue serves as a stop emotion that protects individuals from overspending energy, and conserve it for the moment that a more rewarding activity presents itself (Hockey, 2011; van der Linden, 2011). When sufficient task rewards are presented (i.e., after the rewards manipulation), the imbalance between costs and rewards can be restored and participants will reengage in the task.

PRACTICAL IMPLICATIONS OF BREAKING THE MYTH OF RESOURCE DEPLETION

Because of the popularity of the resource depletion approach, many fatigue countermeasures are based on principles that derive from depletion theories. Now that we know that there are situations in which these theories fall short on adequately explaining the effects of fatigue, it is important to consider the possibility that the interventions that derive from these theories may also be suboptimal. Therefore, I will shortly describe the most conventional fatigue countermeasures, and the principles that they are based on, and critically evaluate the implications of the findings from this dissertation.

In essence, all resource depletion counter-measures are focused on the restoration of the resource or the enhancement of this resources' capacity. During the first decade after Baumeister's original study in 1998, there has been a lengthy debate about what this resource could actually be. Eventually, the group around Baumeister presented blood glucose levels as the main prospect for the limited energy source (Gailliot et al., 2007). Gailliot and colleagues found that the depletion of blood glucose levels would lead to failure of self-control and that restoring glucose levels (e.g., by drinking high glucose drinks) improves self-control. However, many attempts to replicate these findings have failed. For example, Lange and Eggert (2014) gave half of their participants a high glucose drink and the other half an artificially sweetened drink between two self-control tasks. They did not find any counteracting effects of the glucose drink. In another study that failed to find a connection between glucose depletion and problems with self-regulation, Kurzban (2010) even suggested that because there is no plausible candidate for the putative energy resource, the resource metaphor should be abandoned. He goes on stating that from a computational perspective, the resource account is the wrong kind of explanation for performance decrements to begin with, and that correct explanations might be found in the domain of computation. The results of this thesis underpin these claims and suggest that looking at psychophysiological processes that involve utilitarian tradeoffs between costs and rewards are worth considering. There could be ways to temporarily override the effects of fatigue tapping into the processes that lead to task engagement. When resorting to the use of stimulating substances, it may be worth looking into those substances that directly (e.g., NE stimulating substances such as NE reuptake inhibitors) or indirectly (e.g., stimulating the sensitivity to reward by substances such as dopamine agonists) stimulate the LC-NE system, instead of blood glucose levels.

The use of stimulating substances could in many cases (e.g., at work or in sports) be a measure that is too extreme and invasive. Therefore, a more subtle intervention is often preferred. Traditional work recovery strategies are often focused on types of activities between workdays or workweeks, to ensure one is well rested at the start of the next workday or week. Sonnentag and Fritz (2007) distinguish three main categories in which these activities may be placed. They describe: a) relaxation activities, in which one minimizes mental or physical workload, b) detachment activities, that can be more active and focus on changing one's mind from work to something else, and c) mastery experiences, where one develops their skills in other domains and thereby increases positive affect. While all of these types of activities possibly lead to recovery and could be very beneficial to prevent errors that are caused by fatigue, they provide more of a long term solution. When you are already fatigued on a Tuesday, relaxation activities that are planned for the next weekend are still very far away and do not help your performance and well-being during the upcoming workdays. Therefore, we also need sustainable ways to have a more immediate effect on fatigue and its dangers. A good option for this could be to apply measures that prevent situations in which fatigue is likely to occur. The information from this thesis could be used to predict these situations more precisely.

Traditionally, based on the limited resources approach, fatigue is often expected after long consecutive hours of work. Therefore, work times and shifts are introduced to provide small recovery moments. While having enough breaks could certainly be helpful (e.g., Trougakos, Beal, Green, & Weiss, 2008), the timing of those breaks is often based on traditions and habit, rather than elaborate thoughts about task demands. For example, imagine a surgeon who has to operate on many people over the course of a workday. The traditional approach to make sure that these surgeries go according to plan and do not suffer under the influence of fatigue, is to regulate the amount of time between surgeries. However, assuming surgeons are well-rested physically, the cost-reward tradeoff during surgery is actually very positive. The stakes are high, and there is a high probability that a surgeon likes to engage in the activity of operating, assuming this is why he or she became a surgeon in the first place. Therefore, mistakes that are caused by mental fatigue may actually be relatively uncommon in these situations. However, one could also expect that the preparations and piles of administrative work that have to be done before and after the surgeries, is not one of the surgeons' favorite activities to engage in. Therefore, I would predict that these are the times that errors, caused by mental fatigue, occur most commonly and could lead to catastrophic events (e.g., a patient getting a wrong dosage of medicine). Based on my findings, I propose to not only look at the energetical state of a person, but also take the characteristics of the work activities that person has to engage in into account. This way, one could craft interventions and protocols that ameliorate fatigue when it is needed the most. One way to do this would be to increase job resources (e.g., allowing more autonomy or providing more social support), at those moments fatigue is most likely to occur (cf. JD-R theory; Bakker & Demerouti, 2014).

PART 3: CONQUERING FATIGUE: HOW FAR DID WE GET AND WHAT BATTLES LIE AHEAD?

Summarizing and discussing the results of the studies shows that the present dissertation contributes to new insights into the psychophysiology of mental fatigue and the influence of motivational cost/reward tradeoffs in this process. This dissertation lays the foundation for mental fatigue models that incorporate the LC-NE system to explain task disengagement and decreased task performance during episodes of mental fatigue. But where do we go from here? In what ways does the information in this dissertation enhance the reality of the world around it? What questions arise from these studies and how do they apply in practice? In the remainder of this chapter, I will critically point out what challenges still lay ahead and speculate about the implications of these findings for future directions.

The first topic that deserves further elaboration, is the place of the LC-NE system in the human psychophysiology of fatigue as a whole. While the studies in this dissertation are the first to extensively investigate the role of the LC-NE system during fatigue, other systems have also been associated with mental fatigue and the way they influence cognition and performance. Based on various psychophysiological markers, it has been suggested that the dopamine pathways, that are involved in the evaluation of reward information, also play an important role in the effects of mental fatigue (e.g., Lorist et al., 2009). Examples of psychophysiological indicators that were used include brain potentials like the Error Related Negativity (ERN) and the novelty P3a. With a relatively similar manipulation of task rewards, Boksem and colleagues (2006) showed that after two hours of cognitive performance, fatigued participants could partly restore their performance when they would receive a monetary reward. This effect was accompanied by an increase in error related negativity ERPs, which they considered as support for involvement of the dopaminergic reward systems in the fatigue-related decline of performance.

Because the human brain consist of a very complex network of interrelated neuronal connections and neurotransmitter systems, it remains very complicated to isolate a specific system and assign it the label of most important system during a specific set of behaviors. This also seems to be the case for mental fatigue. The approach of such a complex neural network is supported by strong projections to the LC from the orbitofrontal and anterior cingulate cortices (Aston-Jones et al., 2002; Rajkowski et al., 2000), which are known to be important in the evaluation of the rewards and costs of a task and interact with the dopamine system (Gottfried et al., 2003; Holroyd & Yeung, 2012; O'Doherty et al., 2001; Yeung et al., 2005). Therefore, it seems likely that multiple interrelated systems lead up to the characteristic disengaged behavior that is often observed during mental fatigue. Based on the findings in this dissertation, I argue that at least the LC-NE system is very important in regulating engagement versus disengagement during periods of mental fatigue. What would help to disentangle the specific role of certain neurotransmitter systems to a great extent, is a more direct measure of activity of this system in the human brain. In the past years, imaging techniques have had great difficulties to focus on small and deep structures, such as the locus coeruleus. Now that functional magnetic resonance images (fMRI) have evolved, the immediate future may provide more direct insight in these specific small nuclei. An early attempt at such a scan comes from a study by Murphy and colleagues (2014), which shows that pupil diameter covaries with BOLD activity in the human locus coeruleus. This seems to provide additional evidence that the presumed pupil-LC link is well-grounded, and strengthens my conclusions in this dissertation about the involvement of the LC-NE system based on these indirect indicators (i.e., pupil diameter and pupil dilation).

Apart from exploring the role of the LC-NE system in the psychophysiology of fatigue, it is also interesting to speculate about the role of fatigue in daily human life. For example, knowing which neurocognitive systems drive the tendency to reduce task engagement after sustained performance, may also be relevant for developing a workplace environment that prevents mental fatigue or at least minimizes its negative consequences. After all, human factors and specifically mental fatigue, remain the most important reason for errors and accidents in the workplace (Baker et al., 1994; McCormick et al., 2012). Specifically the observation that, during mental fatigue, information is processed less efficiently and gaze could be diverted from focusing on task-related stimuli to exploration of the environment, impacts the direction of work safety and work performance interventions. For example, fatigue prevention measures are, to large extent, still based on the presumption that fatigue is caused by a loss of energy resources in the transportation and industry sectors. A common practice in the transportation sector to prevent fatigue related accidents, is to rest 15-20 minutes every couple of hours (European Commision Mobility and Transport, 2006; Federal Motor Carrier Safety Administration, 2014). Based on the results of this dissertation project, which points out the danger of disengagement when the cost/rewards trade-off becomes unfavorable, it seems worthwhile to also explore ways to motivate drivers to focus on the road again. This is particularly important, since resting for 15-20 minutes does not necessarily seem to change the costs or rewards for engaging in driving after the break. Therefore, only resting could still leave the driver disengaged from his or her primary task (i.e., driving safely). There is an interesting opportunity for future research to compare the efficiency of a motivational intervention, based on the ideas I have proposed in part 2 of this chapter, directly to traditional resting interventions.

The laboratory setting of the studies in this dissertation may restrict the possibilities for direct implementation to some extent, but it does lay a solid foundation for future studies that try to generalize the effects of mental fatigue in real-life settings. The study in Chapter 4 takes a first step in enriching the environment in which fatigue is tested by adding task irrelevant rewarding stimuli. While it was interesting to see how the introduction of face stimuli influenced a fatigued participant's attention towards the task-related stimuli, this form of distraction also has its limitations. Chapter 4 serves as a good example of the complexity of the rich real-life environment, in which even more different types of stimuli appear. To ameliorate the specific limitation of Chapter 4, future studies could examine whether other task-unrelated rewarding stimuli, that use more cognitive resources, are more harmful to task performance during mental fatigue. However, when it comes to measuring the effect of fatigue on attention in real-life settings, we have to advance even further and new research designs will be needed to account for the complexity of real life environments.

While there may be a challenge to develop new research designs that allow for broader generalization, there are also many opportunities to use the foundation this dissertation lays to test interventions that could improve safety and well-being. One particular example that comes to mind is to use the motivational cost/reward approach of this dissertation to design flexible workday schedules. In such a design, employees could be reminded (e.g., by a smart phone message) of the danger of disengagement when there is an impeding imbalance in the costs and rewards of the current activity. Effectively managing such reminders could give an autonomous employee the opportunity to switch tasks at the right time to maximize momentary work engagement. Maximizing momentary work engagement could subsequently have a positive effect on employee well-being and work performance (Bakker, 2014; Beal et al., 2005). The objective measures of task engagement we have used in the lab, would serve as a novel and very precise way to monitor effective work behavior. My expectation is that in the next decade comparable intervention studies, that use objective ways to measure engagement and performance, will shape the way we organize our professional (and possibly our personal) life in the future.

HIGHLIGHTS

- This doctoral dissertation had two main goals. The first goal was to define a psychophysiological framework for mental fatigue. The second goal was to get more insight in the role of motivation during fatigue.

- A classical time-on-task paradigm was used to induce mental fatigue. With increasing mental fatigue we observed that several indicators of activity in the locus-coeruleus norepinephrine system decreased. Based on the analysis of variance and multilevel correlations, I concluded that the locus-coeruleus norepinephrine system plays an important role in task disengagement that coincides with mental fatigue and the resulting impairments in task performance.

- To investigate the role of motivation during fatigue, we increased rewards to engage in the task after participants in the study where already highly fatigued. This reward intervention led to restored subjective engagement, objective task performance and (indicators of) activity in the locus-coeruleus norepinephrine system. Therefore, I concluded that motivational cost/reward tradeoffs guide engagement, and that fatigue can be seen as an adaptive state that signals conflict between what is being done and what else might be done. It signals us to stop working, long before our actual ability to work runs out.

- An important implication of the observation of fatigue as a 'stop emotion', rather than a depletion of energy resources, is that interventions based on a resource depletion approach may be unreliable or inefficient. New interventions that focus on fatigue as an imbalance between costs and rewards are worth the consideration.

- This psychophysiological framework for fatigue, based on the locus-coeruleus norepinephrine system, lays the foundation for future interventions. My expectation is that in the next decade innovative intervention studies, that use objective ways to measure fatigue, engagement and performance, will shape the way we organize our professional (and possibly our personal) life in the future.

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Nederlandse Samenvatting

(Summary in Dutch)

PROBLEMATIEK EN BIJDRAGEN

Mentale vermoeidheid, een toestand die wordt gekarakteriseerd door weerstand tegen verdere inspanning en veranderingen in stemming, motivatie en informatieverwerking, komt vaak voor wanneer iemand langdurig werkt aan cognitief veeleisende taken (Meijman, 1997; van der Linden, Frese, & Meijman, 2003). De hoeveelheid ervaren vermoeidheid kan fluctueren gedurende de dag, bijvoorbeeld als gevolg van dagelijkste werkeisen. Mentale vermoeidheid kan echter ook chronisch zijn en samengaan met ziekten en stoornissen zoals de ziekte van Parkinson (Chaudhuri & Behan, 2004), depressie (Demyttenaere, De Fruyt, & Stahl, 2005) en burn-out (Bakker, Demerouti, & Sanz-Vergel, 2014). Op het werk is mentale vermoeidheid één van de meest voorkomende oorzaken van ongelukken en incidenten (Baker, Olson, & Morisseau, 1994; McCormick et al., 2012). Ondanks het feit dat vermoeidheid vaak voorkomt en grote gevolgen kan hebben voor de werkprestatie en de veiligheid, zijn de psychologische mechanismen die ten grondslag liggen aan vermoeidheid relatief onbekend. Fundamentele vragen zijn: Waarom worden mensen überhaupt vermoeid? Wat is het nut van vermoeidheid? En hoe komt het dat vermoeidheid het cognitief functioneren en de taakprestatie zo drastisch kan beïnvloeden?

Het centrale doel van dit proefschrift was om te onderzoeken hoe vermoeidheid wordt beïnvloed door motivatie en via welke mechanismen dit cognitieve prestatie kan beïnvloeden. Tijdens het onderzoek was taak-betrokkenheid één van belangrijkste concepten. Taak-betrokkenheid is een affectieve, cognitieve en motivationele toestand van bereidheid om inspanning te leveren, om zo het doel van een taak te kunnen bereiken en taak-irrelevante stimuli te negeren (aangepast vanuit Matthews et al., 2002). Tijdens de studies in dit proefschrift is er een set van subjectieve, gedragsmatige en psychofysiologische metingen van vermoeidheid en taak-betrokkenheid uitgevoerd. Met de combinatie van deze metingen werden minimaal drie belangrijke bijdragen geleverd. De eerste bijdrage is nauw gerelateerd aan het centrale doel van het proefschrift. De studies in dit proefschrift dragen namelijk bij aan het formuleren van een psychofysiologisch model voor mentale vermoeidheid wat gebaseerd is op het locus-coeruleus noradrenaline systeem (LCNA systeem). De tweede bijdrage van dit proefschrift is de geobserveerde flexibiliteit van dit systeem. Omdat de negatieve effecten van vermoeidheid ongedaan kunnen worden gemaakt door de motivatie voor taak-betrokkenheid te manipuleren, levert dit proefschrift sterk bewijs tegen klassieke theorieën die uit gaan van de uitputting van energievoorraden. De derde bijdrage van dit proefschrift is dat objectieve taak-betrokkenheid erg consistent kon worden gemeten tijdens alle studies. Dit kan implicaties hebben voor toekomstig toegepast wetenschappelijk onderzoek (bijvoorbeeld in de arbeid- en organisatiepsychologie en de educatiepsychologie), omdat hier een grote vraag is naar sterke objectieve variabelen. Binnen deze onderzoeksgebieden kan taak-betrokkenheid zowel als voorspeller als uitkomst dienen. Hieronder worden de belangrijkste resultaten van de hoofdstukken uit dit proefschrift, die ten grondslag liggen aan de zojuist genoemde bijdragen, genoemd. Dit hoofdstuk wordt afgesloten met een algemene conclusie.

KORTE SAMENVATTING VAN DE UITGEVOERDE STUDIES

In **Hoofdstuk 2 en 3** werden de fundamenten voor een psychofysiologisch model voor mentale vermoeidheid gelegd. In een experimentele taak werd getoetst of mentale vermoeidheid samen hing met taak-betrokkenheid. Deelnemers aan het onderzoek moesten gedurende twee uur tijd aan één stuk door werken aan een n-back taak. Deze taak, waarin letters moeten worden onthouden en vergeleken met eerder getoonde letters, staat bekend door de grote hoeveelheid aandacht en taak-betrokkenheid die vereist is om de taak succesvol uit te voeren (Chen, Mitra, & Schlaghecken, 2008; Cohen et al., 1997; Watter, Geffen, & Geffen, 2001). Tijdens de taak werden, naast de subjectieve toestand van de deelnemers en de prestatie op de taak, ook de amplitude van de P3 golf in de hersenactiviteit (Hoofdstuk 2), pupilgrootte in rust (Hoofdstuk 2 en 3) en pupil verwijding na het tonen van de letters (Hoofdstuk 3) gemeten. Uit eerder onderzoek blijkt dat deze fysiologische metingen sterk samen hangen met activiteit van het LCNA hersensysteem (zie bijvoorbeeld, Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Nieuwenhuis, De Geus, & Aston-Jones, 2011). Uit de analyse van de data bleek dat met toenemende tijd op de taak, vermoeidheid toenam en dat taak-betrokkenheid en prestatie op de taak afnamen. Dit ging samen met een afname van P3 amplitude, de grootte van de pupil en de pupilverwijding. Na twee uur aan de taak te hebben gewerkt, en zeer vermoeid te zijn geworden, kregen de deelnemers te horen dat de resterende duur van het onderzoek afhankelijk was van de hun prestatie op het resterende deel van de taak. We vertelde hen dat afhankelijk van hoe goed ze het deden de resterende tijd tussen de vijf en veertig minuten kon bedragen. Het doel van deze manipulatie was om de motivatie voor de taak te vergroten. Dit bleek te werken, want taak-betrokkenheid nam na de manipulatie sterk toe. Ook prestatie op de taak, de P3 amplitude, de pupilgrootte en de pupilverwijding namen na de manipulatie sterk toe (naar waarden die vergelijkbaar of zelfs hoger waren dan bij aanvang van het onderzoek). Naar aanleiding van deze resultaten concludeerden we dat er inderdaad aanwijzingen zijn dat het LCNA systeem betrokken is bij prestatieveranderingen tijdens mentale vermoeidheid. Ook concludeerden we dat verminderde prestatie tijdens vermoeidheid samenhangt met motivatie voor de taak en niet enkel te verklaren valt door de uitputting van gelimiteerde energiebronnen.

Hoofdstuk 4 bouwt voort op het fundament dat gelegd is in de voorgaande twee hoofdstukken. Nadat duidelijk was geworden dat motivationele kosten/baten afwegingen belangrijk zijn tijdens mentale vermoeidheid, wilden we met deze studie verder onderzoeken wat de afname in taak-betrokkenheid tijdens mentale vermoeidheid nu precies omvat. Een belangrijke vraag die hierbij speelde was of de afname in taak-betrokkenheid na een geruime tijd op de taak ervoor zorgt dat deelnemers meer aandacht gaan richten op andere dingen die mogelijk meer belonend zijn. Het alternatief zou zijn dat de deelnemers hun aandacht nog steeds op de taak richten, maar deze minder effectief verwerken. Om meer inzicht te verkrijgen in deze twee mogelijkheden boden we tijdens dit experiment, dat verder identiek was aan het experiment in Hoofdstuk 2 en 3, naast de letters van de n-back taak ook alternatieve stimuli aan op het scherm die niets met de taak te maken hadden. Aan weerszijde van de letters lieten we plaatjes van gezichten zien. Het is bekend dat gezichten inherent als belonend gezien worden omdat ze een evolutionair adaptieve rol hebben en belangrijke sociale informatie kunnen bevatten (Johnson, 2005; Schmidt & Cohn, 2001). Omdat we op het scherm naast de taak-gerelateerde stimuli ook een belonende stimuli lieten zien die niets met de taak te maken had, konden we door middel van eye-tracking zien of deelnemers hun aandacht nog steeds op de taak richtten of dat zij in toenemende mate aandacht gaven aan de gezichten. Hoewel we vonden dat een afname van taak-betrokkenheid gerelateerd was aan een toenemende mate van het kijken naar de gezichten, konden we geen significante afname constateren in het kijken naar de taak. We kunnen daarom op basis van deze resultaten niet zeggen dat deelnemers over het algemeen vooral op zoek gingen naar andere belonende stimuli. Omdat de taak nog steeds ongeveer evenveel aandacht kreeg, lijken de terugnemende prestaties op de taak voornamelijk te worden veroorzaakt door een minder effectieve werking van de taak. Doormiddel van de eerder genoemde manipulatie, die de beloning van een goede prestatie op de taak vergroot, konden we wederom aantonen dat energiebronnen niet definitief uitgeput waren. Na de manipulatie nam de prestatie op de taak namelijk weer sterk toe. Dit ging gepaard met een toename in aandacht gericht op de taak en een bijna totale afwezigheid van het kijken naar de gezichten. Taak -betrokkenheid was dus weer hersteld, wat wederom aan geeft hoe belangrijk de rol motivatie is tijdens perioden van mentale vermoeidheid. Op basis van de resultaten van Hoofdstuk 2 tot en met Hoofdstuk 4 concludeerde we dat vermoeidheid er voornamelijk voor zorgt dat cognitieve bronnen niet onnodig belast worden op taken waar de opbrengsten niet genoeg af wegen tegen de kosten.

Hoofdstuk 5 bevat een studie die was gericht op het onderzoeken van de rol die mentale inspanning speelt tijdens vermoeidheid. Hoewel de voorgaande studies lieten zien dat kosten/baten analyses en taak-betrokkenheid een belangrijke rol spelen tijdens vermoeidheid, werd er in deze studies niet specifiek gekeken naar de hoeveelheid mentale inspanning die geleverd werd gedurende de taak. De rol van inspanning tijdens vermoeidheid wordt beschreven in belangrijke theorieën over strategische aanpassingen in taak-gerelateerd gedrag. Zo beschrijft Hockey (1997, 2013) bijvoorbeeld dat wanneer mensen moe worden ze, afhankelijke van de karakteristieken van de taak, hun niveaus van inspanning kunnen vergroten om zo de prestatie op de taak vast te kunnen houden. Dit is dan een tijdelijke strategische keuze die wel gepaard kan gaan met meer vermoeidheid en stress. Een alternatieve strategie is dat men door vermoeidheid de inspanning juist verlaagd en daarmee een lagere taak-prestatie accepteert. In de studie in Hoofdstuk 5 gebruikte we een fysiologische indicator van mentale inspanning om te testen of deelnemers hun inspanning tijdens de taak inderdaad proberen te vergroten om de negatieve gevolgen van vermoeidheid tegen te gaan, of dat mentale inspanning juist af neemt om daarmee cognitieve bronnen te besparen. De indicator van inspanning die we hiervoor gebruikte was de cardiovasculaire meting van hartslag variabiliteit in het lage frequentie domein (ook wel het .10Hz domein genoemd). Hoe hoger de variabiliteit in dit domein is, hoe lager de mentale inspanning tijdens de taak. Naar aanleiding van de analyses werd duidelijk dat variabiliteit gedurende de gehele periode van het experiment toe nam. Op grond van deze bevinding concludeerden we dat de hoeveelheid mentale inspanning gedurende de taak steeds verminderde. We konden wederom stellen dat wanneer de motivatie om op te gaan in de taak te laag wordt, vermoeidheid dient als een stop-emotie die ons beschermt tegen het gebruiken van cognitieve bronnen tijdens een taak met een te lage opbrengst.

De laatste studie van dit proefschrift, die in **Hoofdstuk 6**, testte of het veronderstelde psychofysiologische systeem van mentale vermoeidheid, zoals beschreven in Hoofdstuk 2 tot en met 5, ook stabiel is in verschillende populaties. Waar de overige studies uitgevoerd werden onder gezonde adolescenten, hebben we in Hoofdstuk 6 ook een steekproef genomen uit een klinische groep. Om specifiek te zijn hebben we gekeken of het psychofysiologische systeem voor mentale vermoeidheid op een zelfde manier functioneert bij een groep proefpersonen die tekenen vertoonden van een milde vorm van depressie. Deze groep geniet de specifieke interesse omdat naast de depressieve gedachten, vermoeidheid en lusteloosheid onder de belangrijkste symptomen van de depressieve stoornis horen (Demyttenaere et al., 2005). Depressie wordt door verschillende onderzoekers gelinkt aan lage niveaus van psychologische opwinding (de Lecea, Carter, & Adamantidis, 2012) en de cognitieve onttrekking bij depressie wordt vaak (deels) toegewezen aan gebrek aan motivatie en interesse. Dit zou ervoor kunnen zorgen dat vermoeidheid bij depressieve individuen eerder op treed, of dat de gevolgen van vermoeidheid binnen deze subgroep ernstigere gevolgen hebben op de taakprestatie. Dit onderzochten we Hoofdstuk 6 door de klinische steekproef direct te vergelijken met een gezonde steekproef. Net als in de vorige hoofdstukken, vonden we dat subjectieve vermoeidheid gedurende taak toenam, en dat taak-betrokkenheid (subjectief en fysiologisch gemeten) en taakprestatie afnamen. Hoewel we opmerkten dat de mild-depressieve groep een hogere mate van vermoeidheid rapporteerde bij de aanvang van het onderzoek, waren de effecten gedurende de taak gelijk aan die van de gezonde steekproef. Deze resultaten laten de robuustheid van de veronderstelde link tussen mentale vermoeidheid en het LCNA systeem zien. Daarnaast kunnen we op basis van dit onderzoek zeggen dat het hebben van een depressieve stemming niet noodzakelijk een extra risicofactor is, als het gaat om aanhoudende prestatie op een cognitieve taak die vermoeidheid kan veroorzaken.

CONCLUSIE

Dit proefschrift had twee belangrijke doelen. Het eerste doel was een psychofysiologisch model voor mentale vermoeidheid op te stellen. Het tweede doel was om te onderzoeken wat de rol van motivatie is tijdens vermoeidheid. Gebruik makende van een klassiek experimenteel vermoeidheid paradigma, induceerden we tijdens de verschillende studies in dit proefschrift vermoeidheid bij de proefpersonen. Met toenemende mentale vermoeidheid observeerden we dat verschillende indicatoren van activiteit in het locus-coeruleus noradrenaline systeem afnamen. Gebaseerd op variantieanalyses en multilevel correlaties, concludeerden we dat het locus-coeruleus noradrenaline systeem een belangrijke rol speelt bij de afname van de taak-betrokkenheid die samengaat met mentale vermoeidheid en resulterende gebreken in de taakprestatie. Om de rol van motivatie te onderzoeken tijdens vermoeidheid verhoogden we de beloning voor de taak, nadat proefpersoon al zeer vermoeid waren geworden. Deze interventie zorgde voor herstelde taak-betrokkenheid, objectieve metingen van de taakprestatie en (indicatoren van) activiteit in het locus-coeruleus noradrenaline systeem. Daarom concludeer ik dat taak-betrokkenheid gestuurd wordt door motivationele kosten/baten afwegingen, en dat vermoeidheid gezien kan worden als een adaptieve toestand die ons laat weten dat er een conflict is tussen hetgeen we nu doen en wat we verder nog zouden kunnen doen. Het signaleert dat we moeten stoppen met werken, lang voordat onze daadwerkelijke capaciteit om te kunnen werken uitgeput is. Een belangrijke implicatie van de observatie van vermoeidheid als 'stop emotie', in tegenstelling tot een uitputting van energiebronnen, is dat interventies die gebaseerd zijn op een uitputting benadering onbetrouwbaar of inefficiënt kunnen zijn. Het onderzoeken van nieuwe interventies, die focussen op vermoeidheid als een disbalans tussen kosten en opbrengsten, is daarom het overwegen waard. Het gepresenteerde psycho-fysiologische model voor vermoeidheid, gebaseerd op het locus-coeruleus noradrenaline systeem, legt de basis voor toekomstige interventies. Ik verwacht dat in de komende jaren innovatieve interventiestudies, die gebruik maken van objectieve metingen van taak-betrokkenheid, ten grondslag zullen liggen aan de manier waarop wij ons professionele (en wellicht ook persoonlijke) leven zullen organiseren.

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A word from the author

GIVE ME A LEVER LONG ENOUGH AND A FULCRUM ON WHICH TO PLACE IT, AND I SHALL MOVE THE WORLD.

ARCHIMEDES, 200 BC

During the last four year I gained loads of insight on human psychophysiology, mental fatigue and motivated behavior. But what does it mean? *Knowing is not enough, we must apply.* This quote by Goethe drove me towards the software business in 2008, after I graduated as a master of science in biological and cognitive psychology. I thought my studies would mean nothing, if I didn't incorporate my knowledge to enhance the world around me. Software was hot in 2008, so I jumped aboard. I identified many business opportunities and successfully implemented them within the company's organization and its products. All these ideas were without a doubt fueled by my knowledge about human behavior and cognition. I felt that my studies had proven to be increasingly meaningful. But that didn't mean I was satisfied. For every time I implemented an innovation to satisfy a business opportunity, ten new questions would pop up in my head. Why were some ideas more successful than others? Why is there so much difference in how people respond to certain interventions? And why do my theories of human behavior and cognition not always apply? The real world proved to be much more complex than what I learned at the university. I needed to go back. I had to understand more about the human psyche. I needed to learn more. And so I did, writing this book as a result.

And here I am again, evaluating my progression. Am I satisfied now? Do I keep on soaking up new information? Or do I start to implement my new perspective on human behavior? I think the answer must be both. It is my goal to keep learning and applying. However, it could be challenging to reach this goal, because of the way that academia is currently organized. In my opinion, academia still works in a very old-fashioned way. It remains very hierarchical and publication-driven. Despite a slow movement towards more emphasis on valorization of knowledge, output (that is mostly valued by the number of publications) remains the driving factor in many academic institutions. I find it very painful to see that women are still less likely to become professors and researchers manipulate data to keep their heads above water. I think there is a dire need for academia to modernize, and I very much hope to be a part of such a change during the next decade. It will be hard to predict where I end up ten years from now. At least, I promise you that I will keep pursuing to explore real questions and implement real solutions. I will keep on trying to enhance the world around me. Whether I do this from within the academic world or from the outside, is just a secondary detail to me.

After Archimedes over two millennia ago, I will keep searching for a lever that is long enough. I will keep on exploring human behavior. I will keep on pursuing knowledge. But in the meantime, I will not wait with trying to move the world. Even if it's only by a little bit at a time.

Jesper F. Hopstaken