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

Jesper F. Hopstaken[a,*], Dimitri van der Linden[a], Arnold B. Bakker[a], Michiel A.J. Kompier[b]

[a] Department of Work and Organizational Psychology, Institute of Psychology, Erasmus University Rotterdam, The Netherlands
[b] Behavioural Science Institute, Radboud University, The Netherlands

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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 2 h 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 2 h 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.

1. 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, Olson, & Morisseau, 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; Lorist, Boksem, & Ridderinkhof, 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, Meijman, & Lorist, 2006; Hopstaken, van der Linden, Bakker, & Kompier, 2015).

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

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* Corresponding author.
E-mail address: jesperhopstaken@gmail.com (J.F. Hopstaken).

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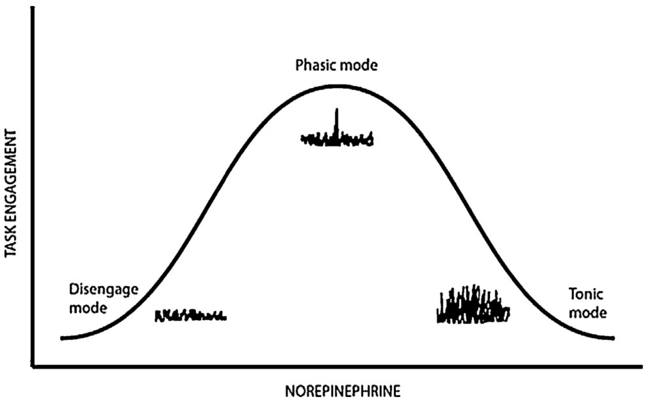

Fig. 1. The output modes of the LC–NE system.

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.

1.1. 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 Fig. 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, Watrous, Yoon, Ursu, & Carter, 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, McClure, & Yu, 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 it 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).

1.2. 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, 1973; Kahneman & Beatty, 1966) 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., 2015), 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

1.3. 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., 2015). 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, Duckworth, Kable, and Myers (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, Schmeichel, and Macrae (2014) and Inzlicht and Schmeichel (2012), who challenge the classical resource depletion model of Baumeister, Bratslavsky, Muraven, and Tice (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., 2015) 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 (2015) showed that 2 h of continuous performance led to the expected increase in fatigue and decrease in task performance. However, increasing rewards after these 2 h 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.

2. Method

2.1. 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 h before the experiment. All participants had normal or corrected to normal vision. Written informed consent was obtained prior to the study.

2.2. 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, 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, Geffen, & Geffen, 2001).

2.3. 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 min (depending on random intervals). The n-back stimuli were displayed for 500 ms with an inter-stimulus interval randomized at 5–5.5 s. 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. After they completed six blocks of 18 min, 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 min, depending on their performance. The better the performance, the shorter the remaining time on the task. Previous studies have shown that after 2 h of continuous performance, this provides a strong incentive to optimize performance (Esterman, Reagan, Liu, Turner, & DeGutis, 2014; Hopstaken et al., 2015). 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., 10 s) between blocks and to read the instructions before the last block (i.e., 15 s) 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.

2.4. 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 (0–150) 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, Gilching, Germany). 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 (>0.1% of the data). To measure baseline pupil diameter, we averaged the pupil diameter in the 500 ms 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, Gilching, Germany) 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 ms 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.

2.5. 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

3.1. 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 toward 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 is displayed in Fig. 2.

3.2. 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 Fig. 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 1.

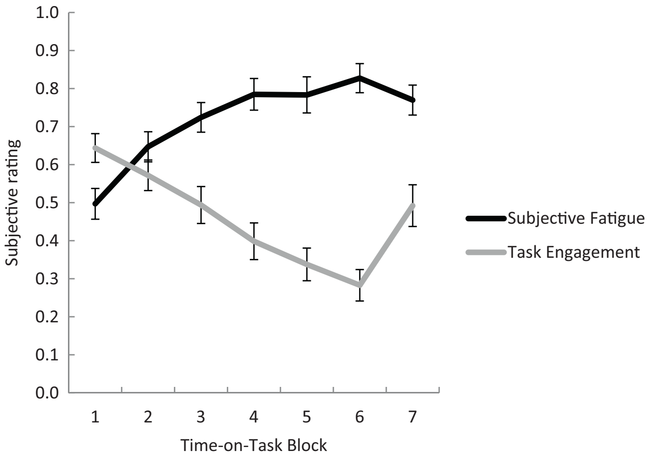

Fig. 2. Subjective fatigue and task engagement ratings with time-on-task.

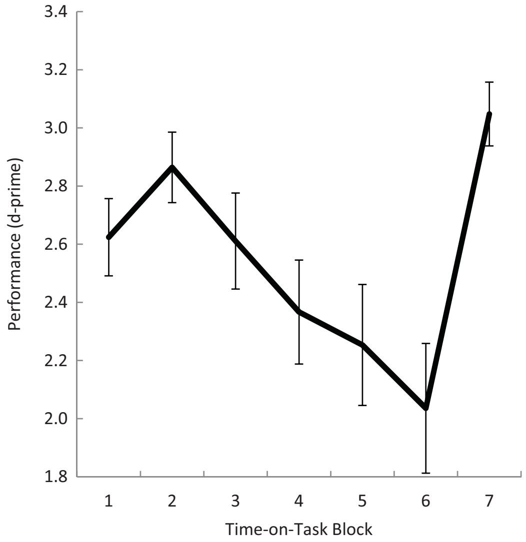

Fig. 3. Performance on the 2-back task with time-on-task.

Table 1
Means of the performance indicators for each of the time-on-task blocks of the experiment.

	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

3.3. 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 Fig. 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 Fig. 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 pupil dilation during each of the time-on-task blocks can be observed in Fig. 6.

3.4. 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

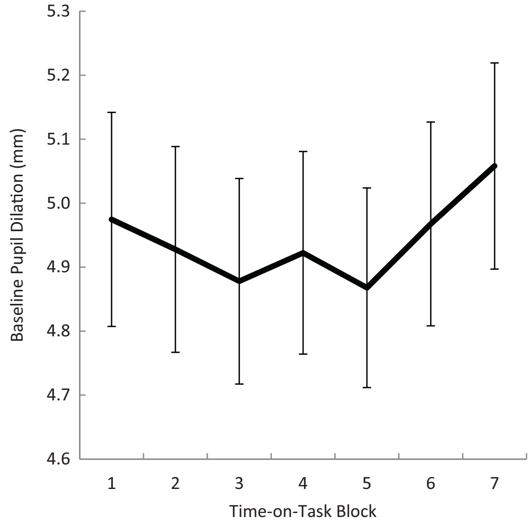

Fig. 4. Baseline pupil diameter with time-on-task.

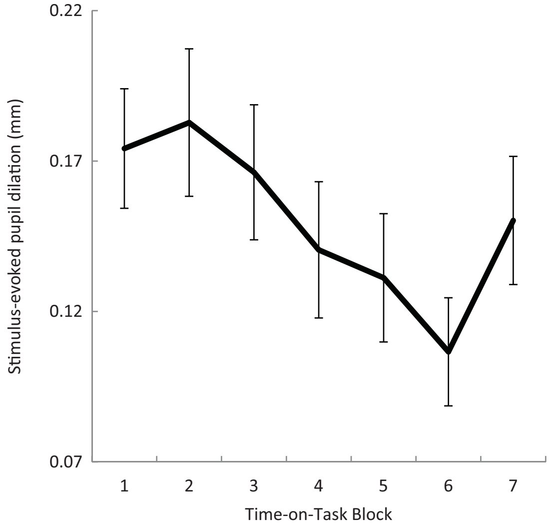

Fig. 5. Stimulus-evoked pupil dilation with time-on-task.

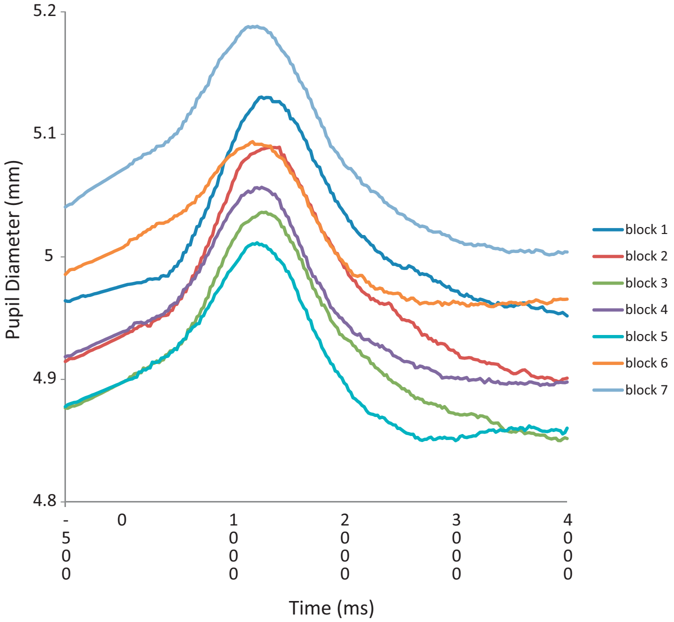

Fig. 6. Average pupil diameter during each time-on-task block of the experiment.

Table 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 (d-prime)	.54	$-.24^{**}$	$.49^{***}$		
4. Stimulus-evoked pupil dilation	.76	$-.33^{**}$	$.42^{***}$	$.32^{***}$	
5. Baseline pupil diameter	.96	.08	−.04	.04	$-.14^{*}$

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

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 2, indicated that there indeed was sufficient variance explained on both levels for each observed variable. Table 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 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.

4. 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.

4.1. 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., 2015). 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; Murphy, Robertson, Balsters, & O'connell, 2011), this suggest 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., 2015), 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., 2015), 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.[1] 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.

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.

4.2. *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. (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 2 h 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 2 h 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 this was not the main focus of this study, we think there is an interesting opportunity for future research. Specifically, it would be interesting see whether other stimuli may still draw attention and lead to engagement if they are perceived to be rewarding, when the task related stimuli become less rewarding and lead to disengagement.

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).

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[1] 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).

5. 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., 2015; 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.

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