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RESEARCH ARTICLE

Cognitive resilience after prolonged task performance: an ERP investigation

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Abstract
Deleterious consequences of cognitive fatigue might be avoided if people respond with increased effort to increased demands. In this study, we hypothesized that the effects of fatigue would be more pronounced in cognitive functions reflecting compensatory effort. Given that the P3a event-related potential is sensitive to the direction and amount of attention allocated to a stimulus array, we reasoned that compensatory effort would manifest in increased P3a amplitudes. Therefore, we compared P3a before (pre-test) and after (post-test) a 2 h long cognitively demanding (fatigue group, $n=18$) or undemanding task (control group, $n=18$). Two auditory tasks, a three-stimulus novelty oddball and a duration discrimination two-choice response task were presented to elicit P3a. In the fatigue group, we used the multi-attribute task battery as a fatigue-inducing task. This task draws on a broad array of attentional functions and imposed considerable workload. The control group watched mood-neutral documentary films. The fatigue manipulation was effective as subjective fatigue increased significantly in the fatigue group compared to controls. Contrary to expectations, however, fatigue failed to affect P3a in the post-test phase. Similar null effects were obtained for other neurobehavioral measures (P3b and behavioral performance). Results indicate that a moderate increase in subjective fatigue does not hinder cognitive functions profoundly. The lack of objective performance loss in the present study suggests that the cognitive system can be resilient against challenges instigated by demanding task performance.

Keywords Mental fatigue · Event-related potentials · Attention · Oddball · Distraction · Effort

Introduction

Acute mental fatigue seems to be an inevitable experience in modern post-industrial society, as most professions require intensive mental work, while physical demands are decreasing. Mental fatigue is predictive of workplace accidents (Tucker et al. 2003) and is often hypothesized to have a detrimental effect on students' and professionals' cognitive performance in high-stake situations (Kanfer 2011).

Acute mental fatigue can be defined as a multicomponent phenomenon with subjective, cognitive and behavioral aspects (van der Linden 2011). Subjectively mental fatigue is mainly associated with aversive states, such as lack of energy, boredom, and strain, and it typically includes a more or less explicit desire for stopping the current activity. On the behavioral level, mental fatigue is usually described as an inability to maintain performance, and it is characterized by slower and/or less accurate cognitive activity.

While people commonly report subjective fatigue even after short periods of mental exertion, behavioral fatigue is often less detectable under laboratory settings (Ackerman and Kanfer 2009). One viable explanation is that at first, fatigue appears only on the subjective level signaling that cognitive performance could be hindered. For a limited amount of time, compensatory effort can prevent adverse behavioral effects by maintaining adequate performance (Hockey 2011). Effort thus seems to be a key component

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in understanding mental fatigue, therefore, in this study we aimed to investigate this construct using behavioral and electrophysiological methods.

Cognitive effort can be interpreted as the individual's voluntary activation of attention to overcome stressors that potentially cause performance decrements (Sarter et al. 2006). Such stressors might include heightened task difficulty, sleepiness, or mental fatigue. While effort is traditionally measured by self-reported questionnaires and indicators of autonomic arousal (Venables and Fairclough 2009), it can also be associated with markers of the central nervous system. Among these, an important marker that can be administered by EEG is the P3b event-related potential (ERP) component. Although the functional significance of P3b is still a matter of debate, increasing evidence support the view of P3b as the neural substrate of perceptual-cognitive decision making (Verleger et al. 2005; Kelly and O'Connell 2013). Accordingly, several studies show P3b amplitude to be correlated with the "amount of attention". For example, P3b is almost fully diminished when the subject ignores stimuli by paying attention to another task (Squires et al. 1973).

Attentional capacity can be voluntarily expanded (Esterman et al. 2014). Given the P3b's sensitivity to the amount of attentional resources, it can be hypothesized that the more attention is devoted voluntarily to task performance, the higher the P3b amplitude will be. This notion is supported by studies of Hopstaken et al. They applied monotonous and slow paced but cognitively demanding tasks and found gradual decrement of P3b amplitude, indicating the waning of attentional processes potentially attributable to boredom and low task engagement. However, they managed to re-increase P3b amplitude after applying a manipulation that enhanced task engagement (Hopstaken et al. 2015a, b).

Based on these, P3b would be a perfect candidate for monitoring voluntary attentional allocation, however, there is a factor that limits its applicability. Besides being sensitive to the amount of attention, P3b is also sensitive to the degree of response certainty. If the subject is uncertain about the correctness of his/her response, either due to decreased alertness (Kelly and O'Connell 2013), or due to low detectability of the stimulus (Squires et al. 1973), the amplitude of P3b will be diminished. Therefore, P3b amplitude varies unpredictably with task difficulty, depending on the balance between increasing effort and decreasing certainty (Kok 2001). Accordingly, P3b is less suitable for monitoring compensatory attentional effort in situations where compensation is no longer sufficient and task performance suffers significant impairment. Therefore, in the present study, we decided to examine compensatory effort with another component, as well. This component is the P3a, which is also thought to reflect attentional capacity.

P3a reflects the bottom-up process of the involuntary capture of attention, which is triggered by highly distinctive stimuli (for reviews see, Friedman et al. 2001; Escera and Corral 2007; Schomaker and Meeter 2015). Despite the fact that it reflects a bottom-up process and can be elicited in the absence of attention (Muller-Gass et al. 2007), a number of top-down effects can modulate P3a (Sussman et al. 2003; Chong et al. 2008). Similarly to P3b, an important predictor of P3a is the amount of attention available. Studies have shown that the amplitude of P3a decreases considerably if the person does not pay attention to the particular stimulation (Friedman et al. 1998). Under dual-task conditions, increased task difficulty in the primary task often results in decreased P3a in the to-be ignored or secondary task (Legrain et al. 2005; Zhang et al. 2006; SanMiguel et al. 2008). Based on all of this, P3a can also be considered a sensitive indicator of the direction and amount of attention. Furthermore, the potential advantage of P3a over P3b is that it is not affected by decision uncertainty, as in most experimental situations P3a is elicited by a clear, distinctive stimulus.

Thus, in the present experiment, we intended to monitor compensatory effort evoked by mental fatigue with the use of P3a (and to a lesser extent with P3b). We hypothesized that if mental fatigue performance declines, P3b will change depending on the unpredictable combination of uncertainty and effort, while P3a will increase as a pure reflection of effort.

The experiment was built on the fatigue-inducing task–testing task scheme with control and experimental groups. Testing tasks were performed before and after a 2 h treatment phase in which the fatigue group performed a cognitively demanding task. The multi-attribute task battery (MATB; Comstock and Arnegard 1992) was applied to induce mental fatigue in the fatigue group. This multimodal task requires vigilance, auditory attention, continuous visuomotor control, and complex processing, especially planning. MATB has been reported to effectively induce subjective fatigue (Harris et al. 1995). Scholars and most participants usually label MATB "engaging" (Wilson et al. 2007), which has the added value that MATB can evoke fatigue without a high degree of boredom. During the treatment phase, members of the control group watched emotionally neutral, non-arousing documentaries.

Two tasks were administered to elicit P3a, so that we can reliably demonstrate that P3a is sensitive to compensatory processes and not confounded by task-specific changes. One of them was a three-stimulus novelty oddball task, in which simple, frequent sounds are interspersed with rare higher simple sounds that require behavioral responses. Additionally, complex environmental noises with no response needed were infrequently presented, which are shown to reliably elicit the P3a component (Barkaszi et al. 2013). The other employed task was an auditory duration discrimination task, the so-called Distraction task, in which the appearance of an infrequent, task-irrelevant stimulus feature (higher pitch) triggers P3a (Schröger and Wolff 1998). Although of secondary importance, with this task we were also able to study how mental fatigue and compensatory effort affect distractibility. In the Distraction task, responses to deviant stimuli that carry the task-irrelevant feature are typically slower and often less accurate than those to standard stimuli (referred to as distraction effect), which can be interpreted as a behavioral sign of distraction.

In addition to the P3a eliciting tasks, we also used a short version of the Psychomotor Vigilance Task (PVT; Dinges and Powell 1985), so that we could exclude the possibility that instead of inducing mental fatigue, our experimental manipulation reduced alertness. As the literature of sleep deprivation reveals, a decline in alertness impairs almost all cognitive functions, but the most significant deteriorations are observed in simple vigilance tasks, such as the PVT (Lim and Dinges 2010).

Materials and methods

Participants

Thirty-six paid volunteers participated in the study, 18 in the fatigue (11 females, mean age 22.17 years, range 20–24 years) and 18 in the control group (8 females, mean age 22.53 years, range 19–28 years). According to self-report, participants were free of neurological disorders and were not using drugs that affect the central nervous system. They had normal or corrected to normal vision and normal hearing thresholds. Participants signed an informed consent prior to the experiment, which conformed to the Declaration of Helsinki and was approved by the Joint Ethical Committee of the Hungarian Psychology Institutes.

Procedure

The experiment consisted of three main sections, pre-test, treatment and post-test phase (see Online Resource 1 for depiction). In the pre- and post-test phases, both groups performed the same set of tasks. The order of tasks was fixed, with the exception that the order of the Oddball and Distraction tasks was counterbalanced. The pre-test and post-test phase was approximately 45–45 min long. During the treatment phase, the fatigue group performed the multi-attribute task battery (MATB), while the control group watched documentary films. This section was two hours long with no breaks allowed. A 10 min long mandatory break was scheduled after the pre-test phase for both groups. After the completion of the treatment phase, the post-test phase began immediately. All participants stayed in the EEG booth for the entire duration of the experiment, except for the mandatory break. The EEG booth was moderately lit. Participants were seated in a reclining chair 1.2 m from the computer monitor.

Participants took part in a practice session 1 or 2 weeks before the experiment, when they were familiarized with the experimental tasks. As for the full length measurement, participants were instructed to arrive at the laboratory after a full night of sleep. Caffeine intake was not allowed during the experiment, but we did not impose strict requirements on the caffeine consumption preceding the experiment (to avoid caffeine withdrawal effects). All measurements started at the same time of the day, at 9 a.m.

Tasks and scales

Pre- and post-test phase

At the beginning of the pre- and post-test phases, fatigue was assessed with the 18 item VAS-F scale (Lee et al. 1991) translated to Hungarian and implemented in a computerized version. Participants responded by moving a small vertical bar along a horizontal line between two endpoints describing opposing statements (e.g., “not at all tired” vs. “extremely tired”).

Fatigue assessment was followed by resting state EEG. Resting state EEG measurements (eyes closed and eyes open states) were 90–90 s long; the results of these conditions will not be reported here.

Resting EEG was either followed by an Oddball or a Distraction task, given that the order of the two tasks was counterbalanced across participants. A three-stimulus auditory novelty oddball was administered (Oddball task). Frequent standards (80%), infrequent targets (10%), and infrequent novel (10%) sounds were presented in pseudo-random order (i.e., targets were always followed by at least one standard). Standards were low tones (composed of a 887 Hz fundamental frequency and the second and third harmonics), targets were high tones (938 Hz fundamental frequency and the second and third harmonics) and novel stimuli were various environmental sounds (e.g., glass breaking, engine starting, etc.). Participants were required to press a button with their dominant hand upon hearing the target sound. The duration of tones was 110 ms (5 ms rise and fall times).

The Distraction task was an auditory two-choice duration discrimination task (Schröger and Wolff 1998). Participants were presented with long (400 ms) and short (200 ms) tones of equal probability and were required to press buttons according to the duration of the tone. The pitch of the tones was 440 Hz in the majority of cases (86%; standard tones), and 480 Hz in rare cases (14%; deviant tones). The assignment of long and short tones to responding hands was counterbalanced between participants. The tones were presented in a pseudo-random order in which deviants were always followed by at least three standards. In both the Oddball and the Distraction task, the mean stimulus onset asynchrony was 1300 ms (jittered randomly between 1200 and 1400 ms). Sounds were presented binaurally via headphones, with an intensity of 60 dB above hearing level, individually adjusted for each participant.

We applied a shortened, 5 min version of the classic Psychomotor Vigilance Task (PVT); (Dinges and Powell 1985). Participants were required to press a button with their dominant hand when a number counter appeared in the center of the screen. The counter displayed the elapsed time since its onset at each screen refresh interval. In case of a valid response, the reaction time in milliseconds was displayed on the screen as feedback. The inter-stimulus interval (ISI) was variable between 2 and 10 s; the distribution of ISIs was flat in this range.

Treatment phase

The fatigue group completed the multi-attribute task battery (MATB; Comstock and Arnegard 1992) during the treatment phase. MATB is a multitasking platform designed to mimic the activities of aircraft pilots. Four subtasks have to be performed simultaneously. In the system monitoring task, participants detect rare off-nominal changes in static and dynamic displays. In the tracking task, participants control an erratically moving circle using a gamepad joystick. In the communications task, participants hear pre-recorded radio messages resembling standard aircraft communication messages and they are expected to tune their virtual radio to the received frequency. The resource management task requires continuous control of two tanks' fuel levels. The tanks are interconnected and receive input from each other through pumps. In case any pump fails, participants have to find alternative routes to maintain the required fuel level. For the present experiment, we created a new schedule of task activities to impose increased workload. The tracking task was continuous during the 2 h, and communication messages, system monitoring changes and pump fails were frequent. At three time points, the fatigue group also completed the NASA-TLX scale (Hart and Staveland 1988) as an assessment of subjective workload (see Online Resource 1).

The control group watched the following documentary films in fixed order: (1) Planet Earth Episode 7 Great plains (2007), (2) When we left Earth: The NASA missions: The Shuttle (2008), (3) Ocean oasis (2000). The films were chosen based on being cognitively undemanding, non-arousing and mood-neutral. All films were dubbed in Hungarian. Prior to watching the documentaries, participants were instructed to pay attention to the films, as they might have to answer questions about them. This aimed to minimize decrements in attention during the non-arousing documentaries. The presented questions in fact were only assessing how interesting and informative the documentaries were.

EEG recording

EEG was recorded with a BrainAmp amplifier (Brain Products, Gilching, Germany), DC-100 Hz, sampling rate 1000 Hz, with active electrodes (ActiCap) on 61 cortical sites positioned according to the extended 10–20 system. Reference electrode was placed at FCz, ground at AFz channel. Electro-oculogram was recorded with electrodes attached to the outer canthi of eyes and below the right eye.

Data analysis

Fatigue scale

Subjective fatigue scores of the VAS-F scale were compared in a repeated measures ANOVA, using the between-subject factor of Group (fatigue, control group) and the within-subject factor of Phase (pre-, post-test).

Behavioral measures

Reaction time (RT) was defined as the time between stimulus onset and button press with a minimum duration of 150 ms in all three tasks (Oddball, Distraction and PVT task). Median of correct responses was calculated in tasks as a RT measure. In the Oddball and Distraction task, accuracy was calculated as percent of correct responses. Standards directly following targets, novels (Oddball task) or deviants (Distraction task) were excluded from the analyses of accuracy to maintain full compatibility between the analyses of behavioral and ERP data. Participants made no incorrect responses to novel stimuli in the Oddball task during the post-test phase, therefore we omitted this variable from the analysis. In the PVT task, we only report RT, as the number of misses and lapses (RTs longer than 500 ms) were negligible.

Data in all tasks were compared with repeated measures ANOVAs, with the between-subject factor of Group (fatigue or control group) and the following within-subject factors. RT to targets in the Oddball task was analyzed with the within-subject factor of Phase (pre-, post-test). Accuracy in the Oddball task was compared with the within-subject factors of Phase and Stimulus (standard, target stimuli). The analysis of RT and accuracy in the Distraction task was accomplished with the within-subject factors of Phase, Deviance (standard, deviant stimuli) and Duration (long, short stimuli). Finally, the PVT task was analyzed with the within-subject factor of Phase. All statistical analysis focused on interactions that involve the Group × Phase interaction in line with the a priori hypotheses. Moreover, we checked the presence of a significant distraction effect (i.e., slower and less accurate responses to deviants than to standards) in the Distraction task with *t* tests against zero.

Greenhouse-Geisser correction was applied when appropriate. We report partial eta squared (η_p^2) as measure of effect size.

Event-related potentials

We analyzed event-related potentials (ERPs) in the Oddball and Distraction tasks. EEG analysis was performed with EEGLAB (Delorme and Makeig 2004) in MATLAB (Mathworks, Natick, USA). After offline 0.5–40 Hz (high-pass: Kaiser window, transition bandwidth 0.5 Hz, passband deviation 0.001 Hz; low pass: Kaiser window, transition bandwidth: 10 Hz, passband deviation 0.001 Hz) bandpass filtering, noisy channels and segments affected by non-stereotyped artifacts were removed and extended independent component analysis was carried out. Resulting independent components were automatically classified to be cortical or artifactual with the MARA plugin (Winkler et al. 2011), using a threshold that a component was classified neural if the probability of being artifactual was maximum 10%.

After MARA data treatment, a similar number of ICs remained in the datasets across groups before and after the Treatment phase (see Online Resource 1). After resampling to 512 Hz, missing channels were interpolated by spherical interpolation. All electrodes were re-referenced to the average of cortical electrodes. Subsequently, epochs (100 ms before and 1000 ms after stimulus onset) containing correct response and voltage not exceeding ± 70 µV at any channel were selected for each phase and stimulus type. Only standards not directly following novels, targets and deviants were selected for further analysis. The mean voltage of the − 100 to 0 ms interval was subtracted from epochs as baseline correction. The average number of epochs included in one ERP is presented in Online Resource 1.

As deviant-minus-standard waveforms computed from long and short stimuli are typically highly similar in the Distraction task (Schröger et al. 2000), we followed the standard approach in the field and collapsed data across the stimulus length factor. Afterwards, deviant-minus-standard difference potentials were computed.

Amplitude measurement windows were identified using the “collapsed localizer” approach (Luck and Gaspelin 2017). The amplitude of components was measured as the mean voltage in 100 ms wide time windows centered around the grand-average peak latency. P3a was measured at Cz, P3b at Pz, where components reached their respective maxima. The latency of P3b in the Oddball task was measured on individual low-pass filtered (6 Hz cutoff frequency) waveforms at Pz channel. Latency was defined by the most positive value between 300 and 700 ms. The statistical analysis of mean ERP amplitudes and latencies was carried out using ANOVA with factors Phase (pre-, post-test) and Group (fatigue, control group).

Correlations An exploratory analysis investigated the correspondence between pre-post changes in P3a and P3b with pre–post changes in subjective fatigue and task performance (see Online Resource 1 for details).

Results

Fatigue scale

One control group participant’s data were missing, thus we report 17 datasets in that group. Subjective fatigue increased more in the fatigue (from 34.44, SE: 3.09 to 51.08, SE: 2.96) than in the control group (from 31.43, SE: 3.18 to 37.97, SE: 3.05), confirmed by the significant Group × Phase interaction [$F(1,33) = 7.04$, $p = 0.012$, $\eta_p^2 = 0.18$]. Post hoc Tukey test showed that the increase in fatigue level was significant only in the fatigue group ($p < 0.001$, control group: $p = 0.098$). These results verify that the fatigue manipulation was successful.

The results of the NASA-TLX workload scale are presented in Online Resource 1.

Behavioral measures

Table 1 and Fig. 1 summarize the results of the behavioral measures (RT and accuracy) for each pre/post-test tasks. Summing up shortly, we obtained no statistically significant effect involving the Group × Phase interaction, revealing that the experimental manipulation (i.e., fatigue inducement) had no effect on any behavioral measures.

As the normality assumption of the ANOVA was violated to a large extent in the case of accuracy both in the Oddball and the Distraction tasks, we ensured the validity of the above findings by conducting additional non-parametric analyses (see Online Resource 1).

The distraction effect in the Distraction task was also unaffected by the experimental manipulation. This effect was significant in the pre-test phase: the RT advantage of standards compared to deviants (data collapsed over the Group and Duration factor) was 8.68 ms [$t(35) = 3.61$, $p < 0.001$, $\eta_p^2 = 0.27$], while the accuracy advantage was 1.75% [$t(35) = 3.13$, $p < 0.01$, $\eta_p^2 = 0.22$]. As the nonsignificant Group × Phase × Deviance interactions in the ANOVAs shows, the fatigue manipulation did not evoke differential changes in these effects for the post-test phase between the groups.

Event-related potentials

Oddball task

Figure 2 shows ERP waveforms and their scalp distribution in the Oddball task. Novel stimuli elicited a very

Table 1 Statistical results for the behavioral and ERP measures in the three pre/post-test tasks

Task	Measure	Effect	*df*	*F*	*p*	η_p^2
Oddball	RT	G×P	1, 34	0.57	0.46	0.02
	Accuracy	G×P	1, 34	0.4	0.52	0.01
		G×P×St	1, 34	0.7	0.39	0.02
	P3a amplitude (novel ERPs)	G×P	1, 34	0.69	0.41	0.02
	P3b amplitude (target ERPs)	G×P	1, 34	1.28	0.27	0.04
	P3b latency (target ERPs)	G×P	1, 34	0.18	0.67	<0.01
Distraction	RT	G×P	1, 34	0.06	0.84	<0.01
		G×P×D	1, 34	1.73	0.20	0.05
		G×P×Du	1, 34	0.22	0.64	0.01
		G×P×D×Du	1, 34	0.02	0.88	<0.01
	Accuracy	G×P	1, 34	2.47	0.13	0.07
		G×P×D	1, 34	0.01	0.94	<0.01
		G×P×Du	1, 34	2.68	0.11	0.07
		G×P×D×Du	1, 34	2.64	0.11	0.07
	P3a amplitude (deviant-minus-standard wave)	G×P	1, 34	0.67	0.42	0.02
PVT	RT	G×P	1, 34	2.87	0.099	0.08

G Group factor, *P* Phase factor, *St* Stimulus factor, *D* Deviance factor, *Du* Duration factor

early, sharp, centrally maximal P3a, with 244 ms peak latency at Cz. Target stimuli evoked a parietal P3b, with 422 ms peak latency on Pz. Both the P3a and P3b peak was strongly right "skewed" (i.e., had a steep gradient from left); to prevent earlier components to be included in the measurement, the measurement window was centered on the peak latency of the 6 Hz low-pass filtered grand-average waveform, corresponding to a 215–315 ms and 372–472 ms measurement window, respectively. Standard stimuli elicited no discernable P3a or P3b, therefore we did not perform a formal analysis of these stimuli.

Table 1 displays the results of statistical analyses of amplitudes (P3a and P3b) and latencies (P3b). We obtained no significant Group × Phase interactions on any tests, which indicates that the mental fatigue manipulation had no effect on ERPs in the Oddball task.

Distraction task

In this task, we concentrated on the deviant-minus-standard difference potentials depicted in Fig. 2. The raw standard and deviant waveforms can be found in Online Resource 1. As Fig. 2e, f illustrate, P3a was elicited in this task over frontal and central leads with 324 ms peak latency on Cz.

The result of the statistical analysis of the P3a amplitude is also listed in Table 1. The Group × Phase interaction was nonsignificant, indicating the lack of effects on P3a amplitude in this task as well.

Correlations

We found weak and nonsignificant correlations between changes in ERPs, subjective fatigue and task performance (see Online Resource 1 for details).

Discussion

The primary purpose of this experiment was to investigate whether mental fatigue induces compensatory effort, which we intended to measure with the P3a ERP component. As an experimental manipulation, the fatigue group performed a demanding cognitive task, while the control group performed a light, non-demanding task. The success of the manipulation is demonstrated by the fact that the self-rated fatigue significantly increased in the fatigue group compared to the control group. However, the experimental manipulation failed to affect task performance during the post-test phase. Event-related potentials also remained preserved, even though we anticipated that mental fatigue would result in increased P3a amplitudes reflecting compensatory effort. Similarly to behavioral performance and P3a, P3b also remained unchanged. We interpret these findings as evidence that the fatigue group was able to maintain neurobehavioral performance, despite previously having been working on a cognitively demanding task for 2 h.

Our result contradicts a substantial body of findings that revealed a deterioration of cognitive performance or a change in specific ERP components using either

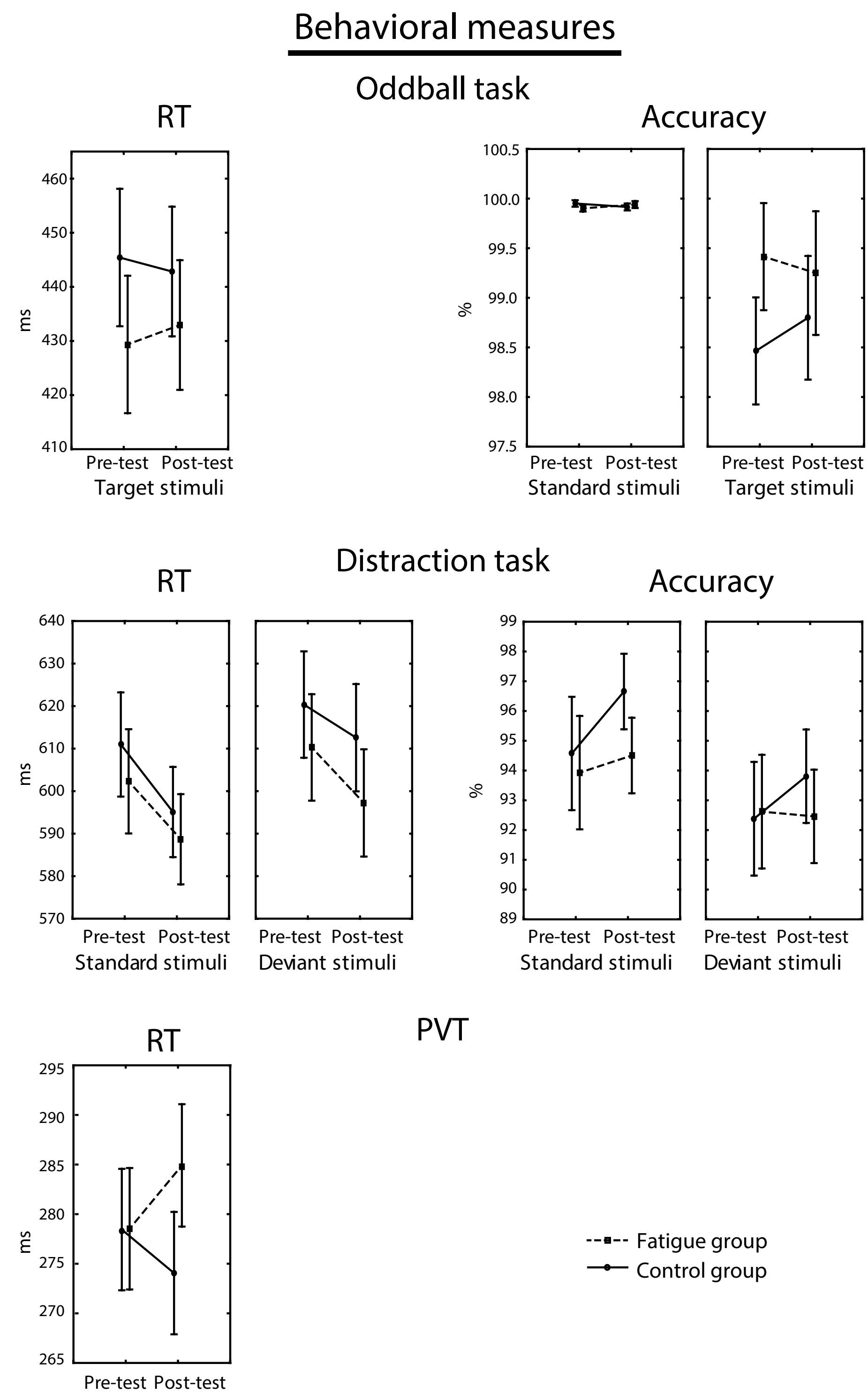
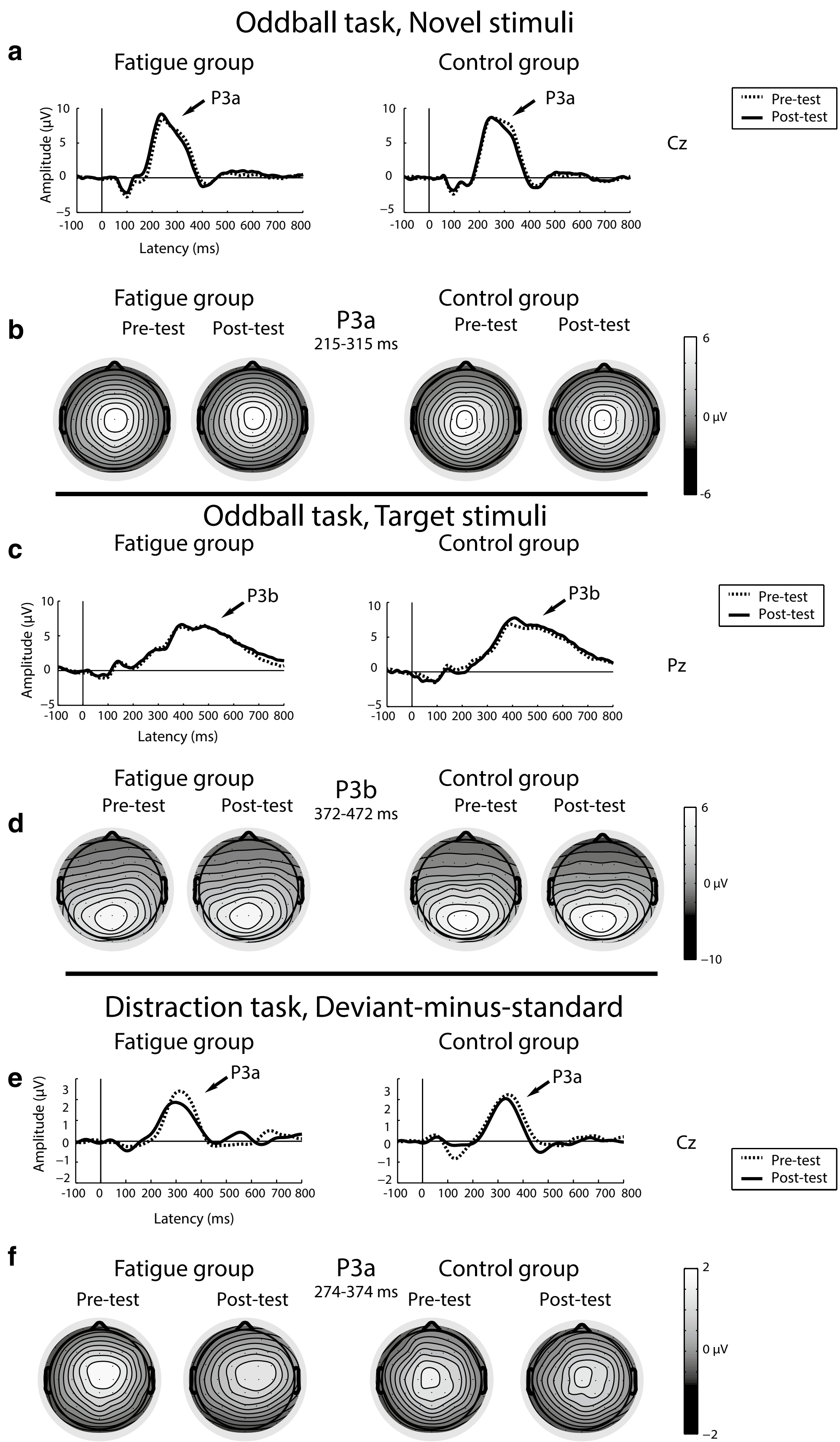


Fig. 1 RT and accuracy in the three pre/post-tasks. Vertical bars denote standard errors

time-on-task (Lorist et al. 2000; Boksem et al. 2005, 2006; Hopstaken et al. 2015a, b; Borragán et al. 2017) or fatigue-inducing task–testing task designs (Benoit et al. 2018, Experiment 2; Gergelyfi et al. 2015; Kato et al. 2009; Persson et al. 2007, 2013; van der Linden et al. 2003, 2006). However, a smaller number of studies are in line with present results (Ackerman et al. 2010; Ackerman and Kanfer 2009; Benoit et al. 2018, Experiment 1; Brewer et al. 2011), as these investigators obtained intact cognitive functioning even after long and demanding task performance.

An apparent limitation of our study is that present results cannot provide a definitive answer whether (A) fatigue group participants did in fact invoke compensatory effort during post-test phase, allowing cognitive performance



Oddball task, Novel stimuli
a
Fatigue group
Control group
P3a
P3a
Pre-test
Post-test
Cz
Amplitude (µV)
Latency (ms)
b
Fatigue group
Pre-test
Post-test
P3a
215-315 ms
Control group
Pre-test
Post-test
6
0 µV
-6
Oddball task, Target stimuli
c
Fatigue group
Control group
P3b
P3b
Pre-test
Post-test
Pz
Amplitude (µV)
Latency (ms)
d
Fatigue group
Pre-test
Post-test
P3b
372-472 ms
Control group
Pre-test
Post-test
6
0 µV
−10
Distraction task, Deviant-minus-standard
e
Fatigue group
Control group
P3a
P3a
Cz
Pre-test
Post-test
Amplitude (µV)
Latency (ms)
f
Fatigue group
Pre-test
Post-test
P3a
274-374 ms
Control group
Pre-test
Post-test
2
0 µV
−2

◂**Fig. 2** **a, c** Grand-average ERPs in the Oddball task elicited by novel and target stimuli, respectively. **e** Grand-average deviant-minus-standard waveforms in the Distraction task. The waveform was low-pass filtered at 10 Hz for display purposes. **b, d, f** Topographical distribution of ERPs

to be maintained, but P3a and P3b were not sensitive to these changes or (B) performance was maintained without any compensatory effort. In our view, the present study is more informative in terms of factors influencing behavioral fatigue in a fatigue-inducing task–testing task design. Since our experimental design was based on a series of premises, it is possible that we failed to induce significant effects in the testing tasks as some of these premises were false. In the following, we will look at these premises in more detail.

Premise: the fatigue manipulation created a suboptimal state for task performance

We interpret the detected changes in subjective fatigue as they represent a state in which conditions for task performance are suboptimal. This idea is rooted in the view that subjective mental fatigue, similarly to other subjective feelings, for example, emotions (Oatley et al. 1992), is a function that may provide useful signals to the organism. A common assumption regarding mental fatigue is that it is a "stop-emotion" whose function is to inform the individual about the imbalance between the cost and rewards associated with task performance (Meijman 2000; van der Linden 2011). High level of subjective fatigue represents a suboptimal state for task performance, as costs are not balanced with rewards. In addition, subjective fatigue can also add to the cognitive load of the task, as the individual must repeatedly make a decision about ignoring the signal or modifying his/her behavior. Taken together, we conclude that our first premise can be considered true.

A somewhat independent question is whether the effect of our fatigue manipulation was large enough compared to other experiments. Previous studies in which the control group watched documentaries (Rozand et al. 2015; Benoit et al. 2018) reported significant increase in subjective fatigue, however, as these studies have not included effect size estimates, we cannot compare the magnitude of our effect to theirs.

Premise: the suboptimal state for task performance persisted long enough

Our second premise was that the induced state of mental fatigue persisted at least for the duration of the testing tasks (45 min). Unfortunately, very little is known about how the brain recovers from mental fatigue and few studies are available that assessed subjective fatigue throughout longer periods of time after the experimental manipulation. Massar et al. (2010) report that 40 min after the fatigue manipulation, subjective fatigue has dropped to the baseline level. During the 40 min, participants either listened to an oddball sequence or drove a driving simulator while the oddball sequence was played in the background. Both tasks are considered fairly easy, making the observed reduction in fatigue reasonable. In the present experiment, we did not measure subjective fatigue during or after the post-test phase. However, in our case, it is less likely that the fatigue group recovered from fatigue in the post-test phase, as the Distraction task is highly demanding, and the other two tasks also require a substantial amount of focused attention.

Premise: the applied measurements are sensitive to the induced suboptimal state

The difficulty of the fatigue-inducing task–testing task design is that it is not enough to choose the fatigue-inducing task appropriately, but the testing task should also be sensitive enough. A variety of theoretical considerations exists concerning the selection of proper fatigue-inducing task–testing task pairs. According to the domain-general idea, the fatigue effect should appear largely independent of the type of testing task (Baumeister 2002). In contrast, the domain-specific approach suggests that the more similar cognitive functions are mobilized, the more likely the transfer of fatigue is between the two tasks (Persson et al. 2007; Anguera et al. 2012).

In the present study, we followed an intermediate approach between the domain-general and domain-specific proposals, as the fatigue-inducing task was not closely matched with the testing tasks regarding their cognitive domain. However, as the MATB is a multi-domain task, there was still a considerable overlap between the cognitive functions taxed by MATB and the testing tasks. Besides multimodal stimulus presentation (visual and auditory), MATB subtasks require the activation of several cognitive functions: vigilance is involved in the system monitoring task, continuous perceptuo-motor control is essential for the tracking task, auditory verbal processing is needed in the communication task, and complex information processing is activated in the resource management task. Additionally, executive functions are required for the multitasking aspect of the MATB, and for the planning and error detection in the resource management task itself. Among our testing tasks, the Distraction and Oddball tasks demand high degree of auditory attention. In the Distraction task, the deviant stimuli are able to distract attention, and frontal lobe mediated (potentially executive) functions are assumed to be necessary to avoid the involuntary capture of attention (Andrés et al. 2006). In the Oddball and the PVT tasks, vigilance is particularly required for successful task performance.

Previous studies demonstrated performance deterioration in testing tasks with a similar degree of testing task–fatigue-inducing task overlap as in our experiment. Klaassen et al. (2014) used a multi-task package (including Stroop, 2-back, 3-back, arithmetic and so-called brain teaser tasks) to induce mental fatigue. These tasks are mainly focused on executive functions, but also require an array of other cognitive functions. The testing task was a Sternberg working memory task, which mainly tests working memory maintenance. Van der Linden et al. (2006) used a modified continuous performance task to induce mental fatigue, which, according to the authors, requires working memory and sustained attention. The testing task was a prepulse inhibition task. Prepulse inhibition is a basic and automatic function, but, to some extent, can be related to executive functions. Both Klaassen et al. and Van der Linden et al. did demonstrate performance deterioration in the testing tasks, thus we can conclude that close functional overlap is not a necessary precondition for behavioral fatigue effects.

Cognitive resilience

There are two main ways of interpreting our results: we either obtained no significant changes in the testing tasks due to some methodological issues, or the lack of mental fatigue-induced changes represents a real phenomenon. As discussed above, however, none of our a priori assumptions proved to be false, making methodological deficiency a less plausible explanation. Thus, present results suggest that performance loss is not an inevitable consequence of subjective mental fatigue.

This interpretation is in line with the emerging view that the human cognitive system can be resilient in many ways. Despite significant chronic hypoxia, isolation and confinement, people may have preserved cognitive functions (Barkaszi et al. 2016). Participants have shown intact executive functions even after being sleep deprived for two nights (Tucker et al. 2010). In the field of fatigue, cognitive resilience is supported by studies that point out that subjective fatigue is not a direct function of working hours. A moderate amount of overtime does not lead to fatigue if it is voluntary and/or adequately compensated with rewards (i.e., time and money) (Van Der Hulst and Geurts 2001; Beckers et al. 2008). Likewise, the seminal study of Ackerman and Kanfer (2009) has shown that the high level of cognitive performance required by the SAT college admission test can be sustained for up to 5.5 h without performance deterioration. A particularly interesting study reported fatigue manipulations on different time scales (Blain et al. 2016). Authors demonstrated that only 6-h long fatigue-inducing sessions resulted in poorer testing task performance, while 1-h long sessions failed to produce such effects, which suggests that cognitive resilience might be prevalent at shorter time scales.

Taken together, the present results support the view that in some situations we are able to preserve an adequate level of performance despite previous mental exertion and subjective fatigue.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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