

Research Report

Effects of mental fatigue on attention: An ERP study

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Abstract

The effects of mental fatigue on attention were assessed. Subjects performed a visual attention task for 3 h without rest. Subjective levels of fatigue, performance measures and EEG were recorded. Subjective fatigue ratings, as well as theta and lower-alpha EEG band power increased, suggesting that the 3 h of task performance resulted in an increase in fatigue. Reaction times, misses and false alarms increased with time on task, indicating decreased performance efficiency in fatigued subjects. Subjects were unable to inhibit automatic shifting of attention to irrelevant stimuli, reflected by a larger negativity in the N1 latency range for irrelevant, compared to relevant stimuli. This difference in negativity was unaffected by time on task. However, N1 and N2b amplitude did change with time on task: N1 amplitude decreased, and the difference in N2b amplitude between relevant and irrelevant stimuli (larger N2b amplitude evoked by relevant stimuli) decreased with time on task. The results indicate a dissociation in the effects of mental fatigue on goal-directed (top-down) and stimulus-driven (bottom-up) attention: mental fatigue results in a reduction in goal-directed attention, leaving subjects performing in a more stimulus-driven fashion.

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1. Introduction

Mental fatigue refers to the effects that people may experience after or during prolonged periods of cognitive activity. In this sense, it is a very common phenomenon in everyday modern life. Still, very little is known about the psychophysiological mechanisms underlying mental fatigue. Here, we will try to gain some insight in the mechanisms that are central to mental fatigue and in the cognitive functions that are most affected by mental fatigue.

When people become fatigued, they usually report difficulties in concentrating and focusing their attention on the tasks they are required to perform. For example, Bartlett [1], in his studies in which pilots were required to fly a simulator for extended periods of time, reported that lapses

in attention happened with increasing frequency and that operators became more easily distracted. Similarly, Brown [3] noted that the main time on task effect in driving is a progressive withdrawal of attention from road and traffic demands, which, as expected, had adverse consequences on task performance. These results suggest that attention is specifically affected by mental fatigue.

Attention is a key feature of dynamic human behavior: it allows us to (i) bias the processing of incoming information [7,37,42] so that we can focus on the information that is relevant for achieving the current goals and (ii) to actively ignore irrelevant information that might potentially interfere with those goals.

In the present study, we will examine how mental fatigue affects these attentional processes. Therefore, we had our subjects perform a visual attention task [40] continuously for 3 h, without rest. Subjects were presented with stimulus displays that consisted of two letters at four possible locations (Fig. 1). They were to respond when a target

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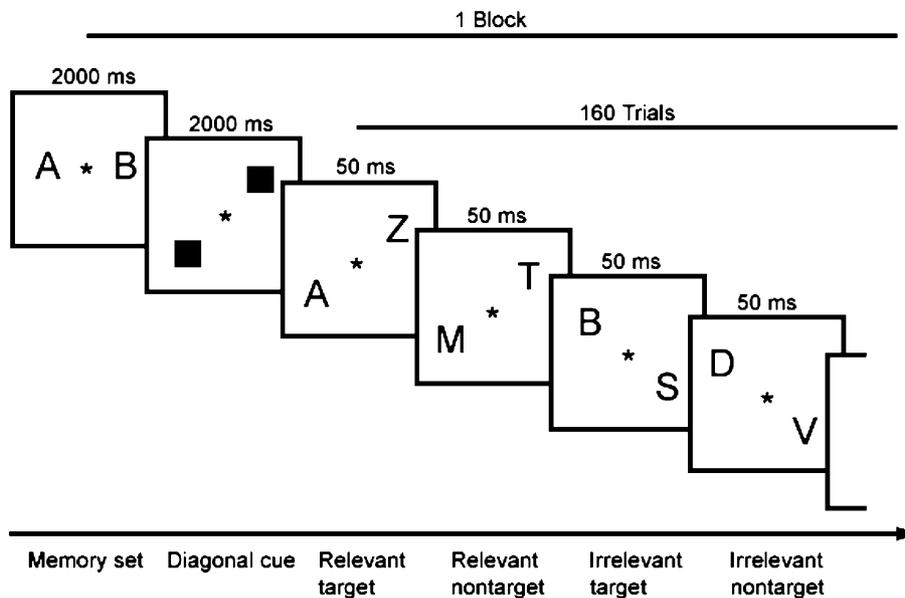


Fig. 1. Stimulus presentation. The numbers above the frames indicate the duration of the presentation in ms. Memory-set presentation is followed by a cue indicating the relevant diagonal. Thereafter, 160 stimulus frames are presented, each during 50 ms with an interstimulus interval between 1000 and 1500 ms. After 160 stimuli (1 block), subjects are presented with either a new memory set or with a new diagonal cue. Four stimulus types are depicted here: relevant target, relevant nontarget, irrelevant target and irrelevant nontarget.

letter appeared at one of the locations that was cued as being relevant. Subjects had to focus their attention on the cued relevant positions and had to ignore stimuli presented on the irrelevant positions. In this way, we were able to detect changes in performance on a task that places high demands on the attentional system, while subjects become more and more fatigued. In addition, by using electroencephalogram (EEG) and event-related potential (ERP) measures, we were able to examine the physiological changes related to fatigue and attention.

Studies on the topic of attention have shown that ERP components reliably reflect the differential processing of attended and unattended information [50]. By recording ERPs to attended and unattended stimuli, direct evidence can be obtained about the level of processing attained by these stimuli. The most consistent finding is a modulation of the posterior P1 (peaking between 100 and 160 ms after stimulus presentation) and N1 (160–210 ms) components by attention (e.g., [8,44,49]). When a particular location is attended, the exogenous P1 and N1 waves elicited by stimuli at that location are enlarged [15,33,34], an effect that has been interpreted as a sign of attentional modulation of sensory processing in the visual pathways [36]. This has been viewed as a representation of a 'sensory gain' mechanism [17]: as a result of biasing the information processing system, the responsivity to stimuli presented at attended locations is amplified, and further processing of these stimuli will therefore be enhanced.

A later component, starting at approximately 200–250 ms post stimulus, consisting of negativity at central electrodes, with a maximum at Cz, has been labeled the N2b component. This ERP component has been found to

reflect the further processing of relevant information (i.e. stimuli that require a response) [25,40,48]. Selective modulation of these attention-related ERP components by the induction of mental fatigue would provide strong evidence that attentional processes are indeed affected by mental fatigue.

One of the most common findings of EEG studies is a shift from fast, low amplitude waves to slow, high amplitude waves when the level of alertness drops. More specifically, under decreased arousal levels, there is a progressive increase in low-frequency theta and alpha activity [23, 24,39], probably reflecting a decrease in cortical activation [5,26]. Therefore, the amount of alpha and theta power provides an adequate index of the level of fatigue that subjects experience. When subjects become fatigued, we would expect the level of arousal to drop, and this would be reflected by an increase in alpha and theta power.

In addition to this objective measure of fatigue, we obtained an indication of the subjective level of fatigue that the subjects were experiencing at that moment. According to Holding [19] and Hockey [18], aversion to further investment of effort in task performance is central to mental fatigue. Therefore, we presented subjects with a visual analog scale on which they could indicate the level of aversion they felt regarding task performance (after Borg [2]), on multiple occasions during the experiment.

In summary, we predict that mental fatigue results in an increase in subjective ratings of the level of fatigue and a shift to slow, high amplitude waves in the EEG. In addition, we predict a selective modulation of ERP components known to be related to selective attention. A deterioration of selective attention would lead to a

decreased ability of subjects to focus their attention on task-relevant items and an increased distractability by irrelevant information. This would result in an increase in the number of missed targets and an increase in false alarms with time on task.

2. Methods

2.1. Subjects

Seventeen healthy participants (8 males), between 18 and 26 ($M = 22$) years of age, were recruited from the university population. They were paid for their participation and had normal or corrected-to-normal vision. Two participants described themselves as being left-handed. None of the subjects worked night shifts or used prescription medication.

2.2. Stimuli

Each experimental block began with the presentation of a fixation cross, which remained on screen throughout a block of trials, and was followed by the presentation of a memory set of two letters (2000 ms). Next, a cue frame, also presented for 2000 ms, was presented to indicate which display positions (left-up or right-up diagonal) were relevant. Thereafter, participants were randomly presented a series of 160 stimulus displays (constituting 1 block), each 50 ms in duration, as illustrated in Fig. 1. Interstimulus intervals varied randomly between 1000 and 1500 ms. Subjects received a new memory set after every odd block and a new diagonal cue after every even block. The following restrictions applied: memory set letters for one block could not be memory set letters for the next seven blocks, and the cued diagonal could not be the same for more than four subsequent blocks.

The stimulus display contained two letters which were randomly presented on either the left-up (50%) or the right-up (50%) diagonal positions. In 25% of the trials, a memory set item appeared at a relevant diagonal position (relevant target), in 25% of the trials, a memory set item appeared at an irrelevant diagonal position (irrelevant target) and in the remaining trials the display contained no memory set items (nontargets). Stimulus letters were randomly chosen from the alphabet, excluding the letters g, i, o, q, u, x and y. The visual angle from the center of fixation to each of the elements was 1.5° . The letters were 0.5° in height.

2.3. Procedure

Subjects were instructed to abstain from alcohol 24 h before the experiment and from caffeine-containing substances 12 h before the experiment. The experimental session started between 12:30 and 14:00 h. After arrival at the laboratory, the subjects handed in their watches. They

had no knowledge of the length of the session other than that it would not last beyond 18:00 h.

Subjects were seated in a dimly lit, sound-attenuated, electrically shielded room at 0.90 m from a 17" PC monitor. The index finger of their preferred hand rested on a touch-sensitive response box. Before the start of the experiment, subjects were given written task instructions, after which they were trained for 4 blocks of 160 trials (approximately 14 min).

Following the application of the electrodes, they were presented with 50 blocks of 160 trials, lasting for 3 h in total. Every block was immediately followed by the next so no rest pauses were given. Subjects were instructed to attend to the relevant display positions as indicated by the cue frame and, in case of the occurrence of a target on one of these positions, to lift their finger from the response button as quickly as possible, maintaining a high level of accuracy.

Before the task and after every 10th block, subjects received a question about the level of resistance they felt at that moment against performing the task (the *aversion scale*). Subjects could respond to this question with a number between zero and ten, zero meaning no aversion, ten meaning maximum aversion.

2.4. Recording

The electroencephalogram (EEG) was recorded using 30 Sn electrodes attached to an electro cap (Electro-Cap International), from positions Fp1, Fp2, Af3, Af4, F7, F3, Fz, F4, F8, Fc5, Fc1, Fc2, Fc6, T7, C3, Cz, C4, T8, Cp5, Cp1, Cp2, Cp6, P7, P3, Pz, P4, P8, O1, Oz and O2. All electrodes were referenced to linked earlobes. The electro-oculogram (EOG) was recorded bipolarly from the outer canthi of both eyes and above and below the left eye, using Sn electrodes. Electrode impedance was kept below 5 k Ω . EEG and EOG were amplified with a 10 s time constant and a 200 Hz low pass filter, sampled at 1000 Hz, digitally low pass filtered with a cut-off frequency of 30 Hz and online reduced to a sample frequency of 100 Hz.

2.5. Data analysis

To investigate the effects of time on task, the data (except for the aversion scale) were divided into four time intervals of 45 min each so that each interval consisted of 12.5 blocks. Data were subjected to SPSS ANOVA for repeated measurements, using the ϵ -adjustment procedure recommended by Quintana and Maxwell [43].

2.5.1. Performance

For the different stimulus conditions in each time on task interval, mean reaction times (RTs), misses and false alarms were calculated. Reactions occurring within a 200–1000 ms interval after the presentation of an attended target were considered as hits. Incidentally, subjects reported that they sometimes forgot the letter set or the relevant diagonal

positions. Therefore, blocks in which performance accuracy was less than 45% were excluded from the analysis. On average, this occurred in about 3 blocks per subject. For the performance measures, we tested the factor time on task.

2.5.2. ERPs

All ERP analyses were performed using the Brain Vision Analyser software (Brain Products). ERPs were averaged off-line. Out of range artefacts were rejected, and eye movement artefacts were corrected, using the Gratton and Coles method [12]. Trials in which subjects made performance errors were also excluded. A baseline voltage over the 100 ms interval preceding stimulus onset was subtracted from the waveforms. The ERPs were averaged over replications and calculated separately for each subject, time on task interval and stimulus category. Using the grand average waveforms, we determined the electrodes showing the largest amplitudes for each of the ERP deflections of interest (P1, N1 and N2B). The P1 was maximal on O1 and O2 and was quantified as the average amplitude in the 100–160 ms latency interval. N1 amplitude was maximal on P7 and P8 and was quantified as the average amplitude in the 160–220 ms latency interval. N2b amplitude was maximal on Cz and was quantified as the average amplitude in the 320–410 ms time interval. The grand averages suggested that overall ERP amplitude on Cz appeared to change with time on task; however, as we were interested specifically in changes in the N2b latency range, we used the difference in amplitude between P2 (quantified as the average amplitude in the 200–260 ms latency interval) and N2b for analysis. Statistical analyses were performed on the average amplitude of the different ERP components in their respective specified time windows, testing the factors time on task, relevance (relevant diagonal vs. irrelevant diagonal) and target (the presence or absence of a memory set item).

2.5.3. EEG spectral power analysis¹

In addition to the ERP analysis, we performed a spectral analysis on the data. Every time on task interval was segmented into 50% overlapping, 5.12 s segments. After artefact detection and ocular correction as described above, the data were submitted to a fast Fourier transform, using a 100% Hanning window. After averaging, power was determined in five separate frequency bands for each subject, electrode and time on task interval. Average power

in these frequency bands was log-transformed (ln) for normalization [11]. We tested for effects in the delta frequency band (0.5–3.5 Hz), theta frequency band (3.5–7.5 Hz), the lower-alpha band (7.5–10 Hz), the upper alpha band (10–12.5 Hz) and the beta band (12.5–30 Hz) on frontal electrodes (F3, Fz, F4), central electrodes (C3, Cz, C4), parietal electrodes (P3, Pz, P4) and occipital electrodes (O1, Oz, O2). Average EEG band power was analyzed for effects of laterality (left, midline and right), region (frontal, central, parietal and occipital) and of course time on task.

3. Results

3.1. Aversion scale

With time on task, subjects developed more aversion against continuation of task performance. Scores increased from 1.0 (SD = 0.9) at the beginning of the experiment to 8.6 (SD = 2.3) at the end, i.e., from hardly any to very strong aversion to continue task performance ($F(5,80) = 40.97, P < 0.001$).

3.2. Performance

The average RTs, percentage of misses and false alarms are shown in Table 1. Subjects on average slowed down and missed more targets with increasing time on task ($F(3,48) = 6.97, P < 0.001$ and $F(3,48) = 7.65, P < 0.005$, respectively). In addition, the number of false alarms increased with time on task ($F(3,48) = 2.97, P < 0.05$). Most false alarms were made when nontargets are presented on the relevant diagonal; almost no false alarms were made when nontargets are presented on the irrelevant diagonal. When targets were presented on the irrelevant diagonal, the number of false alarms lies somewhere in between the other two conditions ($F(2,32) = 34.39, P < 0.001$). This difference in false alarms between conditions was not modulated by time on task ($F(6,96) = 0.41, n.s.$).

3.3. EEG analysis

3.3.1. Delta power

Delta power was greatest on midline electrode positions on Cz and Pz (Region-by-Laterality, $F(6,96) = 19.80, P <$

¹ As suggested by a reviewer, the ongoing band power is potentially confounded with evoked band power: changes in ongoing band power with time on task might also result from changes in evoked band power. Therefore, we performed an additional analysis in which the average evoked activity was subtracted from the EEG before performing the FFT [45]. This analyses revealed that results were minimally affected by this subtraction, indicating that the contribution of evoked activity band power to ongoing band power is negligible. For reasons of clarity, the results without evoked activity subtraction are presented here.

Table 1
Effect of time on task on performance

	Interval 1	Interval 2	Interval 3	Interval 4
RT (ms)	539 (12.0)	550 (11.2)	557 (11.5)	567 (10.3)
Misses (%)	11.5 (1.6)	13.8 (1.4)	16.1 (2.1)	19.7 (2.8)
False alarms (%)	1.5 (0.1)	1.7 (0.2)	2.0 (0.2)	2.1 (0.3)

Shown are reaction times (RT), misses, false alarms and their standard errors for the four time on task intervals.

0.001). No change in delta power was found with time on task ($F(3,48) = 2.39$, n.s.).

3.3.2. Theta power

Theta power was greatest on frontal midline electrodes (Fz and Cz; Region-by-Laterality, $F(6,96) = 36.23$, $P < 0.001$). Theta power increased with time on task ($F(3,48) = 9.81$, $P < 0.001$; Fig. 2). This increase in theta power, however, was the same for all electrode positions.

3.3.3. Lower-alpha power

Lower-alpha power was greatest on Pz (Region-by-Laterality, $F(6,96) = 13.61$, $P < 0.001$). Lower-alpha power increased with time on task ($F(3,48) = 35.66$, $P < 0.001$; Fig. 2), especially on electrodes on parietal sites (Time on task-by-Region, $F(9,144) = 6.43$, $P < 0.005$). Interestingly, the increase in power in this frequency band was positively correlated with the increase in scores on the aversion scale ($r = 0.44$, $P < 0.05$).

3.3.4. Upper-alpha power

Upper-alpha power was largest over occipital sites (Region, $F(3,48) = 27.34$, $P < 0.001$). No effects of laterality could be observed. Power in this frequency band

also appeared to increase with time on task, but this failed to reach significance ($F(3,48) = 3.28$, $P = 0.07$).

3.3.5. Beta power

Beta power was greatest on lateral frontal sites (F3 and F4; Region-by-Laterality, $F(6,96) = 8.73$, $P < 0.001$). Beta power also increased with time on task ($F(3,48) = 6.65$, $P < 0.005$), although the difference was rather small (17% increase). This increase was not different on different electrode positions.

3.4. ERPs

3.4.1. P1

There was no statistical difference in P1 amplitude between electrodes O1 and O2 so amplitude effects in the P1 latency range (100–160 ms) will be reported collapsed over these electrodes. In accordance with findings reported in the literature, averaged ERP waveforms showed a larger positive deflection for stimuli presented on the relevant positions, compared to stimuli presented on irrelevant display locations ($F(1,16) = 29.65$, $P < 0.001$; Fig. 3). P1 amplitude was similar for targets and nontargets. No change in P1 amplitude with time on task could be observed.

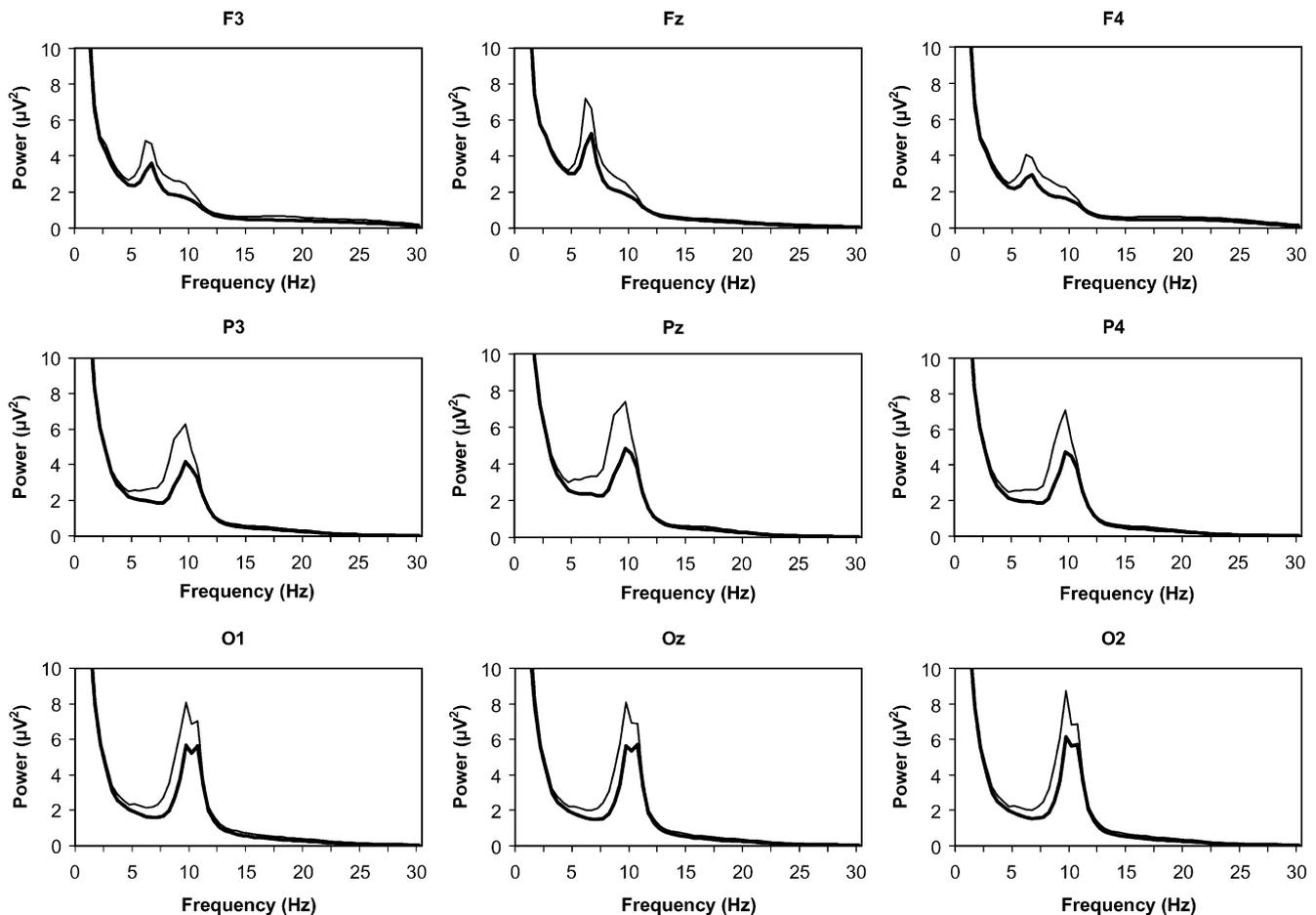


Fig. 2. Effect of time on task on EEG power on frontal (F3, Fz, F4), parietal (P3, Pz, P4) and occipital (O1, Oz, O2) sites in the first (strong line) and last (thin line) time on task interval.

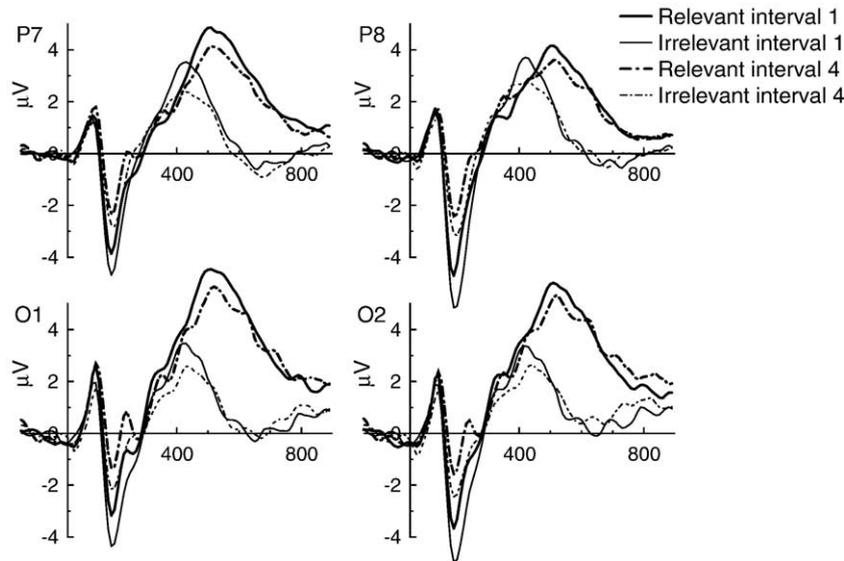


Fig. 3. ERP waveforms on parietal (P7, P8) and occipital (O1, O2) sites for stimuli presented at relevant (strong lines) and irrelevant locations (thin lines) in time on task interval 1 (solid lines) and interval 4 (dashed lines).

3.4.2. N1

Again, there was no statistical difference in amplitudes measured on P7 and P8 so effects will be reported collapsed over electrodes. Contrary to previous findings [15,33,34], stimuli displayed on the irrelevant diagonal showed a larger amplitude in the N1 latency range (160–220 ms) compared to stimuli presented on relevant diagonal positions ($F(1,16) = 23.88$, $P < 0.001$; Fig. 3). This difference was not affected by time on task. In general, however, N1 amplitude decreased with time on task ($F(3,48) = 21.69$, $P < 0.001$; Fig. 3) independent of stimulus type.

3.4.3. N2b

The N2b amplitude (350–410 ms) increased with time on task ($F(3,48) = 8.21$, $P < 0.005$). This change was found to be dependent on whether a relevant or an irrelevant diagonal was presented (Time on task-by-Relevance, $F(3,48) = 7.15$, $P < 0.01$). As shown in Fig. 4, in interval 1, the N2b amplitude for stimuli presented on the relevant diagonal is much more pronounced than the amplitude for stimuli presented on irrelevant display locations. This difference, however, disappeared with time on task as the N2b amplitude for stimuli presented on the irrelevant diagonal increases to the level of the N2b amplitude for stimuli presented on the relevant diagonal. The effects of diagonal were independent of whether a target or a nontarget was presented on these positions.

4. Discussion

Mental fatigue is a very common phenomenon that can have major consequences for everyday task performance. Fatigued people often experience difficulties in concentration and appear more easily distractible. This seems to

indicate a problem in the focusing of attention. In the present experiment, we examined the effects of mental fatigue on attention, using a visual attention task. To induce fatigue, subjects performed this task continuously for 3 h without rest.

Subjects reported increased aversion to continue task performance with time on task. According to Holding [19] and Hockey [18], aversion to invest further effort into task performance is the most reliable characterization of mental fatigue. In this view, the observed increase in subjective levels of aversion against continued performance indeed indicates that subjects became more fatigued during task performance. Additional support for this was gained from the observed increase in alpha, theta and beta power during 3 h of task performance. An increase in alpha and theta band power has been found to be related to a decrease in arousal [23,26,39,41,46]. In addition, Klimesh [23] argued that an increase in lower-alpha power is related to increased efforts (and probably difficulties) of subjects to maintain an alert state. Furthermore, it has been proposed that an increase in beta power results from increased efforts to stay alert [24], possibly reflecting a mounting tension in cranio-facial muscles. Only the observed increase in lower-alpha power in the present experiment was shown to be significantly correlated with the increase in subjectively reported levels of fatigue. Together, this suggests that, in the present experiment, subjects developed increasing difficulties in staying alert and sustain attention so that they could continue to perform the task at an acceptable level. Moreover, the observed increase in scores on the aversion scale and the increase in lower-alpha, theta and beta power suggest that we were able to induce mental fatigue by using time on task.

This increase in fatigue was associated with a clear decrement in performance. Reaction times and the number

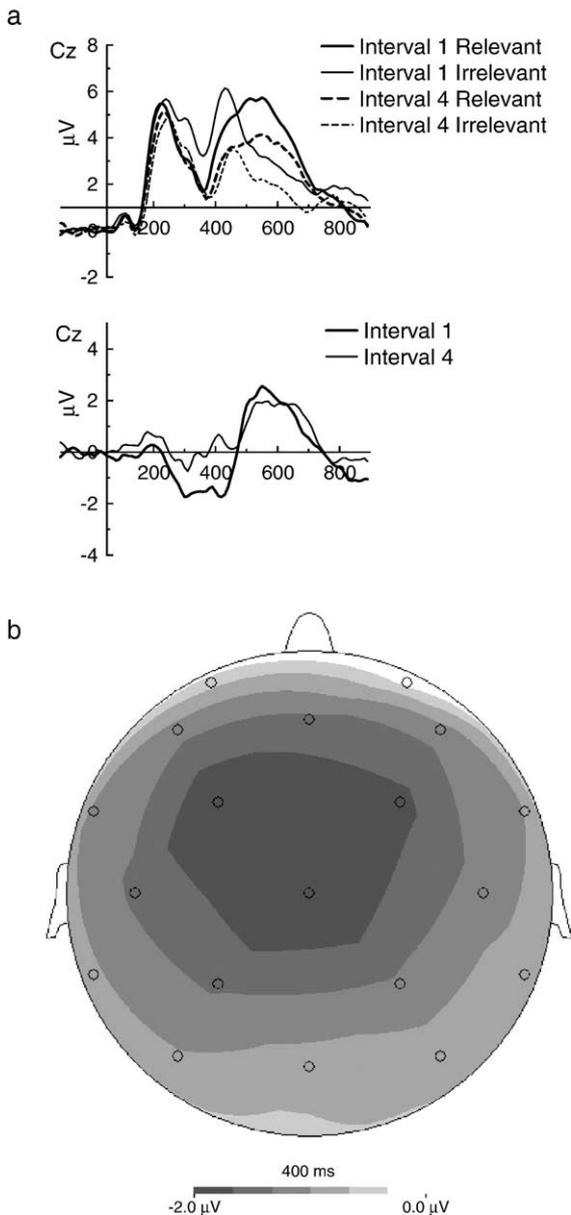


Fig. 4. (a) Top: Effect of time on task on N2b amplitude. Shown are ERPs for stimuli presented at relevant and irrelevant locations in interval 1 and interval 4 on Cz. Bottom: Difference waves (relevant–irrelevant) for interval 1 and interval 4 on Cz. (b) Topography of the effect of time on task on the difference in N2b amplitude between relevant and irrelevant stimuli.

of false alarms and missed targets increased significantly during 3 h of task performance. The fact that the number of false alarms increased suggests that the rather dramatic increase in missed targets was not due to a simple reduction in the number of responses: the number of responses to nontargets even increased. This suggests that the observed deterioration of performance is not caused by task disengagement but may result from increasing difficulties for subjects to correctly identify targets. To examine whether the changes in performance resulted from changes in efficiency of attentional mechanisms, we now turn to the ERP data.

Selective attention mechanisms regulate which information has most impact on behavior by enhancing sensory processing of relevant information and suppressing irrelevant information [21,37]. Selectivity prevents us from reacting reflexively to stimuli in the environment and enables flexibility of behavior [50].

In the present study, we found selective attention effects on the early visual ERP components (P1 and N1). These effects, however, were quite different for both components: P1 amplitude was larger for stimuli presented at relevant locations compared to irrelevant locations, while the exact opposite was true for N1 amplitude. Moreover, N1 amplitude decreased with time on task, while P1 amplitude did not. These differential effects on P1 and N1 indicate that these early attention-related components cannot reflect a single concept like sensory gain. The dissociation between P1 and N1 effects observed in the present study is not a novel finding: several experiments have shown that the P1 attention effect may be observed in the absence of the N1 attention effect and vice versa [14,31,35]. While the P1 may reflect the rather exogenous facilitation of early sensory processing within the focus of attention, the N1 may reflect additional top-down modulation of this early sensory processing.

Here, stimuli presented on the relevant diagonal elicited a larger P1 amplitude, compared to stimuli presented on the irrelevant diagonal. This seems consistent with the gain control function that is thought to be reflected by this component [8,9,16]; the P1 may represent a facilitation of early sensory processing of items presented at locations where attention is focused [31]. Subjects were attending to the relevant diagonal, and processing of stimuli displayed on the other diagonal did not receive as much amplification as did the processing of relevant stimuli. This attentional process was not affected by time on task.

Compared to the P1, the attentional mechanism that is reflected by the N1 component is less clear. As already mentioned, several authors have proposed that these components reflect distinctly different kinds of attentional processes [10,14,29,31,32]. In addition, it has been argued that more than one attentional process is active in the N1 latency range [13,30,32,47]. First, the N1 attention effect (i.e. larger N1 amplitude for attended stimuli) appears to reflect an enhanced processing of attended stimuli, probably involving a discriminative process that is applied to a restricted area of visual space [47]. We will refer to this as the ‘N1 discrimination effect’. Second, an enhanced negativity occurs in the N1 latency range when subjects switch their attention from one location to another [13,14,31,51]. We will refer to this as the ‘N1 reorienting effect’.

The amplitude in the N1 latency range changed with time on task, independent of stimulus category (i.e. relevant or irrelevant). This reduction in N1 amplitude might reflect a reduced amplification of the responsivity to both relevant and irrelevant stimuli, resulting in a reduction in the operation of the discriminative process that is reflected by

the N1 component (i.e. N1 discrimination effect). Thus, fatigued subjects appear to be less able to discriminate targets from nontargets, accounting for the observed increase in the number of missed targets and false alarms.

Comparable to the results reported by Heinze et al. [14] and Luck et al. [31], we observed a larger N1 amplitude for stimuli presented at irrelevant locations, compared to stimuli presented at relevant locations. According to these authors, the obtained N1 enhancement resulted from a reorienting of attention: when a stimulus occurred at unattended locations, an automatic orientation to that location was invoked, and this orientation was accompanied by a negative shift in the N1 latency range (see also [51]; but see [13]). It appears that our subjects, even though they were instructed to attend to the relevant diagonal, were unable to suppress the tendency to orient their attention to the irrelevant diagonal, resulting in a more negative deflection in the N1 latency range, the N1 reorienting effect. Importantly, this N1 reorienting effect did not change with time on task, suggesting that the automatic reorienting of attention was not altered when our subjects became fatigued.

While the early effects of attention (i.e. P1 and N1) reflect that the formation of stimulus representations is modified, the N2b reflects the further processing within the focus of attention of the stimulus after an earlier identification process has determined that the stimulus is relevant [25,40,44,48]. The N2b ERP component showed an increase in negativity with time on task. This increase was shown to be restricted to stimuli presented on the irrelevant diagonal. In the first interval of the present experiment, subjects selected only stimuli that were presented on the relevant diagonal for further processing, reflected by the much more pronounced negativity in the N2b latency range for stimuli on relevant locations; subjects processed stimuli that were cued as being relevant to a higher level, compared to irrelevant stimuli. This selectivity, however, disappeared with time on task: the N2b amplitude elicited by stimuli presented on the irrelevant diagonal increased with time on task until it was of comparable magnitude as the amplitude for stimuli presented on the relevant diagonal. It appears that subjects no longer distinguished between relevant and irrelevant display positions, instead selecting stimuli presented at all locations for further processing.

It is noteworthy that already in the first interval subjects oriented their attention to the irrelevant diagonal, as indicated by the N1 reorienting effect which was present in all intervals. However, in the first interval, subjects were able to prevent the further processing of these irrelevant stimuli, as indicated by the smaller N2b amplitude for these stimuli in the first interval, compared to relevant stimuli. In the remaining intervals, they were unable to inhibit this further processing: the N2b difference between relevant and irrelevant stimuli disappeared.

These results provide us with an interesting dissociation in the way the different attention-related ERP components are affected by mental fatigue. Many authors (e.g., [20])

have argued that attention can be under active voluntary control of subjects but can also be driven externally and automatically. Corbetta and Shulman [6] proposed that two separate subsystems of attention can be distinguished. One is involved in applying goal-directed selection of relevant stimuli. The other system is specialized in the (stimulus-driven) detection of salient stimuli.

The present results indicate that these subsystems of attention are differentially affected by mental fatigue. The finding that the N2b amplitude for stimuli presented on the irrelevant diagonal positions increased with time on task to the level of stimuli presented on relevant positions suggests that subjects no longer apply the goal-directed selection of relevant stimuli when they become fatigued. Instead of selecting only relevant stimuli, they also selected irrelevant stimuli for further processing when they became more fatigued; they seem to become more easily distractible. Moreover, the N1 discrimination effect decreased with time on task. This implies that subjects had increasing difficulties in applying the top-down modulation of early sensory processing that is required for extracting relevant information from the focus of attention. Together, these data strongly suggest that goal-directed attention is negatively affected by mental fatigue. In contrast, the automatic shifting of attention when stimuli were presented on irrelevant locations, reflected by the N1 reorienting effect, was unaffected by time on task. This indicates that the more automatic or stimulus-driven processes are relatively unaffected by mental fatigue. This is corroborated further by the observation that the more exogenous P1 component remained unaffected by time on task.

Interestingly, previous studies in which caffeine (a mild stimulant acting on the central nervous system) was administered show results exactly opposite to the present data. Lorist and colleagues [28] reported enlargement of the N2b component in response to relevant stimuli and a smaller N2b component elicited by irrelevant stimuli, illustrating a more effective selection mechanism due to caffeine, which is indeed exactly opposite to what we found in fatigued subjects. Moreover, a robust finding observed in a number of studies concerns the reduction of power in the theta and lower-alpha band after caffeine treatment [4,22,38]. As several studies have shown that caffeine counteracts the effects of fatigue [27], these results argue in favor of interpretation of the present data in terms of mental fatigue, instead of more general stressors.

In summary, the effects of mental fatigue on behavior seem to a large extent to be caused by an inability of fatigued subjects to allocate their attention efficiently. However, a distinction must be made between the effects of mental fatigue on goal-directed and stimulus-driven attention. Goal-directed attention is shown to be negatively affected by mental fatigue, while stimulus-driven attention was largely unaffected. These results account for both the increased distractibility as well as the decrease in flexibility that is characteristic of fatigued people. When behavior becomes

increasingly stimulus-driven, salient stimuli in the environment will have a greater influence on behavior. At the same time, goal-directed control over behavior will decrease, causing behavior to be guided more by automatic stimulus response couplings, resulting in a reduced behavioral flexibility.

This has some clear implications for everyday task performance. For example, driving a car for most people is a highly automatized behavior. When people are fatigued when driving, this results in a decrease in attention for the road and the other traffic. This would not result in major performance decrements if one can rely on automated behavioral patterns. However, when an unexpected and potentially dangerous situation arises, fatigued people lack the flexibility that is needed to handle the new and unexpected situation in an adequate way, which may result in the high number of traffic accidents that are due to driver fatigue.

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