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Mental fatigue and task control: Planning and preparation

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Abstract

The effects of mental fatigue on planning and preparation for future actions were examined, using a task switching paradigm. Fatigue was induced by "time on task," with subjects performing a switch task continuously for 2 hr. Subjects had to alternate between tasks on every second trial, so that a new task set was required on every second trial. Manipulations of response–stimulus intervals (RSIs) were used to examine whether subjects prepared themselves for the task change. Behavioral measurements, event-related potentials (ERPs), and mood questionnaires were used to assess the effects of mental fatigue. Reaction times (RTs) were faster on trials in which no change in task set was required in comparison with switch trials, requiring a new task set. Long RSIs were used efficiently to prepare for the processing of subsequent stimuli. With increasing mental fatigue, preparation processes seemed to become less adequate and the number of errors increased. A clear poststimulus parietal negativity was observed on repetition trials, which reduced with time on task. This attention-related component was less pronounced in switch trials; instead, ERPs elicited in switch trials showed a clear frontal negativity. This negativity was also diminished by time on task. ERP differences between repetition and switch trials became smaller with increasing time on task.

Descriptors: Mental fatigue, Response–stimulus interval, ERP, Task switching, Time-on-task, CNV

One of the observations often reported in studies examining the effects of mental fatigue on task performance is that subjects are still able to perform more simple, automated tasks, but performance in complex tasks deteriorates (e.g., Holding, 1983). A possible explanation for these effects might be related to the level of processing affected by mental fatigue. Human information processing is generally thought of as a sequence of structural processes or elementary operations, mediating the transformation of a stimulus into a response. Besides these different structural processes, which form a necessary condition for task performance, information processing relies on higher level control mechanisms regulating cognitive functioning (e.g., Kuhl & Goschke, 1994). These control mechanisms are important in planning and checking ongoing and future activities. Performance in more complex tasks depends heavily on these cognitive control processes and these processes might in particular be vulnerable to mental fatigue. This position has been supported since Bartlett, already in 1943, noticed that among the operations affected by fatigue are the coordination and the accurate timing of activities. These effects are regarded as phenomena associated with cognitive mechanisms involved in the control of complex mental task performance. In addition, adequate functioning of cognitive control mechanisms are supposed to be closely linked to energetical aspects of the information processing system. If resources are less activated or less available, cognitive control will function less effectively and behavior will be controlled more strongly by situational or external trigger conditions, as might be the case in mentally fatigued subjects (Norman & Shallice, 1986).

The main question in the present study was whether mental fatigue effects do influence these higher level control mechanisms. To verify this hypothesis, the task switching paradigm introduced by Rogers and Monsell (1995, De Jong, in press; De Jong, Emans, Eenhuistra, & Wagenmakers, submitted) was used. In this task switching paradigm control functions involved in the planning and preparation for future actions can be differentiated. In daily life one always concurrently performs a large number of tasks. Changing from one task to another task requires the set up of a new task set, that is, the adoption of a collection of structural processes configured to deal with a specific task. In the task switching paradigm, subjects had to alternate between tasks on every second trial, which means that a new task set was required on every

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second trial. The difference in response latencies between the completion of these trials and trials in which no switch of task set was necessary, were the so-called "switch costs."

It should be noted that in the used task version, task switches were perfectly predictable. From previous research it is known that the process of adopting a new task set is, at least to some extent, initiated endogenously and can be carried out in anticipation of the change in tasks (De Jong, in press; De Jong et al., submitted; Rogers & Monsell, 1995). Manipulations of response–stimulus intervals (RSIs), and thus the time subjects have to prepare for the coming task, were used to examine whether subjects indeed prepared themselves for the task change. At a long RSI the subject is supposed to have enough time to complete preparation processes before the stimulus arrives. Responses are expected to be fast and accurate. At short RSIs, on the other hand, subjects will not be able to execute preparation processes fully in advance, these processes will still be in progress when the stimulus is presented. Responses are supposed to be slow or inaccurate in this condition. Switch costs that are present in the long RSI conditions are defined as residual switch costs. The evaluation of switch costs under different RSIs might thus provide an adequate way to investigate the influence of higher level cognitive control processes on behavior. In addition, because it is expected that energetical resources are less activated or less available in mentally fatigued subjects (Holding, 1983), it is hypothesized that preparation processes will be carried out less effectively with increasing fatigue, and as a consequence, subjects will benefit less from the long RSIs.

The behavior measures were complemented with event-related potential (ERP) measurements. Whereas reaction times (RTs) reflect the end product of various processes taking place *before* and *after* stimulus onset, different ERP components can give more specific information about the nature and time course of specific underlying processes (e.g., McCarthy & Donchin, 1983; Mulder, Gloerich, Brookhuis, Van Dellen, & Mulder, 1984). It has been argued that the latencies of different ERP components reflect the timing of information processing, whereas amplitude variations of the ERPs are supposed to be related mainly to the intensity of information processing, and thus reflect energetical aspects of the information processing system (Kok, 1990; Mulder, 1986). For example, it has been found that anticipatory or preparatory processes appear as an increase in negativity at the cortical level (Brunia, 1993). More specifically, the stimulus-preceding negativity (SPN) is interpreted as a phenomenon reflecting anticipation processes of task-relevant sensory input, unrelated to motor processes (Van Boxtel, 1994). Scalp distributions suggest a parietal source for the SPN. It is known that the parietal cortex plays an important role in the processing of stimuli, especially if the stimulus cues a response. If indeed preparation processes will be less effective as a function of mental fatigue, it is expected that the SPN will become smaller accordingly. Whereas the SPN reflects preparatory processes, the P3 component reflects stimulus related activity. In general the P3 component is related to stimulus evaluation time and is relatively independent of the time required for response selection and execution. The P3 component was found to be dependent on the state of the subject (Humphrey, Kramer, & Stanny, 1994; Lorist, Snel, & Kok, 1994; Lorist, Snel, Kok, & Mulder, 1994; Polich & Kok, 1995). Humphrey et al. (1994), for example, reported increased P300 latencies and decreased P300 amplitudes with extended wakefulness. However, it should be noted that in the above-mentioned studies (Humphrey, Kramer, & Stanny, 1994; Lorist, Snel, & Kok, 1994; Lorist, Snel, Kok, & Mulder, 1994), sleep deprivation was used to induce fatigue. In the present experiment fatigue was induced by time on task,[1] subjects performed the experimental task continuously for 2 hr during normal working hours and their normal sleep/wake pattern was not disturbed by the experimental procedure. Besides the above-mentioned behavioral and ERP measures, which are closely related to information processing activities, subjective measures were used as more general indices of state of the subject.

In summary, the aim of the present study was to examine the effects of mental fatigue on specific cognitive control processes involved in planning and preparation of upcoming activities.

Method

Participants

Sixteen subjects participated in this study (4 men, 12 women), between 18 and 26 years of age ($M = 22.3$ years, $SD = 2.6$). All subjects reported to be in good health. Subjects did not work night shifts, did not use prescription medication, had normal sleep patterns, and had normal or corrected-to-normal vision. The subjects obtained money for participation. Written informed consent was obtained from all subjects.

Stimuli and Apparatus

During task performance subjects were seated in a dimly lit, sound-attenuated room facing a VGA color monitor of an IBM-compatible PC (640×480 pixels) at a distance of 70 cm. Stimulus presentation and the collection of behavioral data were controlled using Micro Experimental Laboratory Professional Software (MEL v2.0), in conjunction with the Psychological Software Tools' Serial Response Box.

After the presentation of the task instructions, a white square (4×4 cm), subdivided into four squares (2×2 cm), was displayed continuously at the center of the black screen. Stimuli were presented, one by one, in the center of one of these small squares, in a clockwise fashion, starting in the upper left square (see Figure 1). The stimuli were randomly chosen from the set A, E, O, U, G, K, M, and R. The color of the stimuli was randomly chosen from the set red and blue. Stimuli were displayed in an uppercase font (MEL: SWD-S30), and were about 0.5×0.8 cm. Stimulus letters remained on the screen until subjects gave a response by pressing one of two response buttons, or until 2,500 ms had elapsed. After a randomly chosen RSI of 150, 600, or 1,500 ms the next stimulus appeared on the screen. Half of the subjects were instructed to make a left- or right-hand response based on the color (red/blue) of the stimulus if the stimulus appeared in either of the two upper squares, and to respond on base of letter identity (vowel/consonant) if the stimulus appeared in either of the two lower squares (vertical switch). The other half of the subjects were instructed to base their response on color if the stimulus appeared in either of the two right squares, and on letter identity if the stimulus appeared in either of the left squares (horizontal switch). Thus, subjects were instructed to switch tasks every second trial. In the color task subjects were

[1] A point of consideration is that the induction of mental fatigue by time on task is confounded with mental fatigue due to time awake or time of day. In the present study, time on task was manipulated explicitly, therefore we refer to effects of mental fatigue as effects of time on task, to clarify that these effects reflect differences in information processing found by comparing performance observed in different time intervals during the experimental session. However, it should be realized that although time awake was not manipulated differentially in this study, the reported effects of mental fatigue might be due to a combination of both time on task and time awake.

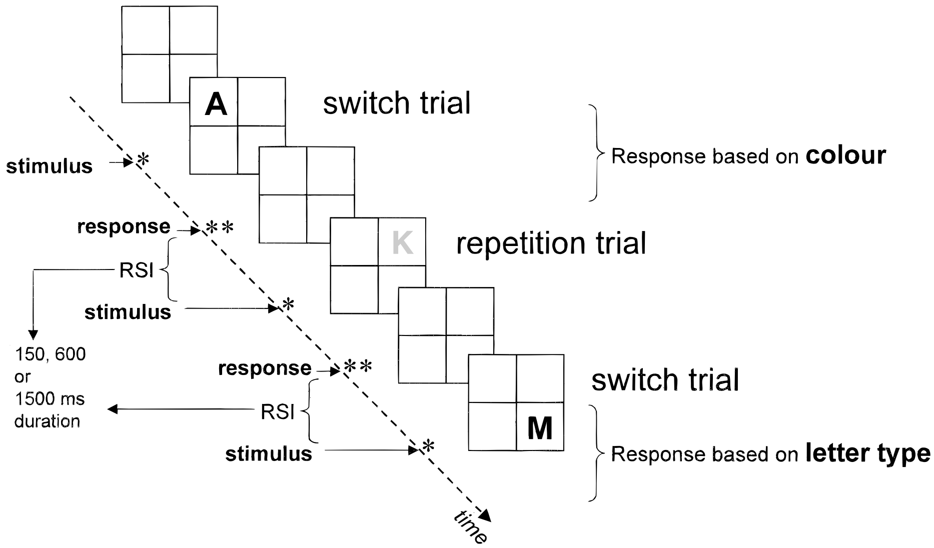

Figure 1. Example of the switch task. In the presented task version, subjects had to give a reaction based on color if the stimulus appeared in the upper squares (red letters are depicted as black letters and blue letters are depicted as gray letters), and a response based on letter type if the stimulus appeared in the lower squares. The asterisks on the time axis represent zero of the stimulus-locked poststimulus event-related potentials (ERPs). The double asterisks represent zero of the response-locked prestimulus ERPs.

instructed to respond to red stimuli with a left-hand button press and with a right-hand response to blue stimuli. In the identity task subjects had to give a left-hand response to vowels and a right-hand response to consonants.

Electroencephalogram (EEG) Recordings

The EEG was recorded, using tin electrodes attached to an electrocap, from midline electrodes at Fz, Cz, Pz, and Oz (10/20 system). All EEG electrodes were referred to the left earlobe. The electrooculogram (EOG) was recorded bipolarly from tin electrodes placed by the outer canthi of both eyes and above and below the left eye. The Ag/AgCl electrode for grounding the subject was placed on the sternum. Electrode impedance was kept below 5 kΩ. The signals were amplified with a bandpass set at 30 Hz and a time constant of 10 s. The signals were digitized at a rate of 100 Hz, using an IBM-compatible PC, the hard- and software functions of which were extended with a data acquisition set.

Subjective Measurements

Mood was measured using the short version of the Profile of Mood States (POMS; Wald & Mellenbergh, 1990). This questionnaire consists of 32 adjectives commonly used to describe momentary mood states. Subjects indicated how they felt at that moment for each of these adjectives on a 5-point scale, ranging from 1 (not at all) to 5 (very much). The five clusters of adjectives representing specific mood states were: tension (score range 6–30), depression (score range 8–40), anger (score range 7–35), fatigue (score range 6–30), and vigor (score range 5–25).

The Scale of Perceived Load (SPL; Dutch: Schaal voor Ervaren Belasting; Meijman, 1991) was filled out as well. The SPL is an easily administered and scored 16-item questionnaire designed to measure various degrees of mental fatigue (e.g., insufficiencies in the willingness to spend capacity and flaws in the capability to spend capacity), that is, fatigue is regarded as an evaluative-motivational assessment of the continuation of activity. To calculate the total score on this questionnaire, the 5-point scale is recoded (1 = 3, 2 = 2, 3 = 1, 4 = 1, 5 = 0; see Meijman, 1991) and subsequently the scores are added (score range 0–48).

Subjects indicated on a simple rating scale, using verbal statements as anchors, the amount of aversion they experienced to perform the next task. Scores varied from 0 (not at all) to more than 10 (maximal).

Procedure

Subjects were tested individually. They passed through a training session, followed, a day later, by an experimental session. In the training session, subjects practiced 40 trials of both the individual color and identity tasks. Thereafter, a task switching condition was practiced for 10 min, in which feedback was given by presenting a tone after the subjects made a wrong button press or missed a trial. The feedback condition was followed by a 10-min version of the task switching condition without feedback.

The experimental sessions started at 1:00 p.m. After subjects arrived at the laboratory the EEG electrodes were applied. This electrode application took approximately 45 min. Subsequently, the subjects were seated in the experimental room and the POMS and the SPL were completed. Then subjects performed the switch task for 2 hr. The task started and ended with a question about the level of aversion subjects felt at that moment against performing the task. Half of the subjects received that question every 20 min during task performance, as well. Subjects were instructed to respond as quickly as possible, maintaining a high level of accuracy. To minimize RTs, it was stressed that the participants should make effective use of the RSI interval to prepare in advance for the upcoming task. After task performance the POMS and SPL were completed, and the electrodes were removed.

Data Reduction and Statistical Analyses

The first 10 trials of the switch task were regarded as practice trials and excluded from analysis. For the remaining trials, the mean RTs and error percentages were calculated separately for switch trials and repetition trials for each RSI, in each time-on-task condition. Behavioral and subjective data were subjected to SPSS multivariate analysis of variance (MANOVA) for repeated measures. Within subject variables were time on task (6 periods of 20 min), RSI (150/600/1,500 ms), and trial type (task repetition/task switch). When the main analysis indicated a significant interaction (α = .05) between factors, follow-up analyses were performed, adjusting error rates according to Bonferroni.

Besides the overall analyses, additional analyses were performed on the behavioral data. To examine the effects of mental fatigue on different parts of the RT distribution, the entire distribution was split into three equal parts, for each subject and condition, the so-called tertiles. The first tertile contains fast responses, the second intermediate responses and the third tertile slow responses. Average RTs were computed for the tertiles and submitted to SPSS ANOVA for repeated measurements, using the $\tilde{\epsilon}$*-adjustment procedure recommended by Quintana and Maxwell (1994). Analyses were performed with time-on-task, RSI, trial type and tertile (fast, mediate, slow) as factors. Because of the much smaller numbers of trials, tertile analyses were not calculated for errors.

Average ERPs were computed separately for each electrode position for the different conditions, that is, time-on-task (2 periods of 20 min),[2] RSI (150/600/1500 ms) and switch condition (task repetition/task switch). The averaging epoch started 100 ms prior to stimulus onset and lasted until 1000 ms poststimulus (see Figure 1). Trials containing ocular- and amplifier saturation artifacts and errors (incorrect responses, misses) were excluded from analysis. The EOG rejection criterion was 50 μV. All averages were aligned to a 100-ms prestimulus baseline. For further analysis mean amplitudes were calculated in 12 periods of 50 ms each, from 100 to 700 ms poststimulus. The mean ERP amplitudes were entered as dependent variables to SPSS. For the statistical analysis of the ERP data the univariate approach for repeated measures was used, using the adjustment procedure recommended by Quintana and Maxwell (1994). Analyses were performed with time-on-task, RSI, trial type and electrode position (Fz, Cz, Pz, and Oz) as factors.

To evaluate the effects of planning and preparation on brain activity, ERPs were computed in the 150-, 600-, or 1,500-ms interval (dependent on RSI) prior to stimulus onset (see Figure 1). These averages were aligned to a 100-ms preresponse (response to the previous stimulus) baseline. After artifact removal, each ERP was divided into periods of 50 ms, and the mean amplitudes in these intervals were calculated and submitted as dependent variables to SPSS. Variables included in the analyses were time on task, RSI (between 0 and 150 ms postresponse: RSI 150, 600, and 1,500 ms; between 150 and 600 ms postresponse: RSI 600 and 1,500 ms; between 600 and 1,500 ms postresponse: RSI 1,500 ms), trial type, and electrode positions (Fz, Cz, and Pz). To evaluate whether no remaining differences in EOG movements over the course of the session were present, analyses were performed on both prestimulus and poststimulus horizontal and vertical EOG signals with time on task as factor.

[2]For the ERP analysis two time-on-task levels were used to reduce the number of repeated levels in order to prevent a precipitous drop in power. Although no signs of practice were observed during the first time-on-task level in the behavioral data, the second time-on-task level (20–40 min) was used in the ERP analysis to ensure that mental fatigue effects were not obscured by practice effects. ERPs elicited in the second time-on-task interval were compared to ERPs elicited in the 100–120-min interval.

Results

No differences in task performance were observed between tasks in which subjects made a horizontal or a vertical task switch, $F(1,14) = 0.87$, *ns*. There were no significant differences observed between the task versions with and without interpolated questionnaires, $F(1,14) = 2.03$, *ns*. Moreover, no interactions between these factors and the other variables were revealed in the statistical analyses, therefore the data were pooled over both horizontal and vertical switch conditions and over task versions with and without interpolated questionnaires for further statistical analyses.

Subjective Measurements

POMS. As expected, feelings of vigor decreased during the experimental session ($M = 15.7$, $SD = 2.9$ and $M = 11.3$, $SD = 4.2$ for the first and second measurement, respectively), $F(1,15) = 21.1$, $p < .001$, and subjects showed higher scores on the fatigue subscale at the end of the session than in the beginning ($M = 11.1$, $SD = 4.8$ and $M = 13.8$, $SD = 5.2$ for the first and second measurement, respectively), although this difference did not reach significance, $F(1,15) = 3.6$, $p = .08$. All subjects reported higher levels of tension during the beginning of the experimental session ($M = 8.7$, $SD = 2.8$) compared with the end of the session ($M = 7.2$, $SD = 1.6$), $F(1,15) = 9.64$, $p = .007$. For the depression and anger subscales of the POMS, no differences were observed between the first and second measurement, $F(1,15) = 2.0$, *ns*, and $F(1,15) = 0.1$, *ns*, for the depression and anger subscale, respectively.

SPL. In accordance with scores on the vigor and fatigue subscales of the POMS, feelings of fatigue as measured with the SPL were higher at the end of the experimental session as compared with scores measured at the start of the session ($M = 15.6$, $SD = 5.9$ and $M = 25.2$, $SD = 8.3$ for the first and second measurements, respectively), $F(1,15) = 22.6$, $p < .001$.

Aversion scale. During task performance subjects developed more aversion against task performance (Figure 2). Scores increased from 1.9 ($SD = 1.3$) to 7.1 ($SD = 2.8$), that is, from hardly any to very strong feelings of aversion to continue with the switch task, $F(1,15) = 62.74$, $p < .001$. The amount of aversion before and after the experimental session did not differ between the group of subjects who received the aversion scale before and after the experimental session and the group of subjects who received the aversion scale each 20 min, $F(1,14) = .01$, *ns*.

Correlations were calculated between the subjective measurements (POMS, SPL, and an aversion score, calculated by subtracting the amount of aversion against task performance measured at the end of task performance from scores measured at the beginning of the switch task) in the total group of 16 subjects. These analyses indicated that there was a significant positive correlation between the scores on the fatigue subscale of the POMS and fatigue measured with the SPL (.55, $p < .05$). As expected, the scores on the vigor subscale of the POMS and the SPL scores showed a significant negative correlation ($-.79$, $p < .01$).

Subjects who scored relatively high on the POMS fatigue subscales reported higher levels of negative feelings (correlations between the fatigue and depression and anger subscales of the POMS were .80, $p < .01$ and .51, $p < .05$, respectively). The aversion scores correlated .47 with the SPL, whereas the scores on the fatigue and vigor subscales of the POMS and the aversion scores correlated .10 and $-.10$, respectively.

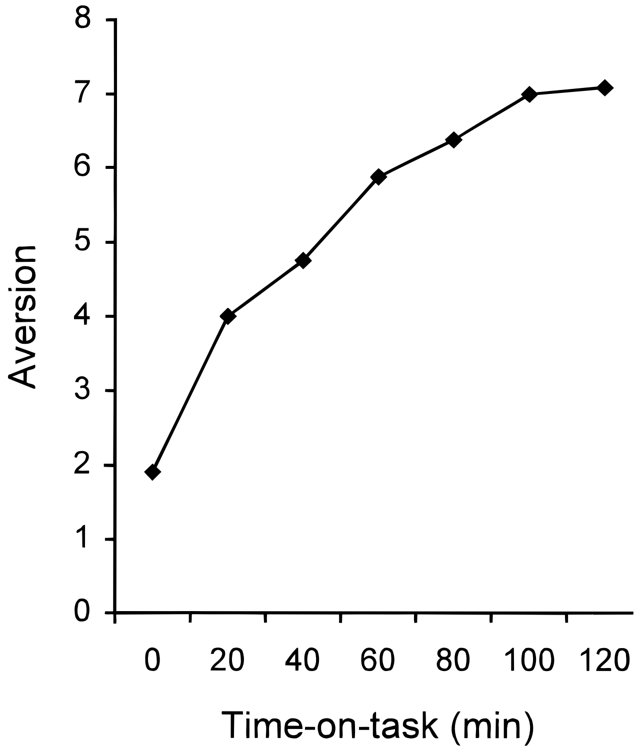

Figure 2. Mean aversion scores depicted as a function of time on task. The first and the last point in the Figure are based on the scores of all subjects, the intermediate scores are based on the scores of those subjects who received the aversion scale each 20 min.

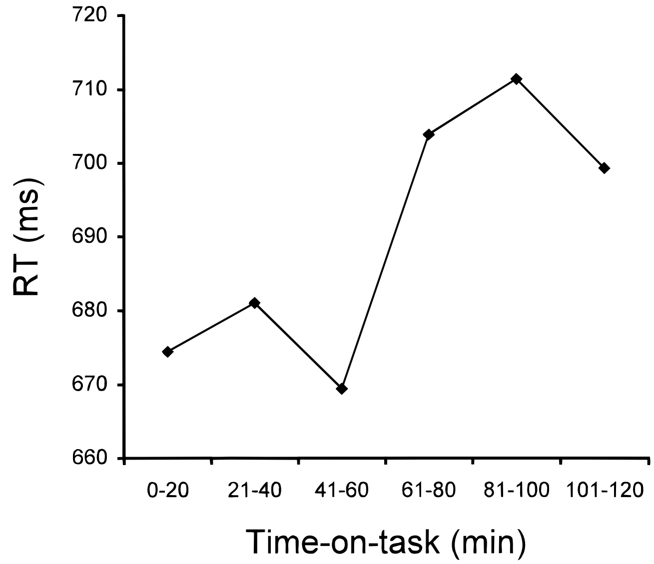

Figure 3. Mean reaction times (RTs) depicted as a function of time on task. The RTs are averaged across different response–stimulus interval (RSI) conditions and trial types.

Performance

RT. The RT data (see Table 1 and Figure 3) showed that subjects on average slowed down during the experimental session, $F(5,11) = 3.59$, $p = .036$, although in the third and sixth time-on-task intervals a small decrease in RTs can be seen as compared with the preceding time-on-task interval. In accordance with previous studies (e.g., De Jong, in press; De Jong et al., submitted), subjects reacted faster on repetition trials (590 ms) in which no change in task set was required than on the switch trials, 793 ms: $F(1,15) = 74.37$, $p < .001$. The overall costs of task set reconfiguration was 200 ms in the present experiment. However, the data indicated that subjects used the long RSI intervals to prepare for the processing of subsequent stimuli. For the switch trials, average RTs became faster with increasing RSIs, RSI × Trial type: $F(2,14) = 39.53$, $p < .001$, and the switch costs were reduced by about 40% as the RSI lengthened from 150 to 1,500 ms. The RTs for the repetition trials did not show a significant difference between the 150- and 600-ms RSI conditions, but in the 1,500-ms RSI condition, instead of a decrease in RT as in switch trials, an increase in RT was observed as compared with RTs in the shorter RSI conditions. The differences between switch trials and repetition trials seemed to be independent of time on task, Time on task × Trial type: $F(5,11) = 0.58$, *ns*.

Errors. The number of false alarms increased significantly during the experimental session from 5.7% to 10.0%, $F(5,11) = 3.43$, $p = .041$. Subjects responded with a wrong button press more often on the switch trials than on repetition trials, $F(1,15) = 70.19$, $p < .001$. No interactions between the factors reached the level of significance.

The number of trials in which no button press was made was low. However, besides the larger number of errors in the switch condition, subjects missed more trials in this condition than in the repetition condition (1.5% and 0.9% for the switch and repetition trials, respectively), $F(1,15) = 6.13$, $p = .026$.

RT distributions. As expected, RTs in the three tertiles differed significantly, $F(1.01,15.22) = 148.17$, $p < .001$ (Figure 4). Inspection of Figure 4 indicates that the differences between repetition and switch trials increased with increasing RT, resulting in the most pronounced differences between trial types in the third tertile, that is, on the slow reactions RT, Trial type × Tertile: $F(1,15) = 74.0$, $p < .001$. Furthermore, Figure 4 shows that the difference between the RSI conditions in the first and second tertile are more pronounced for the switch trials than for the repetition trials. In the switch trials, the fastest RTs were observed in the 1,500-ms RSI condition in which there was enough time available to execute preparation processes. In the 150-ms RSI condition the RTs were slowest. However, this interaction effect did not reach the level of significance in the statistical analysis, RSI × Trial type × Tertile: $F(2.4,36.02) = 2.81$, $p = .065$. In the third tertile, significant differences between RSI conditions were restricted to the repetition trials, $F(1.68,25.17) = 15.42$, $p < .001$. This effect seems to be due mainly to the RTs in the 1,500-ms RSI condition, which were on average 65 ms slower than in the other RSI conditions (814, 828, and 886 ms in the 150-, 600-, and 1,500-ms RSI conditions, respectively). The effects of time on task were most pronounced for the higher end of the RT distribution, that is, in the third tertile, $F(2.22,33.27) = 5.74$, $p = .006$.

To summarize, the RT results are consistent with those of previous studies, indicating that RTs were faster in repetition trials than in switch trials in which a change in task set was required (e.g., Rogers & Monsell, 1995). With increasing time on task, RTs and number of errors increased.

ERPs

Data of three subjects had to be discarded for the ERP analysis. Their ERP signal contained too many eye movement artifacts to

Table 1. *Mean RTs as a Function of Time-on-Task and RSI Condition*

	RSI = 150 ms		RSI = 600 ms		RSI = 1500 ms	
Time-on-task	Switch	Repetition	Switch	Repetition	Switch	Repetition
1–20	830	561	760	559	734	602
21–40	830	576	783	560	732	605
41–60	812	564	769	563	727	573
61–80	850	595	795	586	776	621
81–100	853	602	802	612	784	615
101–120	830	601	792	595	759	618

Note: RT = reaction time (ms); RSI = response–stimulus interval.

compute reliable ERPs. Statistical analysis on the EOG signals of the remaining subjects did not reveal an effect of time on task on either the prestimulus response-locked average or the poststimulus stimulus-locked average.

Prestimulus ERPs. The ERPs superimposed for both trial types and time-on-task conditions, averaged over the three RSI conditions are presented for Fz and Pz in Figure 5.[3] As shown in this figure, the ERPs elicited after a response has been given and before the next stimulus was presented were characterized by a gradual increasing negativity, reaching a maximum after 600–800 ms postresponse at Pz. During the first 250 ms postresponse this negativity did not differ across the task conditions.

After 250 ms postresponse the ERPs started to differ as a function of time on task and trial type. ERPs elicited at the end of the experimental session were less negative going as compared with ERPs elicited in the beginning of the experimental session. The effects of trial type were dependent on electrode position. At the frontal electrode position, the switch trials were more negative going than the repetition trials, while this pattern was reversed at Pz. Differences between trial types were least evident at Cz.

The observed differences between repetition and switch trials decreased with time on task. More specific, the effects of time on task on the difference between trial types reflect a reduction of the negative deflection of the ERPs elicited by switch trials in the 250–550-ms area with a frontal maximum, whereas in the 800–1,050-ms and 1,150–1,500-ms areas the time-on-task effects were mainly due to an effect on the ERPs elicited by the repetition trials, taking the form of a reduction of the parietal negative shift (see Figure 6; Trial type × Electrode position in the 350–850-, 900–1,050-, 1,100–1,200-, and 1,250–1,300-ms areas: $F = 4.67$–11.32, all $ps \leq .041$; Time on task × Trial type × Electrode position in the 250–450-, 550–750-, 800–1,100-, and 1,200–1,500-ms areas: $F = 3.64$–8.75, all $ps \leq .046$; Time on task in the 450–600-ms area: $F = 5.01$–10.78, all $ps \leq .045$). No significant effects of RSI condition were found.

In summary, an increase in negativity in the ERP wave was observed after a response was given. This negativity became less pronounced with increasing time on task. Differential time-on-task effects of repetition and switch trials were observed at frontal and parietal electrode sites. Early effects of time on task at Fz were most pronounced for switch trials, whereas the parietal electrode position reflected effects of time on task on repetition trials.

Poststimulus ERPs. In Figure 7 ERPs are presented for the repetition and switch trials in both time-on-task conditions, super-

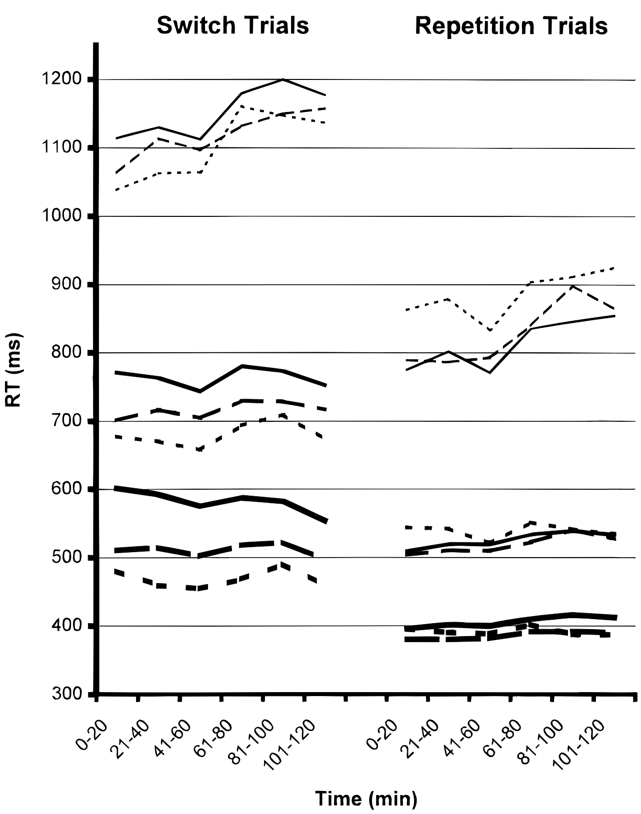

Figure 4. Reaction times (RTs) for the different tertiles for switch (left) and repetition trials (right), superimposed for the three response–stimulus interval (RSI) conditions (solid lines: 150 ms; long dashed lines: 600 ms; small dashed lines: 1,500 ms; thin lines: first tertile; intermediate lines: second tertile; thick lines: third tertile).

[3]It should be noted that in the 0–150-ms interval these averages are calculated over three RSI conditions, in the 150–600-ms interval the ERPs are averaged over the 600- and 1,500-ms RSI conditions, and in the 600–1,500-ms interval Figure 5 shows the ERPs elicited in the 1,500-ms condition.

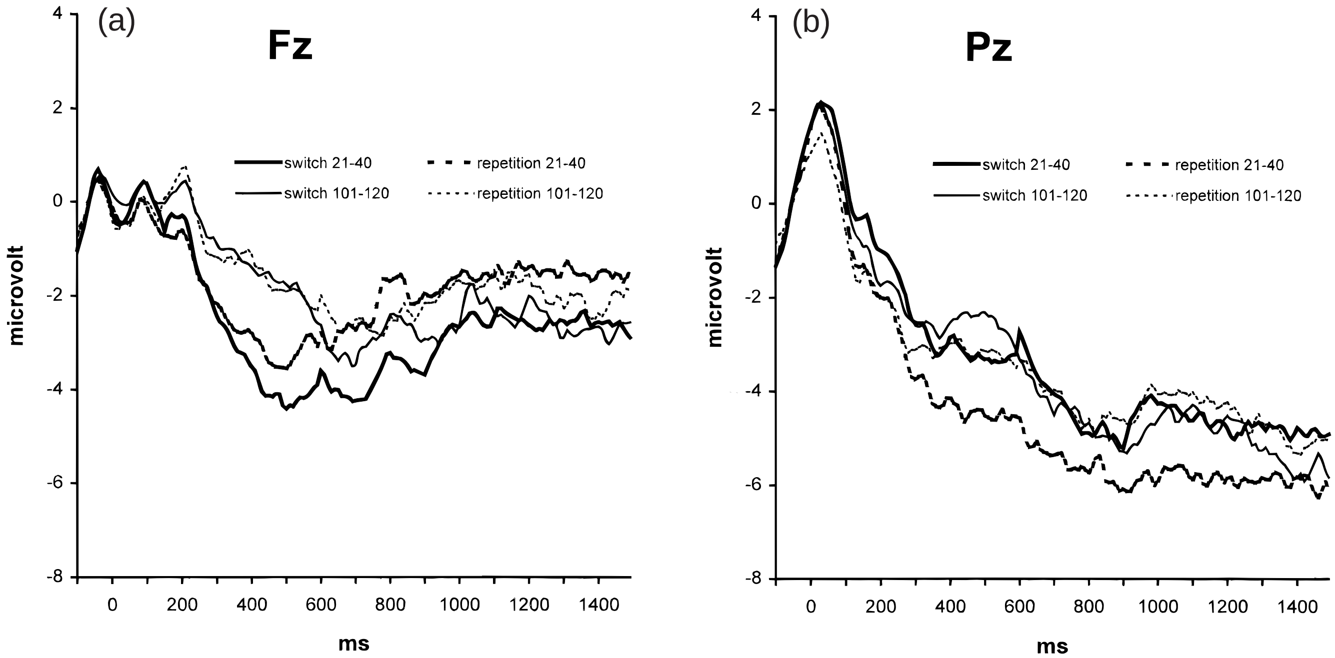

Figure 5. Average response-locked event-related potential (ERP) waveforms as recorded from Fz (a) and Pz (b). The ERPs are averaged across response–stimulus interval (RSI) conditions.

imposed for the three RSI conditions. As shown in this figure, the ERPs were composed of a pattern of P2, N2, and P3 deflections.

RSI. The pattern of ERP components elicited by stimuli in the short RSI (150 ms) condition differed somewhat from the ERPs elicited in the other two RSI conditions. Besides the negative shift of the ERP waveform in comparison to the ERPs elicited in the other RSI conditions, the presence of the P2 component is less prominent than in the 600- and 1,500-ms RSI conditions. From the prestimulus ERPs it is clear that preparation processes, reflected in a cortical negativity, did not reach a maximum amplitude within 150 ms after a given response. It seems therefore plausible that

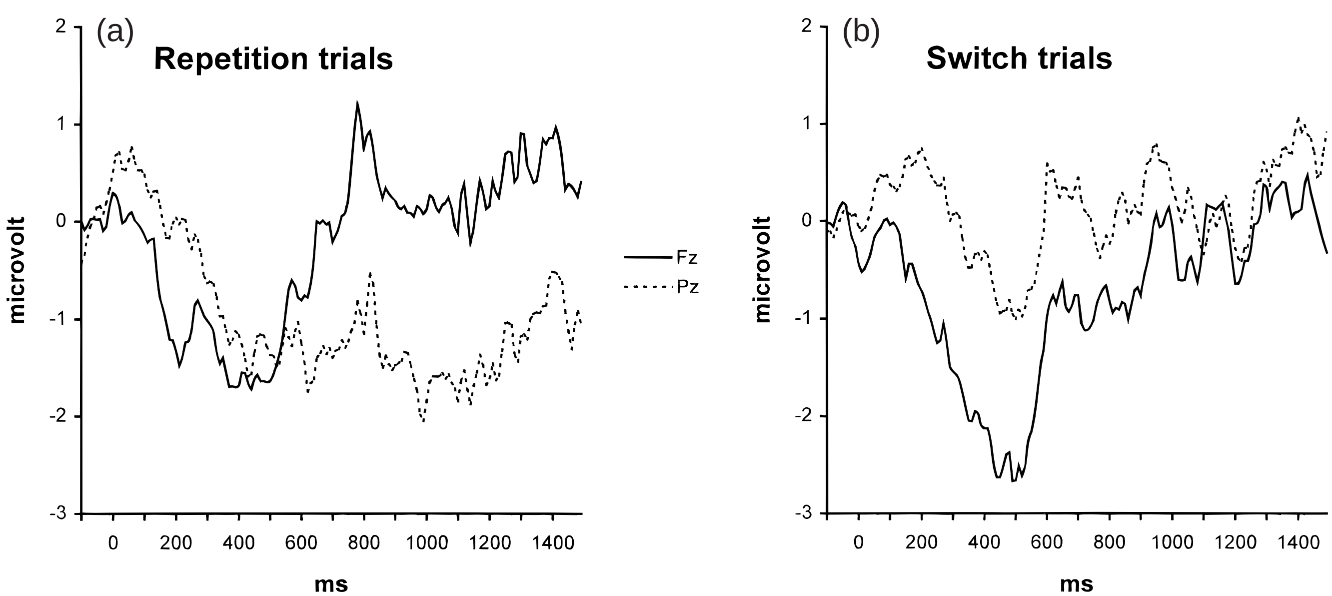

Figure 6. Difference waves of response-locked event-related potentials (ERPs), for the repetition trials (a) and switch trials (b), obtained by subtracting average ERPs for the last time-on-task level (101–120 min) from average ERPs for the second time-on-task level (21–40 min). The difference waves are superimposed for frontal (Fz) and parietal (Pz) electrode sites. The ERPs are averaged across response–stimulus interval (RSI) conditions.

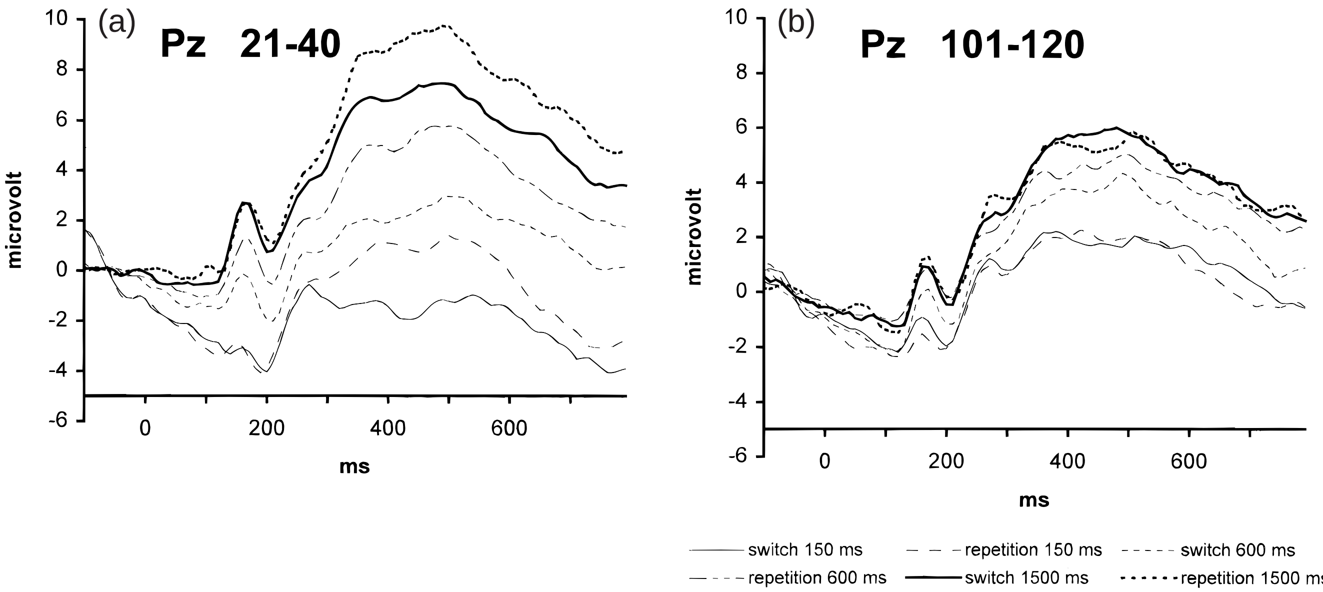

Figure 7. (a) Average stimulus-locked event-related potential (ERP) waveforms evoked during the second time-on-task interval (21–40 min) and (b) last time-on-task interval (101–120 min) as recorded from Pz.

preparation processes continue in the 150-ms RSI condition after stimulus presentation, overlapping with stimulus related brain activity, resulting in the observed negativity.

Focusing on the 600- and 1,500-ms RSI conditions, Figure 7 shows that the ERP components show similar patterns; however, the ERPs elicited in the 600-ms RSI condition are more negative going than ERPs elicited in the 1,500-ms condition (additional analysis; RSI in the 100–700 ms area: $F = 7.56$–32.54, all $ps \leq .018$). It cannot be ruled out that preparation processes are responsible for this negative shift, as well. As in the 150-ms condition, preparation processes could have interfered with stimulus-related information processing in the 600-ms RSI condition. The differences in ERPs elicited in the 600- and 1,500-ms RSI conditions did not differ across electrode positions.

Trial type. Brain potentials to repetition and switch trials differed significantly between 200 and 700 ms. ERPs elicited by the repetition trials were more positive going than in trials requiring a task switch; this effect was most pronounced at the anterior electrode positions (trial type in the 200–700-ms area: $F = 4.99$–24.98, all $ps \leq .045$; Trial type $\times$ Electrode position in the 350–600-ms area: $F = 5.29$–10.25, all $ps \leq .015$). The onset of the observed difference between trial types was dependent on RSI condition (Trial type $\times$ RSI in the 150–300-ms area: $F = 3.58$–4.53, all $ps \leq .043$). Separate analyses for each of the RSI conditions indicated that differences between trial type in the 150-ms condition started around 300 ms (trial type in the 350–600-ms area: $F = 4.89$–8.51, all $ps \leq .047$; Trial type $\times$ Electrode position in the 300–350- and 400–700-ms areas: $F = 5.62$–18.61, all $ps \leq .019$). In the 600-ms RSI condition trial type was already significant in the 100–150-ms area (trial type in the 100–700-ms area: $F = 7.18$–27.70, all $ps \leq .020$). In the long RSI condition (1,500 ms) subjects seemed to have enough time to prepare for the next stimulus, ERPs elicited by both the repetition and switch trials did not differ until 500 ms poststimulus (trial type in the 500–550- and 600–650-ms areas: $F = 5.19$–5.78, both $ps \leq .042$).

Time on task. Time-on-task effects differed across the three RSI conditions. Separate analyses for each RSI condition showed that in the 150-ms RSI condition time-on-task effects started around 250 ms. ERPs were more negative going during the beginning of the experimental session than in the end of the session. Until 400 ms poststimulus this effect was most pronounced at the anterior electrode sites, Time on task $\times$ Electrode position in the 250–400-ms area: $F = 4.52$–4.85, all $ps \leq .030$; time on task in the 350–700-ms area: $F = 5.01$–8.12, all $ps \leq .045$. In the 600-ms condition, time-on-task effects were present between 150 and 700 ms, Time on task $\times$ Electrode position: $F = 4.70$–9.35, all $ps \leq .021$. At frontocentral electrode sites the time-on-task effects took the form of an increased negativity with time on task. At Oz the effects of time on task were caused by a more positive going ERP at the end of the experimental session as compared with the ERPs elicited in the beginning of the session. In the 1,500-ms RSI condition the effects of time on task reflected a negative shift of the ERPs recorded during the end of the experimental session in comparison with the ERPs recorded in the beginning of a session, Time on task $\times$ Electrode position in the 100–200-, 250–400-, and 500–650-ms areas: $F = 3.01$–5.33, all $ps \leq .049$ (between 400–500 and 650–700 ms a trend was observed, all $ps \leq .87$). In addition, the difference between time-on-task effects in the short RSI condition and the 600- and 1,500-ms RSI conditions were most pronounced at the anterior electrode sites, while differences between the 600- and 1,500-ms RSI condition were maximal at posterior electrode sites.

In sum, poststimulus ERPs were overlapped by a clear negativity, especially in the short RSI condition, probably resulting from preparation processes initiated before stimulus presentation. The ERP differences between trials requiring a new task set and repetition trials were dependent on the time available to execute preparation processes, as well. In general, however, ERPs were more positive going for repetition trials than for switch trials.

Discussion

Effects of mental fatigue on cognitive control functions involved in the planning for future actions were examined using a task switching paradigm. Task control is attributed to special executive mechanisms that are supposed to be functionally different from the structural processes that are organized by these processes.

The switch task seemed to be demanding in terms of effort investment and attentional requirements, as reflected in increased levels of fatigue and decreased levels of vigor with time on task. Moreover, aversion against task performance, measured as the experiment passed, increased. Feelings of mental fatigue were accompanied by effects on negative moods (e.g., depression and anger) in subjects scoring high on the POMS fatigue subscale. The observed correlation between the SPL and the aversion scores indicated that increases in levels of mental fatigue were translated into an aversion against task performance or continuation to perform the task at hand.

RSI

The behavioral data observed in the present study replicate the findings of previous studies (e.g., De Jong, in press; De Jong et al., submitted; Rogers & Monsell, 1995); the configuration of a task set takes time. Responses on repetition trials were faster than on switch trials. From the literature it is known that if enough time is available preparation processes can be performed in anticipation of the task switch (De Jong, in press; De Jong et al., submitted). The time necessary to prepare oneself in advance for a new task is about 600 ms. Although Rogers and Monsell (1995) found no decreases in switch costs with increasing RSIs in a task in which RSIs varied randomly between 150 and 1,200 ms, in the present experiment switch costs were found to decrease significantly by about 40% with increasing RSI. It should be noted, however, that the switch costs did not disappear completely in the long RSI condition despite ample time to complete preparation. De Jong et al. (submitted) found that using very short task blocks (12 trials) switch costs almost disappeared in the 1,500-ms RSI condition. However, using longer task blocks (96 trials), switch costs were reduced by no more than 50% (De Jong, in press; De Jong et al., Experiment 2 and 3, submitted). They argued that the execution of preparation processes might be susceptible to mental fatigue. The increase in time on task and therefore the increase in mental fatigue might have interfered with these processes. The further increase in residual switch costs in the present experiment as compared with previous studies supports this notion. In this study, subjects performed on average 4,500 trials during 2 hr of task switching.

In sum, although subjects were found to be able to execute preparation processes in advance of a new task, the behavioral results of the present study indicate that subjects did not always do that. They did not take full advantage of the long RSI conditions, that is, switch costs did not disappear in these conditions. A reason for this effect, suggested in the literature, might be related to effects of mental fatigue on preparation processes.

Time on Task

It was hypothesized in the Introduction that cognitive control functions would become less efficient with increasing mental fatigue. The behavior results indicated that performance indeed deteriorated with time on task, that is, RTs became longer with increasing mental fatigue. During the first hour of task performance subjects seemed to be able to perform at a rather stable level, thereafter, however, a sudden increase in RTs was observed. The occurrence of errors show a different pattern. Several RT studies have suggested that speed and accuracy of performance are closely linked. For example, increases in speed are usually associated with a decrease in accuracy (Pachella, 1974; Wickelgren,1977; Wood & Jennings, 1976). The data of the present experiment show, however, that increases in RT with time on task were accompanied by an increase in error rate, that is, the number of errors increased gradually during the experimental session. These results indicate that with time on task, subjects tried to maintain their speed of performance, as was stressed in the task instructions. However, in order to do so they sacrificed accuracy. After 1 hr of task performance subjects seemed to readjust their strategy again: besides sacrificing accuracy they also modified their speed levels.

It should be stressed now that the behavioral effects of time on task did not differ across both the repetition and switch trials, although switch trials relied more heavily on preparation processes, which are supposed to be vulnerable to mental fatigue than repetition trials in which no change in task set was necessary. It might be questioned whether the underlying processes affected by time on task in both switch and repetition conditions differ.

Repetition trials. Using a task switching paradigm in which task switches occurred less frequently than in the present study, it was found that in normal healthy subjects RTs did not improve further after the first task repetition. It can be concluded that task set configuration is indeed completed after one trial; therefore, in repetition trials subjects do not have to set up the task set again. However, if subjects reached a fully prepared state before the next stimulus arrived, it is necessary to maintain that state in the repetition trials. It is known that this maintenance requires effort (Niemi & Näätänen, 1981). The increase in RT for the repetition trials in the 1,500-ms RSI condition as compared with the short RSI conditions in the third tertile might suggest that subjects prepared but that the prepared state wanes during the long RSI condition. In case subjects are able to maintain the prepared state adequately, RTs are expected to be fast and no differences across RSI conditions are expected. This is exactly what can be seen in Figure 4. In the first and second tertile, the RTs did not differ across RSI condition. In the third tertile, the RTs in the 1,500-ms RSI condition were slower than in the other two RSI conditions. Although, the time-on-task effects are more pronounced in the slow RTs, these effects did not differ significantly across RSI conditions. The question remains whether time-on-task effects in the repetition trials on RTs in the third tertile reflect that the process of task set maintenance is vulnerable to mental fatigue.

Switch trials. In the switch trials the effects of time on task or mental fatigue might influence the execution of preparation processes. In case subjects make use of the available time they have to prepare themselves for a new task, RT will be short. However, as said before, 150 ms is not enough to set up a new task set completely. Switch trials in the 150-ms RSI condition are therefore not or not completely prepared. De Jong et al. (submitted) showed that even if the preparation interval was long enough, subjects did not use the RSI to prepare on all occasions. The average RT in the 600-and 1,500-ms RSI conditions might therefore be regarded as a mixture of prepared and unprepared trials. The tertile analyses confirmed these ideas. The difference between prepared and unprepared stimulus processing, that is, between the RSI conditions, was most pronounced in trials in the fast end of the RT distribution. RTs measured in the 600- and 1,500-ms RSI conditions ending up in this part of the distributions are faster than RTs measured in the 150-ms condition. Due to adequate preparation in the long RSI conditions, differences between repetition and switch trials are small. Slow unprepared trials end up in the third tertile. Concerning these trials no differences were revealed between the three RSI conditions. Although subjects had ample time in the 1,500-ms RSI condition and to a lesser degree in the 600-ms condition they did not seem to use this time consistently. However, effects of RSI condition in the fast end of the RT distribution did not change with time on task. These results therefore, do not support the hypothesis that mental fatigue has an influence on the execution of preparation processes.

Motivation. An alternative explanation for the observed time-on-task effects might be related to the association of the effects of mental fatigue and motivational aspects of cognitive task performance (Bartley & Chute, 1947; Cameron, 1973; Gaillard & Steyvers, 1989), which in turn are strongly related to effort allocation (Sanders, 1983). Sanders argued that these energetical factors have the characteristic that their effect varies strongly across trials. As a consequence, changes in motivational variables are expected to be most pronounced at the higher end of the RT distribution. The data showed that the difference between the time-on-task levels was indeed most pronounced for the slow RTs. In addition, subjects reported an increase in aversion against task performance. Moreover, as mentioned above, the behavioral data indicated that subjects changed their strategy by sacrificing accuracy and speed levels. The attitude or approach to the task in hand seemed to have changed with increasing time on task. As a consequence of changes in internal motivation with increasing mental fatigue subjects might have become more stimulus driven. For the switch trials, for example, this change might have resulted in an increase in the number of trial in which subjects initiated task set configuration processes only after the presentation of a stimulus instead of in anticipation of stimulus presentation.

Prestimulus ERPs

The behavioral data showed that the RTs and the number of errors increased with time on task. As noted above, the question was whether the underlying processes affected by time on task in both switch and repetition conditions differ. Based on theoretical considerations, it can be argued that preparation processes play a more important role in the switch trails, whereas maintenance of a preparatory state seems an important process in the processing of repetition trials. Alternatively, motivational factors play a role in the processing of both repetition and switch trials. Besides behavioral measurements, brain activity was measured during task performance. The ERPs might provide more information about the timing and specific processes involved in the processing of the different trial type conditions.

In the present experiment, a negative-going ERP was observed after a response had been given and before the next stimulus appeared. The data indicate that two separate components could be discerned concerning this negative shift: An early frontal negativity, which was maximal in ERPs elicited by switch trials, and a later parietal negativity, which showed a maximum amplitude in repetition trials.

Switch trials. The early frontal effect might be related to the early contingent negative variation (CNV) wave, which was interpreted as a reflection of a process that controls task performance (Böcker, 1994; van Boxtel, 1994). In the present study, the key press response to the previous stimulus can be regarded as a warning signal, providing information concerning the moment of stimulus occurrence. Although the subjects could not predict exactly when a next stimulus was presented, they knew it would be within 1,500 ms. In the instructions it was stressed that reaction speed was important and that to minimize RTs the RSI interval could be used to prepare in advance for the upcoming task. The enlarged frontal negativity in switch trials as compared with repetition trials presumably reflects these control processes involved in task set reconfiguration, indicating that subjects indeed anticipated to upcoming trials to be able to react quickly. The reduction of this frontal negativity with time on task indicates a reduced response to the warning stimulus. These results support the hypothesis that mental fatigue has an influence on the execution of preparation processes.

Repetition trials. The ERPs elicited by repetition trials showed a less pronounced frontal maximum, instead they elicited a clear negativity at Pz. It is known that stimulus preceding negativity with a parietal maximum can be recorded in anticipation of task relevant stimuli. This parietal negativity recorded during the foreperiod has been related to attentional processes (Böcker, 1994; Brunia, 1993; van Boxtel, 1994). The enlarged parietal negativity in the present experiment in repetition trials as compared with switch trials might reflect attentional processes necessary to maintain the prepared state. The decrease of this negative component with time on task seems to endorse the hypothesis that task set maintenance is vulnerable to mental fatigue. This finding is consistent with that of Aguirre and Broughton (1987), who found that the parietal negativity was sensitive to the state of the subjects. They reported a more pronounced parietal CNV in patients who had daytime sleepiness in comparison with control subjects. In addition, a study by Naitoh, Johnson, and Lubin (1971) demonstrated a reduction in CNV amplitude after one night of sleep deprivation. Peeke, Callaway, Jones, Stone, and Doyle (1980), however, failed to find an effect of sleep deprivation on CNV amplitude.

Poststimulus ERPs

The gradual increasing negativity did not reach its maximum until on average 800 ms after a response had been given, which might indicate that, according to the hypothesis, subjects were not able to execute preparation processes completely in advance in the short RSI conditions in the switch trials. Poststimulus ERP results indicated that if there was insufficient time to complete preparation processes in advance, these processes continued after the presentation of the stimulus, which might have resulted in the observed slowing of RTs in the short RSI conditions. The brain potentials elicited in response to the presentation of a stimulus were modulated by this negative shift in those conditions in which preparation processes were not completed, that is, in short RSI conditions. In these conditions the P3 amplitude was smaller in the switch trials than in the repetition trials. Assuming that the P3 amplitude is a valid measure of energetical resources required in stimulus evaluation processes (Isreal, Wickens, Chesney, & Donchin, 1980; Kramer & Spinks, 1991), the results indicate that these resources are addressed in a greater amount in the switch trials than in the repetition trials, which might reflect a residual of incomplete preparation processes or delayed perceptual processes. An alternative interpretation of the observed P3 effects might be related to the observation that the amplitude of endogenous components, such as the P3, are in general smaller in difficult tasks (Kramer, Wickens, & Donchin, 1983; Näätänen & Gaillard, 1983). Therefore, the smaller P3 in the switch trials might indicate that task complexity is higher in the switch trials as compared with the repetition trials.

This study has uncovered several important factors that are associated with the effects of mental fatigue. It should be stressed that fatigue was not induced by disturbances of the normal sleep/wake cycle or by using patient groups with sleepiness. Within-subject effects were studied on subjective, performance, and ERP measures during 2 hr of cognitive task performance (see Footnote 1). In discussing the behavioral data, we suggested that the time-on-task effects in the repetition and switch trials might be caused by differential effects of mental fatigue in both conditions. Evidence for this conclusion was provided by the ERP data. The attention-related negative shift, elicited in anticipation of a task repetition, became less pronounced with time on task. This effect was interpreted as an indication of the vulnerability of task set maintenance to mental fatigue. The influence of mental fatigue in the switch trials was restricted mainly to an effect on the frontal CNV component. The frontal lobes are important in maintaining the level of cortical activity required for controlled task performance (Van Boxtel, 1994). The effects on the frontal leads with increasing mental fatigue can, therefore, be interpreted as a reduction in the involvement of prefrontal cognitive control processes, and as a reduction in the anticipation of a task switch.

In summary, then, the results showed that the observed increase in subjective levels of fatigue with time on task were accompanied by deterioration in performance. ERP data indicated that different processes seemed to underlie these effects of mental fatigue. The increase in levels of mental fatigue had an effect on preparation processes involved in the planning for future actions. In addition, there were indications that the maintenance of a prepared state seems to be negatively affected by mental fatigue.

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