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Mental fatigue and the control of cognitive processes: effects on perseveration and planning

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Abstract

We tested whether behavioural manifestations of mental fatigue may be linked to compromised executive control, which refers to the ability to regulate perceptual and motor processes for goal-directed behaviour. In complex tasks, compromised executive control may become manifest as decreased flexibility and sub-optimal planning. In the study we use the Wisconsin Card Sorting Test (WCST) and the Tower of London (TOL), which respectively measure flexibility (e.g., perseverative errors) and planning. A simple memory task was used as a control measure. Fatigue was induced through working for 2 h on cognitively demanding tasks. The results showed that compared to a non-fatigued group, fatigued participants displayed more perseveration on the WCST and showed prolonged planning time on the TOL. Fatigue did not affect performance on the simple memory task. These findings indicate compromised executive control under fatigue, which may explain the typical errors and sub-optimal performance that are often found in fatigued people.

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1. Introduction

Working on cognitively demanding tasks for a considerable time often leads to mental fatigue, which can impact task performance. In industry, many incidents and accidents have been related to mental fatigue as the result of sustained performance (Baker, Olson, & Morisseau, 1994). Therefore, in order to prevent or deal with fatigue related errors it is important to understand the nature of mental fatigue and its specific effects on behaviour. However, despite many studies on fatigue, it is remarkably difficult to get a grip on mental fatigue and the cognitive processes underlying its behavioural manifestations (Broadbent, 1979; Desmond & Hancock, 2001; Hockey, 1997; Holding, 1983). The current study was conducted to provide some additional insights into fatigue and its underlying processes. In this study we define mental fatigue as a change in psychophysiological state due to sustained performance (Desmond & Hancock, 2001; Job & Dalziel, 2001). This change in psychophysiological state has subjective and objective manifestations, which include an increased resistance against further effort (Meijman, 2000), an increased propensity towards less analytic information processing (Sanders, 1998), and changes in mood (Broadbent, 1979; Holding, 1983). Sustained performance, in this definition, does not necessarily involve the same task but can extend over different tasks that require mental effort, such as fatigue because of a day in the office (which often also involves several different tasks).

One of the interesting questions in fatigue research is in what way cognitive control of behaviour changes under fatigue. Some researchers proposed that mental fatigue affects those control processes that are involved in the organization of actions and that play a major role in deliberate and goal-directed behaviour (Bartlett, 1943; Hockey, 1997; Lorist et al., 2000; Sanders, 1998). Already 60 years ago, Bartlett (1943) reported observations that support this 'control view' of fatigue. Specifically, after more than 2 h of skilled work, pilots in a flight simulator (the famous Cambridge Cockpit studies) were still able to perform individual actions well, but it was the overall organization of these actions that seemed to suffer. Bartlett stated "... all the time the general drift in the operator is towards a less closely organized and effective central control." (p. 256).

Another relevant finding in fatigue research that supports the 'control view' is that performance on simple or well-learned tasks, which can be executed in a more or less automatic way, can be upheld over long periods of time, after sleep deprivation, or after (mentally) demanding activities. On the other hand, complex tasks that require the deliberate control of behaviour are generally difficult to perform under such circumstances (Broadbent, 1979; Hockey, 1993; Holding, 1983; Sanders, 1998).

These typical effects on different levels of information processing that are found in several fatigue studies and the specific disorganization of behaviour that tends to occur under fatigue both suggest that mental fatigue is mainly characterized by deterioration of *executive control*. Executive control refers to the ability to regulate perceptual and motor processes in order to respond in an adaptive way to novel or changing task demands (Baddeley & Logie, 1999; Miller & Cohen, 2001; Norman & Shallice, 1986). In the current study we examine whether fatigued people indeed show deficits in task performance that indicate that their executive control on behaviour is compromised.

1.1. The nature of executive control

Through executive control humans are able to "... transiently couple almost any response to almost any stimulus, even when there are neither innate nor acquired connections between stimulus and response." (Goschke, 2000, p. 331).

The literature shows that there is some debate about the nature of executive control processes, for example controlled attention (Engle, Kane, & Tuholski, 1999), inhibition of irrelevant information (Fuster, 1989; Miyake et al., 2000), task set maintenance, task set switching (Engle et al., 1999; Fuster, 1989; Miyake et al., 2000; Rogers & Monsell, 1995), and working memory updating (Miyake et al., 2000) have all been proposed as core aspects of executive control. On the other hand, several researchers have also proposed that all these processes have a "... underlying commonality" (Kimberg & Farah, 1993, p. 415), which indicates that there may be some more basic process responsible for the behavioural manifestations of control. In the current study we use a conceptualization of executive control that is assumed to be such a basic control process (Braver et al., 2001; De Jong, 2000, 2001; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Kimberg & Farah, 1993), namely that the control of goal-directed behaviour depends on the ability to keep goals and goal-reated information active in mind (Anderson, 1993; Braver et al., 2001; De Jong, 2000, 2001; Duncan et al., 1996; Kimberg & Farah, 1993). Goals and goal-related information refer to all information regarding the conditions under which certain actions are executed (some researchers refer to this as task context, Braver et al., 2001; Kimberg & Farah, 1993). Such information can be considered a set of end-states and task rules (e.g., when the task is X, then when A and B are both present, do Y) which, when held actively in mind, can indirectly exert their influence on the selection of actions, thereby biasing behaviour towards goal-attainment (Anderson, 1993; Duncan et al., 1996; Kimberg & Farah, 1993). For clarity, we henceforward refer to the activation level of goals and goal-related information as goal-activation (Duncan et al., 1996).

During compromised executive control, it is not the mental representation of the goal itself that is affected. Instead it is the activation level through which a goal can influence the selection of actions, that is reduced (De Jong, 2000; Duncan et al., 1996; Kimberg & Farah, 1993). During periods of reduced goal-activation, actions are guided by more automatic processes, which are triggered by situational or external cues, even when this is inappropriate. Duncan et al. (1996) referred to such periods as goal-neglect, which may be underlying many of the problems of executive control. In general, Duncan et al. (1996) argued that when executive control is compromised "... in different contexts the patient (which has difficulties with executive control) may appear perseverative or distractible, rigid or inappropriate, passive or impulsive and disinhibited" (p. 258). We assume that fatigued people display a tendency to reduce executive control, and consequently show similar deficits in task performance.

1.2. Mental fatigue and executive control

There are only few studies that explicitly investigated the effects of mental fatigue from an executive control perspective. One set of studies investigated the effects of fatigue on response planning and task switching, both being important aspects of executive control. Lorist et al. (2000) used behavioural and EEG-data to study the effects of time-on-task (i.e., mental fatigue) on planning and task switching. The EEG-data of their study showed that with increasing time-on-task there was a reduced involvement of those brain areas that are associated with the exertion of executive control (the frontal lobes). This result supported their initial expectations on the effects of mental fatigue. In addition fatigue led to an increased number of errors and an increase in reaction time (Lorist et al., 2000). However, the study did not reveal differential effects of fatigue on switch and non-switch trials, nor did it show effects of fatigue on response planning. Thus, at the behavioural level, a specific effect of mental fatigue on task switching (executive control) was not found.

De Jong (2000) also studied the effects of fatigue (time-on-task) on task switching and response planning. He investigated whether reaction time costs of task switching were due to periods in which participants did not engage in response planning even though they had the opportunity to do so. Moreover, he assessed whether fatigue influenced the number of periods in which participants did not seem to engage in planning. In this study, fatigue did not affect response planning.

Thus, even though fatigue literature suggests that fatigue affects high-level information processing, the studies by De Jong (2000) and Lorist et al. (2000) did not unambiguously showed an effect of mental fatigue on executive control. There are several possible explanations. In the studies by Lorist et al. and de Jong, mental fatigue was operationalized as the time spent on the same task. Thus, after some time, participants in the task switching studies (De Jong, 2000; Lorist et al., 2000) might have had so much practice that some of the processes of task switching could have been executed automatically. However, executive control on behaviour is particularly important when a task is novel (Dias, Robbins, & Roberts, 1997; Duncan et al., 1996). For example, Dias et al. (1997) found that inhibition problems in task switching were mainly found in situations where a switch was novel and not well practiced. Hence, with well-practiced participants it would be much more difficult to detect effects of fatigue on executive control processes. Moreover, in a task-switching paradigm, participants are told exactly what to do, which reduces the need to develop own strategies and to engage in complex problem solving. However, developing strategies in a complex task and reacting to changes in task circumstances are situations that typically put heavy demands on executive control (Duncan et al., 1996; Fuster, 1989; Miller & Cohen, 2001) and thus these types of behaviour may be vulnerable when mentally fatigued.

In the current study we investigated the effects of mental fatigue with a different design. First, we induced fatigue by using tasks that are different from the experimental tasks. Thus, we measured the effects of mental fatigue between-tasks instead of within-tasks. The advantage of this approach is that the tasks after the fatigue manipulation were novel and can be expected to put heavy demands on executive control. Second, we used tasks that are not strongly structured but that required the participants to develop their own strategies and to adequately process feedback. Specifically, we expect that in such complex tasks, fatigued people show deficits in two major aspects of problem solving that are considered hallmarks of executive control, namely, flexibility and planning (Fuster, 1989; Gazzaniga, Ivry, & Mangun, 1998; Norman & Shallice, 1986; Shallice, 1982). A deficit in flexibility often manifest itself in behaviour as a tendency to perseverate or to hold on to an ineffective strategy (Milner, 1963; Norman & Shallice, 1986), whereas deficits in planning can be observed by a tendency to initiate actions without considering a strategy beforehand, by ineffective plans, or by increased planning time (Oaksford, Frances, Grainger, & Williams, 1996; Owen et al., 1995; Shallice, 1982). To test whether fatigue leads to these specific changes in task behaviour we used tasks that have been used extensively in executive control research, namely, the Wisconsin Card Sorting Test (WCST) (Milner, 1963) and the Tower of London (TOL) (Shallice, 1982).

1.3. The Wisconsin Card Sorting Test

WCST was used to test whether fatigue concurs with increased perseveration, which would indicate compromised executive control. In the WCST, participants have to discover how to sort cards that hold geometrical figures. Sorting rules in this task are based on the colour, shape, or number of figures on the cards. However, because no detailed instructions are given, participants have to discover the sorting rules by themselves through systematic exploration. In the WCST, such exploration is supported by feedback after each trial. Once participants discovered the currently active sorting rule (which in the WCST is operationalized as 10 correct responses after each other), the rule changes without notice. Subsequently, participants have to use the feedback to notice that the sorting rule has changed and then they have to discover the new sorting rule.

Many clinical studies showed that the most common measures to assess executive control in the WCST are the number of perseverative errors and the number of discovered sorting rules (Heaton, 1981; Milner, 1963; Norman & Shallice, 1986; Somsen, van der Molen, Jennings, & van Beek, 2000). Perseveration in the WCST means that people tend to continue applying previous sorting rules that are no longer valid. In accordance with the conceptualization of executive control we employ in the current study, Kimberg and Farah (1993) used cognitive modelling to show that perseveration in the WCST can be ascribed to decreased goal activation. When feedback information about the invalidity of the current sorting rule is not held sufficiently active in mind, actions continue to be guided by previous sorting rules, which already had a high activation level (Kimberg & Farah, 1993). As a result of perseveration and the use of inflexible strategies to search for the sorting rule, sub-optimal executive control has also been associated with a low number of discovered sorting rules (Milner, 1963).

Besides perseverative errors, there are also other types of non-perseverative errors that people make on the WCST (Heaton, 1981; Milner, 1963). Several underlying reasons have been proposed for non-perseverative errors. For example, incorrect guessing when trying to discover the sorting rule, or difficulties in holding the current sorting rule active in mind (lapse in task set maintenance, Hartman, Bolton, & Fehnle, 2001; Paolo, Troster, Axelrod, & Koller, 1995). Studies that also examined non-perseverative errors in the WCST, showed somewhat mixed results. Some studies report that compromised executive control did not only lead to perseverative errors but also to non-perseverative errors. Paolo et al. (1995) reported that in the elderly (who show deficits on the WCST) perseverative and non-perseverative errors were positively related ($r = 0.64$). However, in most studies, an increased number of perseverative errors were the most frequent result (cf. Heaton, 1981). Thus, we expect that mental fatigue will mainly coincide with increased perseveration.

Somsen et al. (2000) argued that the WCST consists of two qualitative different types of problem solving, namely rule application and rule search. Rule application means that, once the sorting rule is discovered, participants have to remember by which rule to sort and to perform some relatively simple cognitive operations (e.g., match the cards on colour). On the other hand, when the current sorting rule is unknown, participants have to engage in Rule search, which involves flexible reactions to task feedback and conceptualization of new task rules. There are several (psychophysiological) studies showing that rule search put heavy demands on executive control processes, whereas rule application does not (Barcelo, Munoz-Cespedes, Pozo, & Rubia, 2000; Konishi et al., 1999). The response times that participants show during Rule search and rule application may provide additional insight into the processes underlying task behaviour. Specifically, several studies showed that automatic response selection takes less time than response selection that involves executive control (Monsell & Driver, 2000; Sanders, 1998; Shiffrin & Scheider, 1977). Thus, shortened response times during rule search and increased perseveration would support the idea of compromised executive control during conceptualization of sorting rules. On the other hand, prolonged response times and increased perseveration would indicate that executive control is exerted yet is ineffective in preventing inappropriate actions. In the current study, we analyse response times during Rule search and rule application to examine which pattern of response time and errors in the WCST may occur under fatigue.

1.4. The Tower of London

We used the TOL, (Shallice, 1982) to test planning processes under fatigue. The TOL is a puzzle in which participants have to rearrange coloured beads over pegs until they match a goal-state. The TOL measures planning because effective performance requires goals and sub-goals to be determined before one starts to act (Hodgson, Bajwa, Owen, & Kennard, 2000; Owen et al., 1995; Shallice, 1982). In addition, the TOL also assesses flexibility as each new TOL-trial requires the development of new strategies and the 'inhibition' of previous strategies that are no longer valid in the current task context (Hodgson et al., 2000). Because planning and flexibility depend on the ability to let behaviour be guided by task goals (Duncan et al., 1996) and because the TOL was designed as a relatively pure measure of executive control (Shallice, 1982), we expect that fatigued people show planning deficits on the TOL. Quality of planning is assessed by the combination of reaction time and performance measures. An important reaction time measure in the TOL is the time between the presentation of a trial and the first move. This time is generally considered to reflect planning processes (Anderson, 1993; Hodgson et al., 2000; Owen et al., 1995; Shallice, 1982). In addition, the number of moves to solve a TOL-trial is an important performance measure that reflects how effective the initial planning was (Oaksford et al., 1996; Shallice, 1982).

In the TOL task, fatigued participants may become more impulsive, meaning that they will minimize or skip planning. However, because of poor planning they would need more moves and may also need more time to solve the trials. In the TOL, such performance deficit manifests itself in short first-move times and increased number of moves. Similar patterns of performance deficits on the TOL are found in people with frontal lobe damage, who are impaired on executive control (Goel & Grafman, 1995; Hodgson et al., 2000; Owen et al., 1995; Shallice, 1982). Compared to such groups of patients, it can be expected that the effects of fatigue on executive control in normal participants are much less severe and may even arise from different underlying (neurological) processes. Consequently, we expect that fatigued people may still attempt to plan their behaviour, yet such planning may be inefficient. If this is so, then actual performance on the TOL in terms of number of errors and problem-solving time may not show strong deficits yet planning time would be prolonged. Such specific effects on the TOL are sometimes reported in studies on the effects of mood or in studies on Parkinson disease patients, who are impaired on executive control (Cools, Stefanova, Barker, Robbins, & Owen, 2002; Hodgson et al., 2000; Owen et al., 1995).

1.5. Control measure

Although the main emphasis in the current study is on the WCST and the TOL, we also used a forward digit span as a control measure. Compromised executive control under fatigue implies that not all aspects of cognitive performance are affected under fatigue but only those aspects that involve flexibility, planning, and the deliberate regulation of actions (Norman & Shallice, 1986; Riccio et al., 1994; Shallice & Burgess, 1991). The forward digit span task requires to keep information in mind for a short period and to reproduce that information, which does not heavily rely on executive control (Baddeley & Logie, 1999; Norman & Shallice, 1986). Norman and Shallice (1986) argued that the digit span is relatively insensitive to compromised executive control because the task relies on "..maintenance rehearsal schemas, which in most people is a well-learned routine skill" (p. 15). Moreover, Kimberg and Farah (1993) argued that simple memory tasks are not affected by compromised executive control because these tests do not involve different sub-sets of goals that may interfere with each other (as in the WCST or the TOL). Hence, holding goals and goal-related information in mind and updating this information in the light of changing task context is not an issue in these tasks.

When digit span performance stays unaffected by mental fatigue this indicates that effects of fatigue on the WCST and TOL may not be ascribed to a 'simple' inability to hold information in mind or to general lack of compliance of fatigued participants.

2. Method

2.1. Participants

Fifty-eight undergraduate college students participated in this study (15 males and 43 females, Mean age = 21 years, SD = 2.5). Participants were paid €20 for sessions that lasted approximately 4 h. Participants were randomly assigned to a fatigue ($n = 31$) or a non-fatigue ($n = 27$) condition.

2.2. Materials

2.2.1. The Wisconsin Card Sorting Test (Milner, 1963)

We used a computerized version of the WCST in which four target cards were presented at the upper half of the computer screen. These target cards differed from each other on the sorting dimensions (colour, shape, and number) and remained visible at each trial. Each trial, a new sorting card was presented at the lower half of the computer screen. Participants sorted a card by pressing a button on the keyboard that corresponded to a target card (buttons '1', '2', '3', and '4' on the keyboard). After a sorting response, a big plus sign with the word 'Correct' in it was presented when the sort was correct or a big minus sign with the word 'Wrong' when the sort was incorrect. The feedback stayed on the computer screen until participants pressed the ENTER-button, after which the next card was presented.

When participants had discovered the sorting rule, the rule switched without notice. The WCST had six rule-switches built in. Every sorting rule occurred twice. The WCST ended after a participant discovered all six sorting rules (corrected six time 10 correct sorts) or after a maximum of 128 trials.

Dependent measures. Performance measures of the WCST, were rated by the computer using the algorithms as proposed by Heaton (1981) and comprised perseverative errors, unique errors in which cards were sorted in a way that did not match any of the sorting dimensions (shape, colour, or number), and miscellaneous errors which consists of all errors that were not perseverative or unique errors. In the WCST, unique errors are generally very rare. A large proportion of unique errors indicate that participants did not adopt a reasoning strategy. Therefore, similarly to Somsen et al. (2000) we adopted a criterion of 30% unique errors to exclude participants from further analyses. In the current study, only one participant matched this criterion (this participant had 42% unique errors) and was excluded from further analyses.

Rule Application RT was operationalized as the median RT of all trials that fell within a sequence of 10 correct responses plus the first response thereafter. Rule application was considered a baseline reaction time to perform some simple cognitive operations (e.g., match features of the cards).

Rule Search RT was operationalized as the median RT of those trials that preceded a sequence of 10 correct trials (discovered rule).

2.2.2. The Tower of London (Shallice, 1982)

The TOL consists of three pegs on which three coloured beads have to be configured in the same way as in a given goal-state. We used a computerized version of the TOL in which the pegs and beads were presented in the middle of the screen. The goal-state was presented in smaller format at the upper right corner of the screen. Participants could manipulate beads by dragging and dropping them with the mouse. Restrictions during the task were that the maximum number of beads on a peg was determined by the length of a peg. Furthermore, it was not possible to drag beads that had other beads on top of them. The entire TOL-test consisted of 18 different configuration problems (18 trials).

The main dependent measure of the TOL to assess planning is the median First Move RT from the beginning of TOL-trials. This is the time from the initial presentation of a TOL-trial to the time of the first response. Other measures to assess TOL performance were the average number of moves needed to perform the trials, the median time per TOL-trial, the total number of rule violations (e.g., trying to drag a bead that has another bead on top).

2.2.3. The forward digit span

We used a computerized version of the digit span. Each trial, every second, a digit was presented on the screen. After the presentation of the digits, the participant was prompted to fill in the digits on the screen. The tasks started out with a four-digit sequence trial. If the participant correctly answered a trial, the next trial consisted of a sequence with one digit more. Otherwise the next trial had an equal number of digits. The task consisted of 10 trials. The digit span was measured at the beginning of the experimental session and right after the manipulation.

2.2.4. Fatigue manipulation

Fatigue was induced through a so-called scheduling task on the computer (Taatgen, 1999). In this task, participants had to assign work to fictional employees. The duration of the work and the availability of employee hours differed per trial. Furthermore, in each trial there was a set of conditions, which had to be fulfilled (e.g., tasks B and E had to be performed before A). A limited amount of time was available for each scheduling trial, depending on the number of variables and difficulty of that trial (time ranged from 5 to 12 min). There was no information on intermediate results on the computer screen and no external memory aids were allowed; thus the task required a high degree of mental effort. Moreover, sustained performance on this task has been shown to induce mental fatigue (van der Linden, Frese, & Sonnentag, submitted).

2.3. Manipulation check

2.3.1. Subjective fatigue

Subjective fatigue was measured with the Rating Scale Mental Effort (Zijlstra, 1993) which consists of seven 150-point answer scales that refer to several aspects of fatigue. The Rating Scale Mental Effort is used as a single measure of fatigue (Mean Cronbach's Alpha, pre- and post-manipulation measure = 0.91). The Rating Scale Mental Effort was filled out before and after the manipulation.

2.3.2. Task motivation

We included a measure of motivation to continue with the experiment and to do one's best in the experimental tasks. We constructed four items in a seven-point Likert format in which participants were asked how much effort they were willing to put into the tasks and how much they wanted to do their best. The motivation scale was given directly after the manipulation (Cronbach's alpha = 0.88).

2.3.3. Mood

Because fatigue is generally found to affect mood, we also measured mood states with four sub-scales of the short version of the translated Profile of Mood States (Wald & Mellenbergh, 1990). The sub-scales measured anger, depression, tension and vigour. The sub-scales of the Profile of Mood States were given before and directly after the manipulation.

2.3.4. General intelligence

As an additional control we measured general intelligence to examine whether IQ was related to performance on any of the experimental tasks. Intelligence was measured with Raven's (1962) Advanced Progressive Matrices. We used a paper and pen version and gave the participants a maximum of 30 min to work on the test before the manipulation.

2.4. General procedure

Participants were tested individually in sessions that lasted about 4 h. At the beginning of the session, participants filled out the Rating Scale Mental Effort and the Profile of Mood States. Then they worked respectively, on the digit span task and for 30 min on the Advanced Progressive Matrices. The manipulation followed directly after the Progressive Matrices. Participants in the fatigue group had to work on the scheduling task for 2 h (this implied that participants in the fatigue condition worked on cognitively demanding tasks for 2.5 h: Advanced Progressive Matrices plus scheduling task). The participants in the control group were told they had to bridge 2 h. Within this time they had to stay in the laboratory and were allowed to read some magazines or otherwise spend their time as they wanted (care was taken that they did not engage in any cognitively demanding tasks such as studying).

After the 2-h manipulation, participants filled out the Rating Scale Mental Effort, Profile of Mood States, and the motivation questionnaire. Then participants worked respectively on the digit span task, the TOL (18 trials), and the WCST. Due to technical reasons we decided not to counterbalance the order of presentation of the task.

3. Results

3.1. Manipulation check

3.1.1. Fatigue

Reported fatigue (Rating Scale Mental Effort) was submitted to analysis of variance with time of measurement (before vs. after the manipulation) as a within-subject factor and condition (fatigue vs. not) as between-subject factor. This analysis suggests that our manipulation was successful. We found a significant interaction between time of measurement and condition ($F(1,55) = 42.31$, $p < 0.001$), see Table 1 for means. Post-hoc tests showed that the fatigue and non-fatigue groups did not differ on reported fatigue before the manipulation ($F(1,55) = 0.46$, $p > 0.05$) but significantly differed after the manipulation ($F(1,55) = 17.14$, $p < 0.001$). Moreover, the participants in the fatigue group increased in fatigue after the manipulation ($t(\text{paired}) = -4.14$, $p < 0.001$), whereas the control group did not differ in their pre- and post-measures of fatigue ($t(\text{paired}) = 0.68$, $p > 0.05$).

3.1.2. Task motivation

Willingness to exert effort on the experimental tasks and to do ones best on these tasks, as measured directly after the manipulation, was significantly lower for the fatigued participants than for the non-fatigued participants ($t(54) = 2.53$, $p < 0.05$).

3.1.3. Mood

After the manipulation, participants in the fatigue and non-fatigue conditions significantly differed in feelings of anger ($F(1,55) = 15.07$, $p < 0.001$). With fatigued participants reporting higher levels of anger. Before the manipulation they did not significantly differ on anger ($F(1,55) = 1.40$, $p > 0.05$). Before and after the manipulation the groups did not significantly differ in levels of tension, depression, and vigour.

3.1.4. Intelligence

The groups did not significantly differ on the Raven's Advanced Progressive Matrices, which was given before the manipulation ($t(56) = -0.55$, $p > 0.05$). The mean

Table 1
Means (and SD) of pre- and post-manipulation measures of subjective fatigue

	Pre-manipulation		Post-manipulation	
	M	SD	*M*	SD
Fatigue group	30.29	(17.4)	62.73	(29.39)
Control group	33.88	(22.5)	33.68	(22.2)

number of correct items for the fatigued group was 24.44 (SD = 3.80) before the manipulation, and for the non-fatigue group 23.93 (SD = 5.76) before the manipulation. Thus, any differences in performance on the experimental tasks could not be attributed to pre-existing differences in general intelligence between the groups.

3.2. The Wisconsin Card Sorting Test

We expected fatigue to coincide with increased perseveration and a low number of discovered sorting rules. The analyses of the WCST confirmed these hypotheses as fatigued participants showed higher percentages of perseverative errors ($F(1,55) = 5.01$, $p < 0.05$, see Table 2 for the means) and discovered less sorting rules ($F(1,55) = 7.82$, $p < 0.01$) than non-fatigued participants.

Although fatigued participants tended to have higher percentages of miscellaneous and unique errors, these differences did not reached significance levels ($F(1,55) = 3.35$, $p = 0.08$ and $F(1,55) = 3.07$, $p = 0.09$ for unique and miscellaneous errors respectively).

Response RTs for Rule application and Rule search were submitted to an analyses of variance (ANOVA) with type of RT (Rule application vs. Rule Search) as within subject factor, and condition (Fatigue vs. not) as between subject factor. This analysis revealed a significant main effect of type of RT ($F(1,51) = 42.50$, $p < 0.001$) (see Fig. 1).

Table 2
Means of the experimental tasks

	Non-fatigue group ($n = 27$)		Fatigue group ($n = 31$)	
	M	SD	*M*	SD
WCST				
Number of sorting dimensions[a,**]	5.85	0.74	4.74	2.09
Perserveration[b,*]	0.10	0.05	0.16	0.11
Unique errors[b]	0.02	0.02	0.04	0.07
Miscellaneous errors[b]	0.09	0.05	0.11	0.05
Rule search RT*	2248	638	2035	546
Rule application RT (ms)	1668	231	1757	467
TOL				
Number of moves	5.47	1.60	6.61	2.57
Time per trial (s)	18.64	7.64	20.24	6.16
Rule errors (total)	2.88	4.32	1.90	2.53
Median RT first move* (s)	4.15	1.1	5.01	1.7
Digit span				
Digit span (pre-manipulation)	6.50	0.90	6.12	0.96
Digit span (post-manipulation)	6.83	1.09	6.67	1.24

* $p < 0.05$, ** $p < 0.01$ for differences fatigue vs. non-fatigue group.

[a] Range from 0 to 6.

[b] Proportion score (= divided by number of trials, max 128).

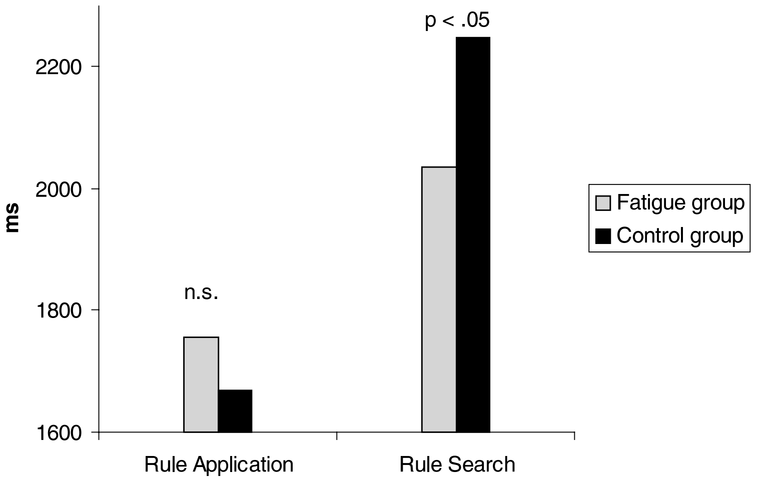

Fig. 1. Means of fatigue and non-fatigue groups on Rule application and Rule search during the WCST.

Post-hoc within-subject *t*-tests showed that both the fatigue and the non-fatigue group took significantly longer to give a response during Rule search than during Rule application $t(\text{paired}) = 5.21$, $p < 0.001$, for the fatigue group and $t(\text{paired}) = 3.88$, $p < 0.001$, for the non-fatigue group (see Table 2). However, there was also a significant interaction between type of RT and condition ($F(1,51) = 5.23$, $p < 0.05$). This interaction showed that the increase in RT from Rule application to Rule search was less pronounced in the fatigue group compared to the non-fatigue group. Post-hoc between group comparisons showed that fatigued and non-fatigued participants did not significantly differ in baseline RT during Rule application ($F(1,52) = 0.51$, $p > 0.05$). However, between-subjects comparison of Rule search RT in which we controlled for Rule application RT (as covariate) showed that fatigued participants took significantly less time to respond after rule switches ($F(1,51) = 4.90$, $p < 0.05$). This analysis suggests that the significantly increased number of perseveration in the fatigue group (see description of the analyses above) concurred with a decreased time allotted to giving a response during Rule search.

3.3. Tower of London

The fatigued and non-fatigued participants did not significantly differ in the average number of moves per TOL-trial ($F(1,54) = 0.73$, $p > 0.05$) or on the mean time per TOL-trial ($F(1,54) = 0.78$, $p > 0.05$, see Table 2 for the means. Nor were there any significant differences in the number of rule errors (violations of the rules in the TOL, $F(1,54) = 1.11$, $p > 0.05$). Thus, the level of induced fatigue did not affect planning accuracy. However, fatigued and non-fatigued participants differed significantly in the mean reaction time for the first move ($F(1,54) = 4.85$, $p > 0.05$), which reflects initial planning time, with fatigued participants being slower to initiate the first move.

3.4. Forward digit span

The digit span was measured before and after the manipulation. We expected fatigue not to affect digit span performance. To test this we submitted digit span performance to an ANOVA with time of measurement (before vs. after the manipulation) as a within-subject factor and condition (fatigued vs. not) as between-subject factor. We found a significant main effect of time of measurement ($F(1,53) = 9.98$, $p = 0.01$), which showed that both the fatigue and non-fatigue groups performed better on the second digit span measure than on the first measure. This indicated a learning effect. However, in line with our expectations there was no significant interaction between time of measurement and condition ($F(1,53) = 0.04$, $p > 0.05$), showing that the level of induced fatigue did not affect short-term memory performance.

3.5. Covariance analyses with mood and motivation

Because the fatigue and non-fatigue groups did differ significantly in anger and task motivation, additional analyses were conducted to examine whether mood and motivation could explain the observed differences on the experimental tasks. Therefore we submitted the results of the WCST, TOL, and digit span to additional analyses of covariance (ANCOVAs) in which we controlled for anger and motivation. With these analyses, all the main results stayed the same or even became more reliable. With the covariance analyses the fatigue and non-fatigue groups still significantly differed in perseveration ($F(1,50) = 4.10$, $p = 0.048$) and number of discovered sorting rules ($F(1,50) = 6.53$, $p = 0.01$). However, unique and miscellaneous errors did no longer reach marginal significance (respectively, $p = 0.24$ and 0.52). These results are in accordance with our expectation that perseveration and number of discovered sorting rules are the strongest indications of fatigue effects in the WCST. The interaction between response time type (Rule search vs. Rule application) and condition was also maintained and even showed a marked increased in significance level ($F(1,50) = 9.0$, $p = 0.01$).

On the TOL, first-move RT differences also stayed significant in the covariance analysis ($F(1,50) = 12, 95$, $p = 0.001$) whereas the other measured did not reached significance nor was there an effect of the covariates on the results of the digit span. Thus, these analyses showed that group differences on the WCST and TOL could not be explained by the different scores on the mood and motivation questionnaires.

4. Discussion

In this study, we examined whether mental fatigue coincides with compromised executive control. We used the idea that executive control depends on the ability to hold goals and goal-related information active in mind so that they can exert their influence on the selection of actions (Braver et al., 2001; De Jong, 2000; Duncan et al., 1996; Kimberg & Farah, 1993). We expected compromised executive control under fatigue to become apparent in lowered flexibility and sub-optimal planning. The overall results support this idea as fatigued participants showed more performance deficits than non-fatigued participants on tasks that required to flexibly generate and test hypotheses (WCST) and to plan (TOL). There was no difference between fatigued and non-fatigued participants in the forward digit span, which does not tap executive control processes but relies on the maintenance and reproduction of information (Baddeley & Logie, 1999; Kimberg & Farah, 1993; Norman & Shallice, 1986). Fatigued participants did not perform worse on all tasks or task aspects but particularly performed worse than non-fatigued participants in those task aspects that were related to executive control, which makes it unlikely that the results are due to general non-compliance or general loss of motivation of the fatigued participants. In contrast, the results suggest that the deficit in task performance of fatigued participants were caused by difficulties in upholding sufficient levels of executive control during the tasks.

4.1. Fatigue and flexible reactions to changing task circumstances

In the WCST, lowered flexibility in task behaviour is operationalized as perseveration. Compared to non-fatigued participants, fatigued participants made significantly more perseverative errors in the WCST, which implied that they repeatedly tried to sort cards according to a rule that already proved faulty in earlier sorting attempts (Heaton, 1981; Milner, 1963). The goal-activation perspective states that during perseveration the representations of task goals themselves may be unaffected, yet their activation may be too low to exert influence on the selection of actions (Duncan et al., 1996; Kimberg & Farah, 1993). This means that people may perseverate even if they are aware that the current actions are no longer appropriate (De Jong, 2000; Duncan et al., 1996; Kimberg & Farah, 1993). Although we could not directly determine to which extent our fatigued participants were aware of their inappropriateness of actions during perseveration, we can assume that they perceived the feedback after a sorting attempt. Namely, after each trial, the computer screen was completely cleared and obvious feedback (a big plus or minus sign) was presented in the middle of the screen. This feedback stayed on the screen until participants decided to continue with the next trial (by pressing a button). Thus, even fatigued participants must have noticed that their sorting action had not been successful; nevertheless, they showed perseveration.

In general, perseveration in the WCST arises from non-cognitive rigid patterns of behaviour and inadequate integration of task feedback for the selection of responses (Heaton, 1981; Norman & Shallice, 1986; Somsen et al., 2000), which may also be responsible for the low number of discovered sorting rules for fatigued participants (Milner, 1963; Somsen et al., 2000).

Although fatigued participants showed a trend towards an increased number of non-perseverative errors compared to non-fatigued participants the results showed that perseverative errors were the most reliable effects of fatigue whereas non-perseverative errors were mainly linked to decreased motivation and increase in anger. Specifically, in analyses in which we controlled for motivation (willingness to do one's best) and mood, trends towards differences in non-perseverative errors between the groups were no longer present whereas group differences on perseverative errors stayed significant.

The reaction time data of the WCST gave additional insight into the lowered flexibility under fatigue. Specifically, response-time data provided some converging evidence that responses of the fatigued participants were more strongly guided by automatic cognitive processes. For fatigued and non-fatigued participants alike, we found an increase in response RT after a rule switch (Rule search RT). As we argued, rule search puts more demands on executive control than rule application (Barcelo et al., 2000). Thus, it is reasonable to assume that the long Rule search RT reflects this deployment of executive control processes. However, in Rule search, the median RT of fatigued participants showed a less pronounced increase in response time than non-fatigued participants. As automatic response selection (based on previous activated response tendencies) generally demands less time than goal-directed, deliberate response selection (Monsell & Driver, 2000; Shiffrin & Scheider, 1977), the RT data indirectly support the idea of insufficient goal-activation.

4.2. Fatigue, planning, and processes underlying task deficits

The results on the TOL suggest that fatigued participants were inefficient on the planning aspect of behaviour regulation. This was in accordance with our expectations. Mental fatigue did not affect overall performance on the TOL. The results showed that, compared to non-fatigued participants, fatigued participants did not need significantly more moves or more time to solve the TOL-trials, nor did they display more violations of TOL-rules. However, we found a significantly prolonged first-move RT for fatigued participants. The first-move RT in the TOL reflects initial planning time (generating sequences of goals and sub-goals, Anderson, 1993; Oaksford et al., 1996; Shallice, 1982).

One question that needs to be addressed when considering the total pattern of results in this study (the TOL and WCST results) is why fatigued people showed increased perseveration and a less pronounced increase in response times during Rule search in the WCST, yet show unimpaired performance but prolonged planning times in the TOL. We have to note that the traditional TOL and WCST task that we used allow the assessment of deficits in flexibility and planning but does not allow detailed insight into the processes underlying such deficits. Thus, a conclusive answer to this question cannot be provided. Nevertheless, comparison of the results of our study with other studies in which similar patterns of results were found may be informative. Specifically, there are studies in which frontal lobe patients and patients with Parkinson's disease showed different deficits on the TOL yet displayed similar impairment on the WCST (Cools et al., 2002; Fournet, Moureaud, Roulin, Naegele, & Pellat, 2000; Hodgson et al., 2000; Owen et al., 1995). Both type of patients are assumed to be impaired on executive control and both groups show increased perseveration on the WCST compared to control groups (Gazzaniga et al., 1998). However, frontal lobe patients typically show unimpaired (or even shorted) initial thinking and time yet perform rather poorly on the TOL. This is generally interpreted as a deficit in planning accuracy (Goel & Grafman, 1995; Owen et al., 1995). On the other hand, patients with mild Parkinson's disease perform normal on the TOL, which indicates that their planning accuracy is not impaired. Yet, their initial planning time is prolonged compared to control groups (Owen et al., 1995). Thus, at the level of observable behaviour on the TOL and the WCST, our results more closely seem to resemble the pattern of performance deficits in Parkinson's disease patients than performance deficits of frontal lobe patients. It is important to note that executive control deficits in Parkinson's disease patients are ascribed to changes in sub-cortical dopamine systems that affect higher cortical levels, such as the pre-frontal cortex (Cools et al., 2002; Harrison, Stow, & Owen, 2002; Owen et al., 1995). Specifically, in Parkinson's disease patients, nigrostriatal, and to a lesser extent mesocorticolimbic dopamine is depleted.

The similarity between the results of our study with results on the WCST and the TOL in Parkinson disease patients may suggest an important role for dopamine in the effects of mental fatigue and executive control. Other theories and findings support this idea, for example, recent theories on the biological substrates of executive control state that dopamine plays a major role in the activation (stability) of goal representations (Braver et al., 2001; Cohen & Servan-Schreiber, 1992; Miller & Cohen, 2001; Robbins et al., 2000). Moreover, dopamine activity has been associated with intrinsic motivation and response readiness (Tucker & Williamson, 1984), both concepts are strongly related to mental fatigue. Finally, it is generally known that coffee intake, which enhances dopamine release, reduces both the subjective and objective effects of mental fatigue (Lorist, 1998). Although it would go beyond the scope of the current study to discuss the possible role of dopamine in detail, this idea poses a direction for future studies on the relationship between mental fatigue and executive control.

4.3. Limitations and suggestions for future studies

Although the current study provides some insight into the cognitive processes of performance regulation under fatigue there were also some limitations. One of these limitations relates to the tasks we used. Both the WCST and the TOL are relatively complex tasks in which different cognitive deficits can lead to similar manifestations on the tasks (as may be apparent from our discussion of the WCST and TOL in the previous section). Thus, future studies might want to aim at a more direct assessment of the processes that are assumed to underlie loss of flexibility and inefficient planning under fatigue. On the other hand, an advantage of using the WCST and the TOL is that the WCST and the TOL have been used in many studies and clinical settings to study executive control (Fuster, 1989; Heaton, 1981; Shallice, 1982). Moreover, there are many neuropsychological studies that directly showed that these tasks yield activation of brain structure that are deemed to subserve the translation of goals into action (Barcelo et al., 2000; Duncan & Owen, 2000).

Another limitation is that we cannot answer specific questions about the motivational issues involved in cognitive performance under fatigue. Executive control strongly overlaps with motivation in the sense that adequate control of behaviour is only exerted when some importance is assigned to task goals (Derryberry & Reed, 2001; Monsell & Driver, 2000; Tucker & Williamson, 1984). For example, people with impaired executive control seem to lack the 'drive' to engage in self-directed behaviour and to initiate actions (Duncan et al., 1996). Such lack of drive or action initiation is also typical for fatigued people (Meijman, 2000).

In the current study, fatigued participants reported a higher level of resistance against further effort and had lower task motivation than non-fatigue participants. However, the results of the current study did not change when we used ANCOVAs in which we controlled for the motivation to perform well on the task. Moreover, we should not conclude from the motivational (questionnaire) measures that all changes in behaviour under fatigue are caused by deliberate decisions not to comply with task goals ('not to do one's best). Alternative to the idea of deliberate non-compliance, we can expect that the loss of intrinsic motivation under fatigue may have caused fatigued participants to experience difficulties in the exertion of executive control even when they, at a conscious level, wanted to do well. Hence future studies may want to differentiate more clearly between "...an involuntary failure to marshal adequate effort" and "...deliberate non-compliance or laziness" (Douglas, 1999, p. 106).

4.4. Theoretical implications

Despite the limitations mentioned above, the current study supports the view that compromised executive control underlies behavioural manifestations of mental fatigue. Although there are several studies showing that fatigue seems to affect high-level cognitive processes (Hockey, 1997; Holding, 1983; Sanders, 1998), to our knowledge the current study is one of the first to explicitly approach fatigue from an executive control perspective. Such a perspective has important implications. For example, compromised executive control under fatigue does not imply that certain basic cognitive processes can no longer be executed at all. Moreover, it also does not imply that cognitive processes are fundamentally changed under fatigue. However, from the (goal-activation) view we adopted in the current study, compromised executive control under fatigue does imply a reduced probability that actions will be guided by task goals or by changing task context (Braver et al., 2001; Duncan et al., 1996). Subsequently there would be an increased tendency for more automatic regulatory processes to guide action selection, even when this is inappropriate. Such lapses in the exertion of executive control may be responsible for the typical slips of action and intrusion errors that are often found in fatigued people (Hockey, 1997; Holding, 1983; Sanders, 1998).

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