Mental Fatigue and the Control of Cognitive processes: Effects on Perseveration and Task Engagement

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Abstract

Although there are several studies on the effects of mental fatigue on task performance, still much is unknown about the cognitive processes that underlie performance deficits under fatigue. In the current study we test the idea that behavioral manifestations of mental fatigue may be linked to compromised executive control. Executive control refers to the ability to regulate perceptual and motor processes in order to behave in a goal-directed way. In complex tasks such compromised control may become manifest as decreased flexibility to changing tasks circumstances and sub-optimal planning. Mental fatigue in this study is defined as a change in psychophysiological state as the result of sustained performance. 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 two hours on cognitively demanding tasks. The results showed that compared to the non-fatigue group, fatigued participants particularly showed increased perseveration on the WCST. The groups did not differ on general performance on the TOL. However, fatigued participants showed significantly prolonged initial planning time. 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 is often found in fatigued people.

PsycINFO classification: ?

Keywords: Mental Fatigue; Executive Control; Cognitive Flexibility; Planning

1. Mental Fatigue and the Control of Cognitive processes: Effects on Perseveration and Task Engagement

Working on cognitively demanding tasks for a considerable time, say several hours, often leads to mental fatigue, which can have a marked impact on task performance. For example, in industry many incidents and accidents have been related to mental fatigue as the result of sustained performance (Baker, Olson, & Morisseau, 1994). Thus, 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 behavior. However, despite the many studies on fatigue, it turned out to be remarkable difficult to get a (scientific) grip on what it means to be mentally fatigued and what cognitive processes underlie its behavioral manifestations (Broadbent, 1979; Desmond & Hancock, 2001; Hockey, 1997; Holding, 1983). Therefore, we conduct the current study to provide some insight into these 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 some subjective and objective manifestations, which involve 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). It is this pattern of subjective and objective manifestations that people generally label as mental fatigue and which is the psychological construct of interest in fatigue studies. Sustained performance, in this definition, does not necessarily involves the same task but can also extend over different tasks that require mental effort, for example, such as in fatigue after a day in the office (which often also involves several different tasks).

One of the interesting questions in fatigue research is in what way the (cognitive) control of behavior changes under fatigue. Some researchers proposed that mental fatigue particularly affects those control processes that are involved in the organization of actions and that play a major role in deliberate and goal-directed behavior (Bartlett, 1941, 1943; Hockey, 1997; Lorist et al., 2000; Sanders, 1998). Bartlett (1943) already sixty years ago, reported observations that support this 'control view' on the nature of fatigue. Specifically, after more than two hours 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 that "…all the time the general drift is towards less closely 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 behavior are generally difficult to perform under these circumstances (Broadbent, 1979; Hockey, 1993; Holding, 1983; Sanders, 1998).

These typical effects on different levels of information processing that is found in several fatigue studies and the specific disorganization of behavior that tends to occur under fatigue, suggest that mental fatigue is mainly characterized by less involvement of so-called *executive control*. Executive control refers to the ability to regulate automatic 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). 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).

Literature shows that there is some debate about the nature of executive control processes (the so-called executive functions), 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, Kane, & Tuholski, 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. Yet, there still is no consensus about the relative contribution of these processes (Miyake et al., 2000). Nevertheless, in the current study we use a particular and promising conceptualization of executive control, namely that the control of goal-directed behavior depends on the ability to keep goals and goal-related information active in mind (Anderson, 1993; Braver et al., 2001; De Jong, 2000, 2001; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Kimberg & Farah, 1993). Goals and goal-related information refers to all information regarding the conditions under which to execute certain actions (some researchers refer to this as task context (Braver et al., 2001; Kimberg & Farah, 1993). Such information can be considered as 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 behavior 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 exeternal cues, even when this is inappropriate. It is this insufficient activation of goals that Duncan referred to as goal-neglect and that may be underlying many of the problems of executive control such as disinhibition, difficulties with task (set) switching and with working memory updating (Duncan et al., 1996). In general, Duncan 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). Thus, when we assume that fatigued people display a tendency to reduce executive control, we can expect that they may show similar deficits in task performance.

Mental Fatigue and Executive Control

Although, there are many studies on fatigue and information processing (cf. (Broadbent, 1979; Holding, 1983; Sanders, 1998), there are only few studies that explicitly investigated the effects of mental fatigue from an executive control perspective. For example, some studies investigated the effects of fatigue on response planning and task switching, which both are considered important aspects of executive control. Lorist et al. (2000) used behavioral and EEG-data to study the effects of time-on-task (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). Thus, this result supported their initial expectations on the effects of mental fatigue. In their study, fatigue led to an increased number of errors and an increase in reaction time. However, the study did not reveal differential effects of fatigue on switch and non-switch trials. Nor did they find effects of fatigue on response planning. Thus, at the behavioral level, a specific effect of mental fatigue on 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. The results of this study also did not show specific effects of fatigue on planning or task switching. Thus, the studies of Lorist et al. (1999) and de Jong (2000) did not unambiguously show an effect of mental fatigue on executive control even though such effect can be expected from research literature that indicates that fatigue particularly seems to affect high-level information processing.

There are several explanations possible for why fatigue did not seem to affect task switching and response planning in the studies of Lorist et al. and de Jong, for example, mental fatigue in these studies was operationalized as the time spent on the same task. However, executive control on behavior is particularly important when a task is novel (Dias, Robbins, & Roberts, 1997; Duncan et al., 1996). For example, Dias, Robbins, and Roberts (1997) found that inhibition problems in set shifting were particularly found in situations were a shift was novel and not well practiced. Thus, after some time on the same task, 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. Hence, 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 an complex task and reacting to unforeseen changes in task circumstances are typical situations that put heavy demands on executive control (Duncan et al., 1996; Fuster, 1989; Miller & Cohen, 2001) and thus these types of behavior may be particularly vulnerable when mentally fatigued.

In the current study we want to investigate the effects of mental fatigue on executive control with a different design as in previous studies. First, we induce fatigue by using tasks that are different from the experimental tasks after the manipulation. Thus, we measure the general effects of mental fatigue between-tasks instead of within-tasks. The advantage of this approach is that the tasks we give to participants after the fatigue manipulation are novel and can be expected to put heavy demands on executive control. In addition, we use tasks that are not overly structured but that require the participants to development own strategies and to adequately process unexpected feedback. Specifically, we expect that in such complex tasks, fatigued people will particularly show deficits on 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 behavior 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 behavior we use tasks that have been used extensively in executive control research, namely, the Wisconsin Card Sorting Test (Milner, 1963) and the Tower of London (Shallice, 1982).

The Wisconsin Card Sorting Test

The Wisconsin Card Sorting Test (WCST) is a task in which participants have to discover how to sort cards that hold geometrical figures. Sorting rules in this task are based on the color, 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 through providing feedback after every trial. Once participants discovered the currently active sorting rule (which in the WCST is operationalized as ten correct responses after each other), the rule chances without notice. Subsequently, participants first 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 modeling to show that perseveration in the WCST can be ascribed to decreased goal activation (similar to goal-neglect, Duncan, et al, 1996). 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 several other types of errors that people can make on the WCST. For example, sorting cards according to an unknown principle that is not linked to any of the sorting dimensions on the WCST (color, number, or shape, (Heaton, 1981). Several underlying reasons have been proposed for these types of non-perseverative errors. For example, incorrect guessing when trying to discover the sorting rule, or difficulties in holding the discovered sorting rule active in mind (lapse in task set maintenance, (Hartman, Bolton, & Fehnle, 2001; Paolo, Troster, Axelrod, & Koller, 1995). Other studies that have also considered these other types of errors in the WCST, showed somewhat mixed results. Under conditions of compromised executive control, non-perseverative errors often also show some trends towards an increase. Paolo et al. (1995) reported that in elderly (who show deficits on the WCST) perseverative and non-persverative errors were positively related ($r = .64$). However, in most studies on compromised executive control and the WCST, an increased number of perseverative errors was the most reliable result. Thus we expect similar result in our study on the effects of fatigue.

It has also been argued that the WCST consists of two qualitative different types of problem solving, namely rule application and rule search (Somsen et al., 2000). Rule application means that once participants know by which rule to sort cards, they have to match the features of the to-be-sorted card with the corresponding target card. Such application of sorting rules requires participants to remember by which rule to sort and to perform some relatively simple cognitive operations (e.g. match the cards on color). On the other hand, when the current sorting rule is unknown, participants have to engage in complex problem solving which involves flexible reactions to task feedback and conceptualization of new task rules. There are several (psychophysiological) studies showing that these problem-solving requirements of the WCST put heavy demands on executive control processes, whereas rule application does not (Barcelo, Munoz-Cespedes, Pozo, & Rubia, 2000; Konishi et al., 1999). This distinction between periods of rule application and rule search in the WCST may be useful to gain some additional insight into the processes underlying task behavior. Specifically, the WCST we use is self-paced, therefore, the time participants take before giving a response during rule application and rule search may be indicative for their reactions to feedback from the previous trial and for the flexibility of their behavior. Particularly the interaction between response time and performance is important because when executive control is indeed compromised under fatigue, several different patterns of results may emerge. For example, when, during rule search, mental fatigue does not lead to increased perseveration but we would find prolonged response times compared to non-fatigued participants, then executive control may be adequately exerted yet is less efficient. Alternatively, if perseveration concurs with short response times, this may indicate that fatigued people did not adequately react to feedback in the sense that increased task demands (in terms of executive control) did not coincide with a corresponding increase in the time allotted to select an appropriate action. In the current study we differentially look at response time during rule application and during rule search.

1.3 The Tower of London

The Tower of London (TOL, Shallice, 1982) is a puzzle in which participants have to rearrange colored beads over pegs until they match a goal-state. The TOL particularly 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 behavior be guided by task goals (Duncan, 1996) and because the TOL was designed as a relatively pure measure of executive control (Shallice, 1982) we expect that fatigued people will show planning deficits on the TOL. In the TOL, quality of planning processes is assessed by the combination of reaction time and performance measures. An important reaction time measure in this task is the time between the presentation of a TOL-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 people 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 would become manifest 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). On the other hand, compared to such groups of patients, it can be expected that the effects of fatigue on executive control are much less severe and may even arise from different underlying (neurological) processes. Hence, we expect that fatigued people may still attempt to plan their behavior, 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 Pakinson disease patients, which are also impaired on executive control (Cools, Stefanova, Barker, Robbins, & Owen, 2002; Hodgson et al., 2000; Owen et al., 1995). Hence, one of the aims of this study is to discover how planning deficits under fatigue become manifest in the TOL.

1.4 Control Measure

Although, the main emphasis in the current study is on the WCST and the TOL, we also use a forward digit span as some sort of control measure. Namely, 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 may indicate 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 Twenty Euro for sessions that lasted approximately four hours. 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 (WCST, Milner, 1963). In the WCST, participants have to discover by which rule to sort cards to four target cards with geometrical figures on it. The WCST comprises three sorting rules; sorting by color, shape, or number. We used a computerized version of the WCST. In the WCST, four target cards were presented at the upper half of the computer screen. These target cards differed from each other on the sorting dimensions (color, shape, and number) and remained visible at each trial and. 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, participants received feedback. A big plus-sign with the word 'Goed' (correct) in it was presented if the sort was correct or a big minus-sign with the word 'Fout' (Wrong) was presented if 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, through feedback, discovered the sorting rule and correctly sorted ten cards in a row, the sorting rule switched without notice. Subsequently, participants again had to engage in hypothesis testing to find the new sorting rule. 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 ten correct sorts) or after a maximum of 128 trials.

Dependent measures. Performance measures of the WCST, were rated by the computer through use of algorithms as proposed by Heaton (1981). Perseverative errors were errors in which the participant, despite negative feedback, continued to apply a sorting rule that was correct in previous trials or in which the participant repeatedly tried out the same (unsuccessful) sorting rule during rule search (Heaton, 1981). Number of discovered sorting rules was measured by the number of times participants performed ten correct card-sorts in a row, which indicates that the participant knows the sorting rule (maximum number of discovered rules is 6). Unique errors were errors in which cards were sorted in a way that did not match any of the sorting dimensions (shape, color, or number). 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 criteria of 30 percent Unique errors as reason to exclude participants from further analyses. In the current study, only one participant matched this criteria (this participant had 42 % Unique errors) and was excluded from further analyses. Miscellaneous errors comprised all errors that were not Perseverative or Unique errors.

Response Reaction time Because the WCST was self-paced we looked at response reaction time, which may provide information about underlying regulatory mechanisms in performance (Douglas 1999; see also introduction). We differentiated between two types of response time; response time during rule application (Rule Application RT), and response time during rule search (Rule Search RT).

Rule Application RT was operationalized as the median RT of all trials that fell within a sequence of ten correct responses plus the first response thereafter. A sequence of ten correct responses in the WCST implies that participants know by which strategy to sort the cards and apply this strategy. Rule application was considered a baseline reaction time to perform some simple cognitive operations (e.g. match features of the cards) that do not heavily tap executive control processes.

Rule Search RT was operationalized as the median RT of those trials that preceded a sequence of ten correct trials. During those trials the participants did not know by which rule to sort cards and thus were engaged in problem solving which is assumed to tap executive control processes.

2.2.2 The Tower of London (TOL, Shallice, 1982). The TOL consists of three pegs on which three colored 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 eighteen 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 mean 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 an 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 consisted of sequence that had an equal number of digits as the previous trial. The task consisted of ten trials. The digit span was measured at the beginning of the experimental session and right after the manipulation.

Fatigue Manipulation. In this study, we compared a group of fatigued participants with a non-fatigued group of participants. Mental fatigue in the fatigue group 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 minutes). There was no information on intermediate results on the computer screen and no external memory aids were allowed, thus the task required much 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

Subjective fatigue. Subjective fatigue was measured with the Rating Scale Mental Effort (RSME, (Zijlstra, 1993) which consists of seven 150-point answer scales in which is asked about several aspects of fatigue. The RSME is generally used as a single measure of fatigue (Mean Cronbach's Alpha (pre- and post manipulation measure) = .91). The RSME was filled out before and after the manipulation.

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 7-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 = .88).

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 (POMS, (Wald & Mellenbergh, 1990). The sub-scales measured anger, depression, tension and vigor. The sub-scales of the POMS were given before and directly after the manipulation.

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 the Advanced Progressive matrices (APM) of Raven (Raven, 1962). We used a paper and pen version and gave the participants a maximum of thirty minutes to work on the test before the manipulation.

2.4 General procedure

Participants were tested individually in sessions that lasted circa four hours. At the beginning of the session, participants filled out the RSME and POMS. Then they worked respectively, on the digit span task and for thirty minutes on the Advanced Progressive Matrices (AMP). The manipulation followed directly after the Progressive Matrices. Participants in the fatigue group had to work on the scheduling task for two hours (this implied that participants in the fatigue condition worked on cognitively demanding tasks for two-and a half hours: APM plus scheduling task). The participants in the control group were told they had to bridge two hours. Within this time they had to stay in the laboratory and were allowed to read some magazines or otherwise spent their time as they wanted (care was taken that they did not engage in any cognitively demanding tasks such as studying).

After the two-hour manipulation, participants filled out the RSME, POMS, and the motivation questionnaire. Then participants worked respectively on the digit span task, the Tower of London (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

Fatigue. Reported fatigue (RSME) 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 showed our manipulation to be successful. We found a significant interaction between time of measurement and condition (F (1, 55) = 42.31, p < .0005). Post-hoc tests showed that the fatigue and non-fatigue group did not differ on reported fatigue before the manipulation (F (1, 55) = .46, p = .49) but significantly differed after the manipulation

(F (1, 55) = 17.14, $p < .0005$). Moreover, the participants in the fatigue group highly increase in fatigue after the manipulation (t (paired) = -4.14, $p < .0005$), whereas the control group did not differ in their pre- and post measures of fatigue (t (paired) = .68, $p = .50$).

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 ($t(54) = 2.53$, $p = .02$).

Mood. After the manipulation, participants in the fatigue and non-fatigue condition significantly differed in feelings of anger ($F(1, 55) = 15.07$, $p < .0005$). With fatigued participants reporting higher levels of anger. Before the manipulation they did not significantly differ on anger ($F(1, 55) = 1.40$, $p = .24$). Before and after the manipulation the groups did not significantly differ in levels of tension, depression, and vigor.

Intelligence. The groups did not significantly differ on the Raven Advanced Progressive Matrices, which was given before the manipulation ($t(56) = -.55$, $p = .59$). The mean 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, compared to non-fatigued participants, fatigued participants showed higher percentages of perseverative errors ($\underline{F}(1,55) = 5.01$, $\underline{p} = .03$, see Table 2 for the means) and discovered less sorting rules ($\underline{F}(1, 55) = 7.82$, $\underline{p} = .007$).

Table 2 about here

Although, fatigued participants also tended to have higher percentages of Miscellaneous and Unique errors, these differences did not reached significance levels ($\underline{F}(1, 55) = 3.35$, $\underline{p} = .08$ and $\underline{F}(1,55) = 3.07$, $\underline{p} = .09$ 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 (Fatigeu vs. not) as between subject factor. This analysis revealed a significant main effect of type of RT ($\underline{F}(1, 51) = 42.50$, $\underline{p} < .0005$) (see figure 1).

Insert figure 1 about here

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 ($T = 5.21$, $p < .0005$, for the fatigue group and $T = 3.88$, $p < .0005$, for the non-fatigued group, see Table 2 for the means). However, there also was a significant interaction between type of RT and condition ($\underline{F}(1, 51) = 5.23$, $\underline{p} = .03$). This interaction showed that, compared to the non-fatigue group, the increase in RT from Rule application to Rule search was less pronounced in the fatigue group. Post-hoc between group comparisons showed that fatigued and non-fatigued participants did not significantly differ in baseline RT during Rule application ($F(1, 52) = .51$, p = .

50). 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 = .03). This analyses shows 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 mean number of moves per TOL-Trial (F(1, 54) = .73, p = .40) or on the mean time per TOL-trial (F(1, 54) = .78, p = .38, 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 = .30). Thus, planning accuracy was not affected by the level of induced fatigue. However, fatigued and non-fatigued participants significantly differed on the mean reaction time for the first move (F(1, 54) = 4.85, p = .03) which reflects initial planning time. Fatigued participants were 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 =.003), which showed that both the fatigue and non-fatigue group performed better on the second digit span measure than on the first measure. This indicated a learning effect. However, there was no significant interaction between time of measurement and condition (F (1, 53) = .04, p =.84), showing that the level of induced fatigue did not affect short-term memory performance.

Covariance analyses with Mood and Motivation

Because the fatigue and non-fatigue groups did significantly differ in anger and task motivation we conducted additional analyses to check 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 in which we controlled for anger and motivation. These analyses were encouraging as all the main results stayed the same or even became more reliable. With the covariance analyses the fatigue and non-fatigue group still significantly differed in perseveration (F(1, 50) = 4.10, p =.048) and number of discovered sorting rules (F(1, 50) = 6.53), p = .01). However, unique and miscellaneous errors did not no longer reach marginal significance (respectively, p = .24 and p = .52). These results are in accordance with our expectation that perseveration and number of discovered are the strongest indications of fatigue effects in the WCST. The interaction between response time type (Rule search versus Rule application) and condition also stayed significant and even became more reliable (F (1, 50) = 9.0, p = .004).

On the TOL, first-move RT differences also stayed significant in the co-variance analysis (F(1, 50) = 12, 95, p = .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

We tested whether mental fatigue coincides with compromised executive control. In this study 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). Specifically, we expected compromised executive control under fatigue to become apparent in lowered flexibility and sub-optimal planning. The overall results support this idea as, compared to non-fatigued participants, fatigued participants showed performance deficits on tasks that required to flexibly generate and test hypotheses (WCST) and planning (TOL). In contrast, fatigued participants did not do worse on a forward digit span task, which relies on the maintenance and reproduction of information but that does not heavily tap executive control processes (Baddeley & Logie, 1999; Kimberg & Farah, 1993; Norman & Shallice, 1986). The finding that fatigued participants particularly performed worse than non-fatigued participants on those task aspects related to executive control makes it unlikely that the results can be ascribed to a general non-compliance of the fatigued participants. If fatigue participants indeed would show general a lack of interest to perform well on the task, we would have found a more general performance impairment throughout all task aspects. However, in contrast to a general lack of compliance, it is more likely that the deficits in task performance of fatigued participants were caused by difficulties in upholding sufficient levels of executive control during the tasks.

4.1 The Wisconsin Card Sorting Test

In the Wisconsin Card Sorting Test, lowered flexibility in task behavior 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). From a goal-activation perspective, perseveration is caused by insufficient activation of goals and goal-related information in mind (Duncan et al., 1996; Kimberg & Farah, 1993). When goal activation is low, the probability increases that actions are regulated by more automatic cognitive processes (Norman & Shallice, 1986). In the WCST, such automatic processes would favor previous response tendencies, which still have a high activation (Fuster, 1989; Kimberg & Farah, 1993). Moreover, the goal-activation account also states that it is not the goal representation itself that is affected under compromised executive control but particularly its ability to exert influence on the action selection (Anderson, 1993; Kimberg & Farah, 1993). This means that people may perseverate even though they are aware that the current actions may no longer be 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 expect that they at least perceived the feedback after a sorting attempt. Specifically, after each trial, the computer screen was completely cleared and very 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 to the next trial (by pressing a button). Thus, even fatigued participants must have noticed that their latter sorting action was not successful, nevertheless, they showed more perseveration.

In general, perseveration in the WCST arises from non-cognitive rigid patterns of behavior 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).

In the primary analyses, fatigued participants also showed a trend towards an increased number of non-perseverative errors compared to non-fatigued participants. However, when controlling for motivation (willingness to do one's best on the task) and mood differences, these trends disappeared, whereas the significant difference between the groups on perseverative errors was maintained. Thus, these additional analyses supported our initial expectations because they showed that the number of perseverative errors was the most reliable effect of fatigue and that non-perseverative errors were mainly linked to decreased willingness to comply with task goals and increase in anger.

The reaction time data of the WCST provided some additional insight into the lowered flexibility under fatigue. 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. This finding provided some converging evidence that the responses of the fatigued participants were more strongly guided by automatic cognitive processes. Namely, automatic response selection (based on previously activated response tendencies or external cues) can be assumed to demand less time than goal-directed response selection, which is based on the processing of the current task context in relationship to task goals.

4.2 The Tower of London

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). Thus, the findings suggest that fatigued participants were particularly inefficient on this planning aspect of behavior regulation, which was in accordance with our expectations.

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 we used allows 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 disease showed different results 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 time yet perform rather poorly on the TOL. Hence planning accuracy is deficit. On the other hand, patients with mild Parkinson disease perform normal on the TOL, which indicates that their planning accuracy is unimpaired. Yet, their initial planning time is prolonged compared to control groups (Owen et al., 1995). Thus, at the level of observable behavior on the TOL and the WCST, our results more closely seem to resemble the pattern of performance deficits in with Parkinson disease patients than performance deficits of frontal lobe patients. It is important to note that executive control deficits in Parkinson disease patients are ascribed to changes in subcortical dopamine systems that affect higher cortical levels, such as the prefrontal cortex (Cools et al., 2002; Harrison, Stow, & Owen, 2002; Owen et al., 1995). Specifically, in Parkinson 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 TOL in Parkinson disease patients puts forward an interesting theoretical underpinning in the relationship between mental fatigue and executive control. Namely, it indicates an important role for dopamine in the effects of mental fatigue and executive control. Besides the results of the current study, there are several other signs that 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). Thus, these theories are in accordance with ideas about the role of goal-activation under fatigue. Moreover, dopamine activity has been associated with intrinsic motivation and response readiness (Tucker & Williamson, 1984), which both are concepts which 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 (Ref). 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 provided 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. The WCST and the TOL have been used in many studies and clinical settings to study executive control (Fuster, 1989; Heaton, 1981; Shallice, 1982). The rationale behind these tasks is that they differentiate rather well between people who have brain damage to those areas related to executive control versus control groups or patients with damage to other brain areas (Heaton, 1981). 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). However, both the WCST and the TOL still are relatively complex tasks in which many different processes play a role and in which different cognitive deficits can lead to similar manifestations on the tasks (as may be apparent from our discussion of the results of the WCST and the 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.

Another limitation is that we could not 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 behavior is only exerted when some importance is assigned to task goals (Derryberry

& Reed, 2001; Monsell & Driver, 2000; Tucker & Williamson, 1984). For example, it is often found that people who are impaired in their executive control seem to lack the 'drive' to engage in self-directed behavior 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 controlled for the motivation to perform well on the task. Moreover, as we argued, it would be invalid to conclude from these motivational measures that all changes in behavior under fatigue are thus caused by deliberate decisions not to comply with task goals ('not to do one's best). Alternatively, 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 noncompliance or laziness" (Douglas, 1999), p. 106).

4.4 Theoretical implications

Despite the limitations mentioned above, the current study to some extent supports the view that compromised executive control underlies behavioral manifestations of mental fatigue. Although, there are several studies showing that fatigue particularly 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 <u>not</u> imply that certain basic cognitive processes can no longer be executed at all. Moreover, it also does <u>not</u> 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 <u>does</u> 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. This line of reasoning also implies that fatigued participants were not generally impaired in reacting to feedback in the WCST and probably did not forgot what was expected of them in this task. More likely, perseverative errors in the WCST concurred with temporary lapses in which goals were not adequately translated into the corresponding actions but in which actions were guided by previous response tendencies, which still had some high activation level. This idea of lapses of executive control under fatigue is in accordance with previous fatigue studies that showed that one of the major characteristics of task behavior under fatigue is lapses in performance (Hockey, 1997; Holding, 1983; Sanders, 1998).

References

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)*

Table 2. Means of the experimental tasks

	Non-fatigue group (n= 27)		Fatigue group (n = 31)	
	M	SD	M	SD
Wisconsin Card Sorting Test				
Number of sorting dimensions[a] **	5.85	.74	4.74	2.09
Perserveration[b] *	.10	.05	.16	.11
Unique errors[b]	.02	.02	.04	.07
Miscellaneous errors[b]	.09	.05	.11	.05
Rule Search RT[c] *	2248	638	2035	546
Rule Application RT[c]	1668	231	1757	467
Tower of London				
Number of moves	5.47	1.60	6.61	2.57
Time per trial[d]	18.64	7.64	20.24	6.16
Rule Errors (Total)	2.	4.32	1.	2

	88		90	.53
Median RT first move[d] *	4.15	1.1	5.01	1.7
Digit Span				
Digit span (pre-manipulation)	6.50	.90	6.12	.96
Digit span (post-manipulation)	6.83	1.09	6.67	1.24

* p < .05, ** p < .01 for differences fatigue vs. non-fatigue group,

[a] Range from 0 tot 6.

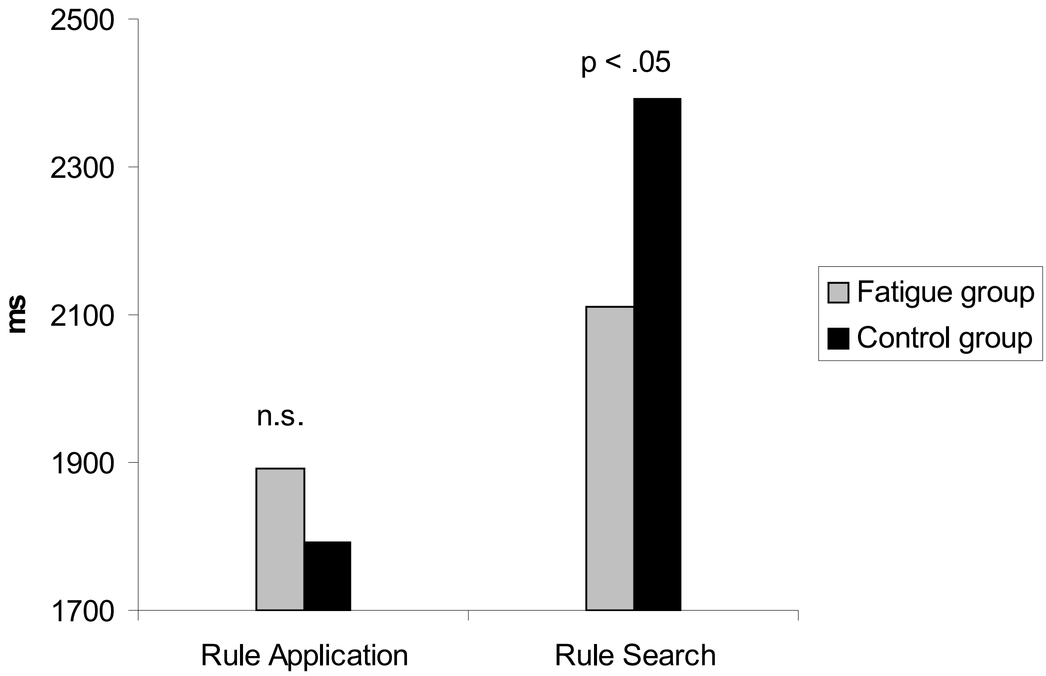
[b] Proportion score (= divided by number of trials, max 128).

[c] Milliseconds

[d] Seconds.

Figure Caption

Figure 1. Means of fatigue and non-fatigue group on Rule Application and Rule search during the WCST.


2500
2300
2100
1900
1700
ms
p < .05
n.s.
Fatigue group
Control group
Rule Application
Rule Search

Authors note

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