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Cognitive flexibility in healthy students is affected by fatigue: An experimental study

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ABSTRACT

Fatigue is a common problem in healthy individuals, but the effects on cognition are poorly understood. The current experimental study investigated the relation between fatigue and cognitive flexibility. Sixty university students were randomly assigned to an experimental group or a control group. The experimental group received a fatigue-inducing session in which they performed cognitively demanding tasks. The control group received non-demanding tasks. After the intervention, both groups performed a switch task with two task rules of unequal difficulty. Both induced fatigue and fatigue state at baseline were evaluated. Difficulties in task switching, irrespective of task rule, were more pronounced in students in both groups who had higher fatigue at baseline. The experimental group responded slower under all conditions. Moreover, the experimental group took longer to switch from the difficult to the easy task rule compared to the opposite direction. These findings suggest that fatigue negatively affects cognitive flexibility in university students.

1. Introduction

Mental fatigue is a common complaint in the general population and it coincides with changes in mood, motivation and cognition (e.g., Boksem, Meijman, & Lorist, 2006; Boksem & Tops, 2008). Fatigue is considered a multi-dimensional state with various origins, such as hormonal changes, stress, unhealthy lifestyle, and disrupted sleep patterns (e.g., Chalder, Power, & Wessely, 2009; Ter Wolbeek, van Doornen, Kavelaars, & Heijnen, 2006; Wessely et al., 1995). It can also be acutely induced by a period of mentally demanding activity (e.g., Van der Linden & Eling, 2006; Van der Linden, Frese, & Meijman, 2003). In the long run, fatigue can affect work productivity and academic performance (Nagane, 2004; Ricci, Chee, Lorandeau, & Berger, 2007), which may strongly influence everyday life and personal development.

Prior studies that examined effects of fatigue on cognition specifically report difficulties with executive functions (Boksem, Meijman, & Lorist, 2005; Lorist, 2008; Lorist, Boksem, & Ridderinkhof, 2005; Lorist et al., 2000, 2009; Van der Linden & Eling, 2006; Van der Linden, Frese, & Meijman, 2003; Van der Linden, Frese, & Sonnentag, 2003). Executive functions refer to a set of cognitive functions that allow for the adjustment of behavior to changing circumstances in accordance with internal goals (Miller & Cohen, 2001). These functions are crucial to abilities in higher education, such as the acquisition of new skills, learning in general, evaluation of the intentions of teachers and of the school system, planning and strategic thinking for the short, medium, and long term, evaluation of feedback, and monitoring of wishes and intentions of significant others (e.g. Miller, 2000; Miller & Cohen, 2001; Zelazo, Müller, Frye, & Marcovitch, 2003). In addition, better executive functions, such as cognitive flexibility, have been related to academic proficiency (e.g., Best, Miller, & Naglieri, 2011; Latzman, Elkovitch, Young, & Clark, 2010).

A key aspect of executive functions refers to the ability to flexibly switch between changing environmental demands (Monsell, 2003). A classic task for measuring cognitive flexibility is the Wisconsin Card Sorting Task (WCST; Grant & Berg, 1948; Heaton, Chelune, Talley, Kay, & Curtiss, 1993). This is a relatively complex task that is likely to simultaneously engage many cognitive functions (Cepeda, Kramer, & Gonzales de Sather, 2001; Huizinga & Van der Molen, 2007; Miyake et al., 2000), rendering it difficult to interpret WCST performance in relation to a specific underlying mechanism (e.g., Huizinga & Van der Molen, 2007; Miyake et al., 2000; Van der Linden, Frese, & Meijman, 2003). One way to assess the ability to switch between task sets in the absence of other cognitive functions, such as problem solving, is the task-switching paradigm (Monsell, 2003). In the task-switching paradigm, participants switch between two or more simple task sets (e.g., responding to the color and responding to the shape of a multi-dimensional stimulus). Two trial types are distinguished: repetition trials, in which the previous task set remains the same; and switch trials, in which the previous task set changes. In general, responses are slower

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and less accurate on switch trials compared to repetition trials (Allport, Styles, & Hsieh, 1994; Meiran, 1996; Monsell, 2003). This decline in performance is also referred to as "switch cost". Switch costs have been explained in terms of preparation for the upcoming task (Meiran, 1996; Monsell, 2003; Rogers & Monsell, 1995), or interference from the previous task (Allport et al., 1994; see Kiesel et al., 2010 and Schmitz & Voss, 2012 for a review).

Only a limited number of studies have investigated the effects of fatigue on cognitive flexibility. These studies suggest a relation between fatigue and decreased cognitive flexibility (Lorist et al., 2000, 2009; Van der Linden, Frese, & Meijman, 2003; Van der Linden, Frese, & Sonnentag, 2003). In healthy individuals, the effects of acute fatigue have been investigated by means of fatigue induction using mentally demanding tasks. Mental fatigue can be induced by "performance across tasks" (i.e., the effect of fatigue induced by one or more tasks on performance of another task), or by "time on task" (i.e., the effect of task duration on performance). Fatigue induced by "performance across tasks" resulted in more rigid behavior on a complex computer task that required thoughtful systematic exploration (Van der Linden, Frese, & Sonnentag, 2003), and more perseverative errors on the WCST (Van der Linden, Frese, & Meijman, 2003). Fatigue induced by "time on task" is also associated with reduced cognitive flexibility (Boksem et al., 2006; Lorist et al., 2000, 2009); while fatigue increased with time on task, behavioral performance decreased on tasks with high response conflict (Boksem et al., 2006) and on switch tasks (Lorist et al., 2000, 2009). However, in the Lorist et al. (2000) study, this effect did not distinguish between repetition and switch trials.

To summarize, fatigue complaints in the general population are common. We suggest that fatigue may relate to degraded academic or work performance due to its effect on cognitive control. There is evidence that fatigue reduces cognitive flexibility, but the complex nature of some tasks used in previous research (e.g., WSCT, Van der Linden, Frese, & Meijman, 2003) renders it impossible to interpret these effects in relation to specific underlying processes during task performance. In studies using more specific tasks, behavioral effects of fatigue do not always differentiate between underlying processes; the lack of a differential effect of fatigue on repetition and switch trials (Lorist et al., 2000) calls into question whether fatigue, induced by time on task, affects processes exclusive to task switching. The present study therefore aims to further explore underlying factors of cognitive flexibility in relation to fatigue in healthy individuals.

1.1. Current study

The current study investigated effects of fatigue on task-switching performance in a healthy student sample. Fatigue was induced by performance across tasks. The advantage of studying effects of fatigue across tasks, as opposed to time on task, is that this allows us to study the possible transfer of fatigue to other tasks or situations. To account for individual differences in fatigue state at baseline, we also measured the subjective experience of fatigue over the past days by means of a questionnaire. As such, we distinguished between effects of acute fatigue, which is a direct result of previous activities (i.e., induced fatigue), and a more permanent fatigue state that has been built up and lasting over a longer period of time with multiple possible causes (i.e., baseline fatigue). Potential interactions between induced and baseline fatigue could elucidate whether students with higher fatigue at baseline are more vulnerable to effects of a fatigue induction.

Effects of fatigue were investigated on switching between tasks of unequal difficulty. In the classroom, students often have to switch between tasks of unequal difficulties, such as considering simple and more complex solutions to a problem, dividing a complex situation into less complicated subcomponents, or switching between complex reasoning and the easier task of noting key words. This method enabled us to examine "switch-cost asymmetry", which commonly occurs during switches between tasks of unequal difficulty and refers to a typically larger switch cost when switching from difficult (e.g., incongruent or less practiced) to easy tasks compared to the other way around (e.g., Allport et al., 1994; Koch, Prinz, & Allport, 2005; Monsell, Yeung, & Azuma, 2000; Yeung & Monsell, 2003). This effect has been attributed to persistence of processes that were involved in the previous more difficult task, such as inhibition of the easier task or stronger priming effects of the more difficult task (Allport et al., 1994; Goschke, 2000; Yeung & Monsell, 2003; see Kiesel et al., 2010 for a review). To examine whether fatigue would affect the ability to overcome this so-called 'proactive interference' (Kiesel et al., 2010), we investigated effects of fatigue on switch-cost asymmetry.

All participants performed a task derived from the task-switching paradigm (see Monsell, 2003), which consisted of two task rules of unequal difficulty. Both task rules required the participants to respond to arrows pointing up or down, and these arrows could be blue or red. In the easier task, indicated by blue arrows, participants were required to respond to the direction of the arrows ("up" for an arrow pointing up and "down" for an arrow pointing down). This task is relatively easy, because it relies mostly on automatic processes. In the difficult task, indicated by red arrows, the participants were required to respond in the opposite direction of the arrows ("up" for an arrow pointing down and "down" for an arrow pointing up). This task is more difficult, as it incorporates response conflict (see also Botvinick, Braver, Barch, Carter, & Cohen, 2001). The stimuli of the task thus varied in color (blue or red) and direction (up or down). A switch in task rule was indicated by a change in color of the stimulus, which occurred unexpectedly in approximately 50% of the trials. We hypothesized that fatigue is associated with a decrease in task-switching performance in terms of accuracy (i.e., decreased accuracy on switch trials) as well as reaction times (i.e., increased RT's on switch trials).

2. Methods

2.1. Participants

Sixty healthy individuals (45 females, $M_{\text{age}} = 20.3$ years, $SD = 1.8$ years) took part in this study. All participated in the first year of the Psychology program at the VU University Amsterdam and received course credits for their contribution (which did not depend on task performance). Each individual had normal or corrected-to-normal vision, no color blindness and provided written informed consent before the start of the experiment. The participants were randomly assigned to an experimental group or a control group.

2.2. Procedure

All participants completed a practice session and a test session. The practice session took place on a different day within a week before the test session. During the practice session, which took approximately 45 min, each participant first completed a set of descriptive questions, followed by a mood state questionnaire (Profile of Mood States (POMS); Wald & Mellenbergh, 1990) to assess fatigue over the last days, then practiced a short version of the switch task for approximately 8 min and another cognitive task (not described here). The test session took place at 2 p.m. on a working day and started with a fatigue manipulation of 1 h. Previous studies used fatigue manipulations of up to 2 h, but fatigue ratings can significantly increase after only 20 min (Lim, Wu, Wang, Detre, & Dinges, 2009). We therefore considered 1 h as sufficient to induce fatigue. The switch task and two other cognitive tasks were performed after the manipulation (results of the other tasks are presented elsewhere: Plukaard & Krabbendam, in preparation). Fatigue questionnaires (POMS and the Rating Scale Mental Effort (RSME); Zijlstra, 1993) were completed before and after the manipulation, as well as at the end of the test session. The duration of the test session was approximately 2 h.

2.3. Fatigue manipulation

Fatigue was manipulated by a fatigue-inducing manipulation for the experimental group and a control manipulation for the control group. The fatigue-inducing manipulation consisted of 15 min of mental arithmetic followed by: 15 min of brainteaser puzzles (such as arithmetic sequences and syllogisms); 10 min of a computerized Stroop task (Stroop, 1935) adopted from Evers and colleagues (Evers, Van der Veen, Jolles, Deutz, & Schmitt, 2009) with extra auditory interference; and an N-back computer task (2- and 3-back) for another 20 min (see also Klaassen et al., 2013 for details). These tasks highly rely on executive control, demanding additional mental effort, and are therefore expected to induce fatigue. A previous study has confirmed that this manipulation increases fatigue ratings in adults (Klaassen et al., 2013).

The Stroop and N-back tasks were programmed in Eprime 1.2 (Psychology Software Tools, Pittsburgh; http://www.pstnet.com/). Participants in the control group spent the same time reading magazines (a collection of magazines was provided). Both manipulations lasted for 1 h.

2.4. Questionnaires

2.4.1. Baseline fatigue

During the practice session, the short version of the POMS (Wald & Mellenbergh, 1990; in Dutch) was administered. This questionnaire contains five mood scales (fatigue, depression, vigor, tension and anger) that consist of several adjectives to describe mood. Participants indicated their mood state over the previous couple of days on a 5-point Likert scale. The fatigue scale (item range: 0–4; total range 0–24) was used to measure “baseline fatigue” which covers general feelings of fatigue over a period of several days (i.e., T0). Cronbach's Alpha for the POMS fatigue scale was .89.

2.4.2. Induced fatigue

During the test session, subjective fatigue was measured before and after the manipulation (i.e., T1 and T2), and after the cognitive tasks (i.e., T3), using the POMS fatigue scale and the RSME (Zijlstra, 1993). The RSME contains seven items that relate to mental fatigue (two items), physical fatigue (two items), visual fatigue (one item), resistance against further effort (one item), and boredom (one item). Items were scored on a visual analog scale, ranging from 0–150 (total RSME range: 0–1050). For the POMS and the RSME, the participants were instructed to rate how they felt at that moment. In this case, POMS fatigue scores indicated acute state as opposed to POMS fatigue scores measured at the practice session that indicated fatigue over the past days (representing a more general and permanent state of fatigue). Cronbach's Alpha, averaged over T1–T3, was .85 for the POMS fatigue scale and .86 for the RSME.

2.5. Switch task

2.5.1. Apparatus and stimuli

The switch task was presented on a HP Compaq Desktop PC (Intel Core 2 processor, 17 in. 60 Hz monitor) running Windows XP and programmed in Eprime 1.2. The task required only right-hand responses using the index finger and thumb. The response button for the index finger was “arrow up”/“8” on the numpad of the computer keyboard and for the thumb “arrow down”/“2” on the numpad.

The target stimuli were arrows that varied in color (blue or red) and direction (pointing up or down). The stimuli (visual angle 7.5° horizontally and vertically; ±5 cm length and width on the computer screen) were sequentially presented against a black background in the center of the screen, placed at 40 cm distance from the participant.

2.5.2. Task design

Participants performed the task by following two rules: blue arrows (representing the easy task) indicated that the participant should press the response buttons in the direction of the arrows (e.g., press “up” for a blue arrow pointing up). For red arrows (representing the difficult task), the rule was to press the response button in the opposite direction (e.g., press “up” for a red arrow pointing down). When an arrow was preceded by an arrow of the same color (regardless of the direction of the arrow), this trial was considered a *task repetition trial* (on these trials, the rule did not change). When an arrow was preceded by an arrow of a different color, this trial was considered a *task switch trial*, as the participant had to switch from one rule to the other rule. The order of the trials was randomized, and the task contained approximately 50% repetition trials and 50% switch trials. Repetition sequences ranged from one to six repetitions.

Each trial consisted of a white fixation cross, which remained on the screen for 500–750 ms (pseudorandomly varied in steps of 10 ms), followed by a target stimulus (500 ms), and a black screen (inter-trial interval (ITI); 500 ms). The response window lasted from the start of the target presentation until the end of the ITI (i.e., 1000 ms). Responses did not affect duration of target presentation or ITI, and no feedback was given. In total, 400 trials were presented, of which 200 blue arrows and 200 red arrows (100 up, 100 down for each color). The order of the trials was randomized. Task duration was approximately 15 min.

2.5.3. Analyses

Prior to the statistical analyses, the data of the switch task were preprocessed according to the following steps: For each participant, the first 5 trials were considered as “warm-up” trials and not included in the analyses. Also, responses faster than 120 ms and extreme outliers (responses slower than 2.5 standard deviations above the mean) were removed. Next, we excluded participants who clearly did not understand the task, or for some other reason did not perform the task according to the task rules. Therefore, participants with accuracy scores below 55% on the repetition trials of either the blue or the red task (from now on referred to as ‘easy’ and ‘difficult’ task resp.) were excluded. A threshold of 55% accuracy is just above chance level and previously used in comparable tasks (e.g., Huizinga, Dolan, & Van der Molen, 2006; Huizinga & Van der Molen, 2007). Participants who scored below this threshold were regarded as not having understood either one of the tasks sufficiently. Finally, participants with scores between 1.5 and 3 times the interquartile range on both the easy and the difficult tasks were considered outliers and were also excluded. For the RT analyses, we excluded all error and post error (PE) trials, as well as the first repetition trial of a series. Both PE trials and trials directly following a task switch are typically characterized by response slowing (Danielmeier & Ullsperger, 2011; Karayanidis et al., 2010), as was currently the case (mean RT: 455 (PE) and 455 (1st repetition) vs 436 ms, $p < .001$ for both comparisons).

Mixed design ANOVAs were used to analyze the accuracy (proportion correct) and response latency (median RT) on the switch task with *Group* (experimental, control) as between-subjects variable, and *Trial Type* (repetition, switch) and *Task Rule* (easy, difficult) as within-subjects variables. Subsequently, we evaluated whether baseline fatigue would influence the effects of induced fatigue. We therefore reran the ANOVAs and included *Baseline fatigue* (as measured with the POMS fatigue scale during the practice session) as a continuous variable of interest. First, we investigated whether *Baseline fatigue* interacted with *Group*. When this was not the case, we only added the *Baseline fatigue* main term, which we allowed to interact with all within-subjects factors. All statistical analyses were carried out with PASW Statistics 18.0 (Chicago: SPSS Inc., IL).

3. Results

3.1. Sample characteristics

We excluded four participants (one male from the control group and one male and two females from the experimental group) based on the procedure described above[1]; the final sample consisted of 56 participants (28 participants per group; see Table 1). The groups did not differ on age, sex, baseline POMS scores (all scales), or POMS fatigue and RSME mental effort assessed at the start of the test session, all p's > .25. In addition, we compared the groups on percentage of trials removed (i.e., extreme outliers) and observed no significant difference (2.0% in the experimental group and 1.6% in the control group: $p = .413$).

Table 1
Sample characteristics — M (SD) and percentages.

		Fatigue	Rest	p
N		28	28	–
Age		20.3 (2.0)	20.4 (1.6)	n.s.
Female		82%	71%	n.s.
POMS	Fatigue	6.5 (5.8)	5.1 (4.0)	n.s.
	Depression	3.8 (4.9)	2.6 (3.6)	n.s.
	Anger	4.1 (3.9)	3.8 (4.6)	n.s.
	Vigor	9.5 (3.8)	8.9 (3.6)	n.s.
	Tension	4.4 (3.2)	3.9 (3.9)	n.s.
POMS fatigue	T1	3.8 (4.4)	3.1 (2.9)	n.s.
RSME	T1	198 (141)	182 (117)	n.s.

3.2. Manipulation check: fatigue and mental effort

Scores on the fatigue scales are presented in Fig. 1. Due to a positive skew on the scales, the assumption of normality was violated. Therefore non-parametric tests were applied (i.e., related-samples Wilcoxon signed rank tests for within group comparisons and Mann–Whitney tests for between group comparisons). First, we compared fatigue scores between T1, T2 and T3 within each group to test for changes in fatigue over time. Second, we evaluated whether the change over time differed between the groups by comparing difference scores (i.e., effects of manipulation: T2 minus T1; effects of cognitive tasks: T3 minus T2) with positive values corresponding to an increase in subjective fatigue. Third, we compared the groups on T1, T2 and T3, to ensure that a group difference in switch performance would correspond to a difference in acute fatigue. A Bonferroni correction was applied to adjust for multiple comparisons, taking into account the mean correlation between all variables (http://www.quantitativeskills.com/sisa/calculations/bonfer.htm). For 18 tests (i.e., nine tests per scale) and a mean correlation coefficient of $\rho = .38$, effects were considered significant at $p < .0083311$, which corresponded to an overall alpha level of .05.

3.2.1. POMS fatigue scale

We observed an increase of marginal significance in POMS fatigue ratings between T1 and T2 in the experimental group (M = 1.5, SD = 3.2, $z = 2.621$, $p = .009$, $r = .35$) and no increase in the control group (M = 0.1, SD = 3.7, $z = 0.263$, $p = .793$, $r = .04$). There was a trend for a group difference with regard to this increase ($U = 262.5$, $z = -1.981$, $p = .048$, $r = .28$). The increase from T2 to T3 was not significant in either one of the groups (experimental group: M = 0.6, SD = 2.0, $z = 1.892$, $p = .059$, $r = .25$; control group: M = 1.2, SD = 3.4, $z = 1.799$, $p = .072$, $r = .24$) and did not differ between the groups ($U = 352.5$, $z = -0.443$, $p = .66$, $r = .06$). Group comparisons revealed no significant differences at T1, T2 or T3 (T1: $U = 385.0$, $z = -0.116$, $p = .907$, $r = .02$; T2: $U = 271.0$, $z = -1.815$, $p = .070$, $r = .24$; T3: $U = 340.0$, $z = -0.857$, $p = .392$, $r = .11$).

Summarized, we detected no group differences at T1, T2 or T3. A trend indicated a larger increase in fatigue ratings as measured with the POMS in response to the manipulation in the experimental group compared to the manipulation in the control group. This effect, however, did not reach statistical significance after a Bonferroni correction.

3.2.2. RSME

There was a large significant increase in fatigue from T1 to T2 in the experimental group (M = 126, SD = 106, $z = 4.205$, $p < .001$, $r = .56$) whereas the control group showed a slight non-significant decrease (M = −15, SD = 98, $z = 0.940$, $p = .347$, $r = .13$). This change over time differed significantly between the groups ($U = 119.5$, $z = -4.353$, $p < .001$ $r = .59$). Both groups showed a trend for an increase from T2 to T3 (experimental group: M = 47, SD = 115, $z = 2.335$, $p = .020$, $r = .31$; control group: M = 61, SD = 130, $z = 2.259$, $p = .024$, $r = .30$), which did not differ significantly between the groups ($U = 389.5$, $z = -0.41$, $p = .97$, $r = .01$). Group comparisons showed that the experimental group scored significantly higher than the control group on the RSME at T2 ($U = 175.5$, $z = -3.549$, $p < .001$ $r = .47$) and T3 ($U = 202.5$, $z = -3.106$, $p = .002$ $r = .42$), but not at T1 ($U = 373.0$, $z = -0.084$, $p = .933$ $r = .01$).

To investigate the specific aspects of fatigue that were affected by the manipulation, we compared the groups on the difference in fatigue score between T1 and T2 as well as T2 and T3 for each of the items. These analyses revealed that the increase in fatigue score from T1 to T2 differed significantly between the groups for all items apart from the ones related to physical and visual fatigue (see Supplementary Table S1). There were no group differences in the change over time from T2 to T3. Altogether, these findings confirmed that the fatigue manipulation increased mental fatigue and mental effort ratings as measured with the RSME.

3.3. Switch task

To adjust for positive skew, the POMS scores were log-transformed. Because the fatigue manipulation successfully increased subjective fatigue ratings (as indicated by a trend on the POMS scores and a significant effect on RSME scores), effects of *Group* are interpreted as representing effects of *Induced fatigue*.

3.3.1. Accuracy

A significant main effect of *Trial Type* indicated that participants were less accurate on switch trials compared to repetition trials, ($F(1,54) = 75.628$, $p < .001$, $r = .76$). There was a significant interaction between *Task Rule* and *Trial Type*, indicating a significant switch-cost asymmetry: switch cost was larger for switches from the difficult to the easy task compared to switches from easy to difficult (9% vs 6%; $F(1,54) = 11.904$, $p < .005$, $r = .43$). There were no effects of *Induced fatigue* ($F(1,54) < 0.576$, $p > .451$, $r < .10$ for all other comparisons) and no additional effects involving *Baseline fatigue* ($F(1,53) < 1.162$, $p > .285$, $r < .15$).

3.3.2. Response latency

A main effect of *Trial Type* was observed, showing that participants responded slower to switch trials compared to repetition trials, ($F(1,54) = 253.704$, $p < .001$, $r = .91$). There was also a main effect of *Task Rule*, indicating longer reaction times for the difficult task rule

[1] We analyzed the sample with outliers included, and found that the results remained stable, except for the following: for accuracy the switch-cost asymmetry was no longer significant with inclusion of *Baseline fatigue* ($p = .219$), for the reaction times we observed no main effect of *Group* ($p = .139$ with *Baseline fatigue*; $p = .131$ without *Baseline fatigue*), and the *Trial type* × *Task rule* × *Baseline Fatigue* interaction appeared significant ($F(1,57) = 4.71$, $p < .05$). The changes were caused by extreme RTs and accuracy values of the excluded participants, which did not distinguish between task conditions (resulting in negative or very small switch costs). The excluded participants were unevenly divided over the groups (three belonged to the fatigue group) and the baseline fatigue variable (three of the excluded participants scored zero), which biased the results related to fatigue.

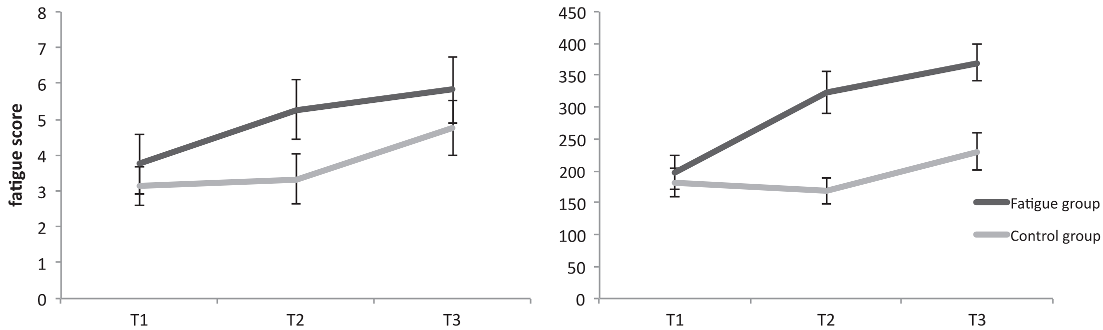

Fig. 1. Mean scores of untransformed data of the POMS fatigue scale (left) and the RSME (right) at three assessments: before the manipulation (T1), after the manipulation (T2) and after the cognitive tasks (T3). Dark gray represents the experimental group and light gray represents the control group. Error bars represent standard error of the mean.

compared to the easy task rule ($F(1,54) = 35.063$, $p < .001$, $r = .63$). We obtained a significant interaction between *Trial Type* and *Task Rule* ($F(1,54) = 15.131$, $p < .001$, $r = .47$).

With respect to fatigue, two important effects were observed. First, a main effect of *Induced fatigue* indicated that overall, the experimental group responded significantly slower than the control group ($F(1,54) = 5.714$, $p < .05$, $r = .31$; 492 ms vs 463 ms). The second effect related to fatigue was a significant *Induced fatigue* × *Trial Type* × *Task Rule* interaction: the experimental group showed a switch-cost asymmetry, with a larger difference between switch and repetition trials for the easy compared to the difficult task, whereas the control group did not show this asymmetry ($F(1,54) = 7.191$, $p < .05$; see Fig. 2). Post-hoc repeated measures ANOVAs confirmed that the interaction between *Trial Type* and *Task Rule* was significant for the experimental group ($F(1,27) = 20.790$, $p < .001$, $r = .66$), but not for the control group ($F(1,27) = 0.759$, $p = .391$, $r = .17$). Other effects with regard to induced fatigue were not significant ($F(1,54) < 1.844$, $p > .179$, $r < .19$).

Next, we included *Baseline fatigue* to the model and observed that this variable did not interact with *Induced fatigue* ($F(1,52) = 2.147$, $p = .149$, $r = .20$). Inclusion of the *Baseline fatigue* main term did not change the results found in the first model. In addition, *Baseline fatigue* interacted significantly with *Trial Type* ($F(1,53) = 4.522$, $p < .05$). Follow-up analysis revealed a positive correlation between baseline fatigue and switch cost ($r = .29$, $p < .05$). Thus, across both groups, higher fatigue scores at baseline were related to higher switch cost. There were no other significant effects involving *Baseline fatigue* ($F(1,53) < 1.883$, $p > .175$, $r < .19$).

To summarize, induced fatigue resulted in overall slower responses, but also interacted with task rule; only the experimental group showed a switch-cost asymmetry in response latencies. Furthermore, switch cost latencies were more pronounced in students with higher fatigue at baseline.

4. Discussion

The current study set out to investigate effects of fatigue on cognitive flexibility in healthy students. Specifically, we examined the effects of an acute cognitive fatigue manipulation (i.e., induced fatigue) and of individual differences in the more permanent state of fatigue at baseline (i.e., baseline fatigue) on switching between tasks of unequal difficulty. We hypothesized that fatigue would reduce task-switching performance in terms of accuracy and reaction times. The findings demonstrate that induced fatigue affected subsequent task-switching performance by reducing overall response speed and cognitive flexibility. Moreover, fatigue scores at baseline were positively related to switch cost for both the group with induced fatigue as well as the control group. These results thus partly supported our hypothesis, as fatigue was associated with reduced task switching performance in terms of reaction times, but not in terms of accuracy.

Fatigue was induced by performance across tasks, a method that has been used previously in the studies by Van der Linden and colleagues (Van der Linden & Eling, 2006; Van der Linden, Frese, & Meijman, 2003; Van der Linden, Frese, & Sonnentag, 2003). The current fatigue manipulation lasted for 1 h and included four cognitively demanding tasks to ensure that induced fatigue would not be specific to one particular task. In comparison, the manipulations in the Van der Linden studies lasted for two or more hours and consisted of one or two tasks. Results showed that subjective fatigue ratings increased more in the group with induced fatigue, as indicated by a significant increase in RSME scores and a trend for an increase on the POMS fatigue scale. The RSME thus appeared to be more sensitive to effects of the present fatigue manipulation. This difference in sensitivity may be due to the fact that the RSME has broader response scales (i.e., 0–150 compared to 0–4 for the POMS) and more detailed items (i.e., questions referring to specific aspects of fatigue compared to single synonyms of fatigue for the POMS). More detailed analyses of the RSME revealed that the

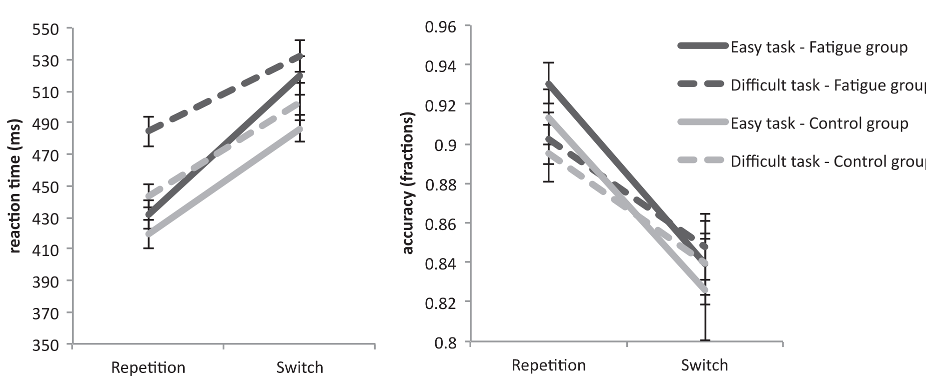

Fig. 2. Mean reaction times (left) and accuracy (right) on repetition and switch conditions for the easy (solid lines) and difficult (dashed lines) task rules. Dark gray represents the experimental group and light gray represents the control group. Error bars represent standard error of the mean.

manipulation mainly affected cognitive aspects of fatigue and not the physical aspects. Based on these findings, we conclude that the current fatigue manipulation, despite its relatively short duration, successfully induced cognitive fatigue.

As expected, cognitive flexibility was affected by induced fatigue and related to baseline fatigue in several ways. First of all, induced fatigue resulted in an overall increase of response latencies, whereas accuracy on both switch and repetition trials was not affected. This main effect must be interpreted with caution, as induced fatigue also interacted with task rule and trial type. The group difference in response latency thus did not hold for all task variables. Nonetheless, all fatigue effects involved changes in response latency (with induced fatigue resulting in slower responses), which suggests that fatigued individuals sacrificed speed in order to maintain a pattern of correct responses. This finding appears to be a robust effect, as previous studies also have shown that fatigue can lead to overall response slowing on a switch task (Lorist et al., 2000; Lorist et al., 2009). Notably, Lorist and colleagues induced fatigue by prolonged performance on the same switch task. In this study we showed that effects of fatigue on task switching could be transferred from other previously performed tasks.

A switch-cost asymmetry in terms of response latencies was observed in the experimental group, but not in the control group. After the fatigue induction, switch costs associated with easy trials (i.e., the difference between easy repetition trials and switches from difficult to easy trials) were larger compared to switch costs associated with difficult trials (i.e., the difference between difficult repetition trials and switches from easy to difficult trials). In line with previous research (Allport et al., 1994; Goschke, 2000; Kiesel et al., 2010; Yeung & Monsell, 2003), this finding could suggest that induced fatigue increases proactive interference from difficult trials due to reduced inhibition or stronger priming effects. Schneider and Anderson (2010) explained switch-cost asymmetry in terms of a temporary reduction in cognitive control capacity evoked by performance on more difficult trials. Difficult trials require more cognitive capacity and because it takes time to restore this capacity, response latencies on subsequent trials increase. This also suggests that switch-cost asymmetry could be enhanced when cognitive resources are depleted, for example by the current fatigue manipulation. The fatigue induction in the current study consisted of several demanding tasks. Sequential cognitive demands are thought to challenge cognitive capacity by depleting a common resource (Baumeister, Muraven, & Tice, 2000), or by reducing motivation to allocate resources (Huizenga, Van der Molen, Bexkens, Bos, & Van den Wildenberg, 2012). The present fatigue manipulation, which consisted of 1 h of sequential cognitive demands, might thus have resulted in a reduction in cognitive capacity, increasing the time required to recover after a difficult trial.

Even though we attributed the observed switch-cost asymmetry to reduced inhibitory control or resource depletion caused by the fatigue induction, an asymmetric switch cost is a typical effect. It is thus remarkable that the control group did not show this asymmetry in terms of response latencies. However, both groups showed an asymmetric switch cost in terms of accuracy, which may indicate that both groups were less successful at suppressing previous difficult trials, but only the experimental group required additional processing time following difficult trials.

We observed individual differences in fatigue state at baseline. Higher reported levels of fatigue over the past days were related to increased switch costs. This is in line with studies in which fatigue-related factors were investigated, such as alertness (increased alertness was related to decreased switch cost: Meiran & Chorev, 2005), sleep deprivation (increased switch cost in a sleep deprived group: Couyoumdjian et al., 2010) and chronic sleep limitation (increased switch cost was found in a group with sleep reduction and switch cost was negatively correlated with nighttime sleep duration: Plessow, Kiesel, Petzold, & Kirschbaum, 2011). The findings thus underscore the importance of participants' physiological state (i.e., fatigue) in relation to the ability to flexibly adjust to changing environmental demands.

The current study extends prior fatigue research by showing that the experienced level of fatigue over the past days (i.e., baseline fatigue) was unrelated to effects of induced fatigue. In other words, students who were fatigued at baseline did not necessarily suffer more from the fatigue induction. Furthermore, both baseline fatigue and induced fatigue were associated with increased switch cost latency (although for induced fatigue this relation was limited to the easy task). This indicates that levels of fatigue experienced over a certain period of time and fatigue directly induced by previous cognitive exertion are not entirely dissociable and possibly share common mechanisms. Perhaps baseline fatigue and induced fatigue would interact at higher levels of fatigue, which for instance could be investigated by comparing participants who differ more in terms of baseline fatigue or by upgrading the fatigue manipulation (e.g., a manipulation of longer duration could lead to higher fatigue). Future research may further unravel this issue. Of note, possible overlap between induced fatigue and baseline fatigue might in the present study be due to the use of the same instrument (i.e., POMS). Yet, we render this unlikely since both scales referred to fatigue in different contexts (i.e., 'over the last couple of days' versus 'at this moment') and induced fatigue was better represented by the RSME (as indicated by a significant group difference on this scale after the manipulation, which was not significant for the POMS). Nevertheless, for future reference this possibility could be ruled out by using different instruments.

We included a practice session to allow the participants to get acquainted with the speed of stimulus presentation and appropriate response buttons. One might argue that this reduced task novelty and that a completely novel task would be even more demanding and sensitive to fatigue. Nevertheless, because the practice version was relatively short and took place on a different day, we expected the influence of the practice session to be negligible.

The current fatigue induction shared commonalities (e.g., a period of task-performance with demands on cognitive control) with interventions used in depletion studies (e.g., Huizenga et al., 2012; Muraven, Shmueli, & Burkley, 2006; Verbruggen, Liefooghe, Notebaert, & Vandierendonck, 2005). Motivation can reduce effects of depletion or even instantly replenish cognitive resources (e.g., Muraven & Slessareva, 2003; for reviews, see Baumeister & Vohs, 2007; Inzlicht & Schmeichel, 2012; Inzlicht, Schmeichel, & Macrae, 2014). In addition, increasing motivation has resulted in reduced effects of fatigue induced by time on task (Boksem et al., 2006). Boksem and Tops (2008) proposed a theoretical framework of mental fatigue, which involves motivational cost-benefit decisions to find a balance between invested efforts and perceived or expected rewards. More research on the potential role of motivation in effects of prolonged fatigue or acute fatigue on cognitive flexibility may be a valuable next step in light of possible interventions aimed at reducing fatigue and related adverse effects.

4.1. Conclusion

After 1 h of cognitive challenge, students became slower and less able to flexibly switch between tasks of unequal difficulty. Moreover, we observed that students who reported higher fatigue levels over the past days took longer to switch from one task to the other. Fatigue may thus play a key role in daily life achievements that require cognitive flexibility, such as learning and academic performance.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lindif.2015.01.003.

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