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Authors
Rauch, Wolfgang
Schmitt, Kathrin

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Fatigue of Cognitive Control in the Stroop-Task

Wolfgang A. Rauch & Kathrin Schmitt (wolfgang.rauch@psych.uni-frankfurt.de)
Department of Psychology, Robert-Mayer-Str. 1
60325 Frankfurt, Germany

Abstract

Working on cognitively demanding tasks for a long time leads to a state of mental fatigue, which involves increased distractability, impaired error monitoring, or more generally an impairment of cognitive control processes. The present study indicates that cognitive control can deteriorate already after about 15 minutes. During a Stroop task, a classical measure of inhibitory control, where a high number of congruent trials encourages goal neglect and thus increases working memory load, error rate and the variability of response times increased over the course of 480 trials. These results can be interpreted as indicative of a gradual impairment of cognitive control due to the continuous exertion of cognitive control.

Keywords: executive function; response time distribution; mental fatigue; inhibitory control; response variability; Stroop.

Cognitive Control and Cognitive Fatigue

Cognitive control is a general concept, which is broadly defined and refers to several abilities: Goal setting, maintaining goal-directed behavior, performance monitoring, and adjusting behavior in case of errors and in the face of distractions and obstacles (e.g. Ridderinkhof, Wildenberg, Segalowitz, & Carter, 2004). Cognitive control can also be defined as the top-down or executive component of cognition. The capacity for cognitive control is of central importance for many behaviors, especially in the pursuit of long-term goals, in emotional and social adjustment, and in many other areas.

The capacity for cognitive control varies across individuals (Miyake et al., 2000). In addition to genetic influences, it is known that age-related declines in neurobiological systems (Braver et al., 2001) as well as psychiatric disorders (e.g. Geurts et al., 2008) can impair the capacity for cognitive control. But the capacity for cognitive control also varies intra-individually: Performance on tasks involving cognitive control can be enhanced as a function of incentives (Sarter, Gehring, & Kozak, 2006), and performance deteriorates after sleep deprivation (Chuah, Venkatraman, Dinges, & Chee, 2006). Finally, working on cognitively demanding tasks for a long time (Boksem & Tops, 2008) and previous exertion of cognitive control (Schmeichel & Baumeister, 2004) impair this capacity.

Losing (Cognitive) Control

Mental Fatigue Cognitive control becomes more difficult when working for a long time. This phenomenon has been called "mental fatigue", which refers to both a subjective feeling of "tiredness or even exhaustion ..., and a decrease in the level of commitment to the task at hand" (Boksem & Tops, 2008, p. 126) and to more objective consequences such as increased distractibility or impaired error monitoring and failure to adjusting one's responses after an error (Boksem, Meijman, & Lorist, 2006; Lorist, Boksem, & Ridderinkhof, 2005). In a simple two-choice reaction task which had to be performed for two hours, Boksem et al. (2006) found a slight decrease of response time (RT) with time on task and an increase of errors with time on task. In addition, they found a post-error slowing of RT which, however, disappeared with time-on-task. The latter finding is of special interest in the context of mental fatigue: it indicates impaired error monitoring and suboptimal behavioral adjustment with mental fatigue. Using a very similar set-up, Lorist et al. (2005) also found a slight decrease of RT with time on task and an interaction of post-error slowing with time on task.

Cognitive Control as a Depletable Resource Whereas mental fatigue has been studied with simple repetitive tasks, social psychologists have studied the loss of cognitive control in more complex settings. Investigating the broadly defined construct of self-control as the "ability to override or change one's inner responses, as well as to interrupt undesired behavioral tendencies and refrain from acting on them" (Tangney, Baumeister, & Boone, 2004, p.275), dozens of studies have shown that self-control for some task is hampered when the task directly follows another task involving self-control (for a review, see Schmeichel & Baumeister, 2004). For example, Hofmann, Rauch, and Gawronski (2007) have shown that suppressing one's emotional expressions impairs subsequent efforts at controlled (vs. automatic) processing: after the emotion suppression task, the amount of candy consumption could be better predicted by an implicit measure of attitudes toward candy than by an explicit dietary restraint scale. Yet attempts at self-control also have an influence on simpler tasks assumed to assess cognitive control. Richeson and Shelton (2003) have shown that efforts at self-control hamper performance in a subsequent Stroop task. In the Stroop task, cognitive control is necessary for an active maintenance of the goal of naming the color instead of reading the word; the controlled processing of naming the color has to be given top-down priority compared with the automatized processing of the word.

Unlike in studies of mental fatigue, studies of self-control loss have until now only focused on group-level comparisons of outcomes after an experimental intervention. In the typical set-up of such a study, the experimental group has to perform two self-control tasks after another, while the control group only performs the second task. Performance on the second task then is used as the dependent variable. Such a design can neither detect interindividual differences in self-control loss nor does it inform about the time evolution of self-control loss. Consequently, it is not yet known whether self-control

gradually decreases with time on task or whether there are more pronounced drops after a self-control consuming task had to be performed.

Inhibition as a Cognitive Control Process

The general construct of cognitive control can be divided into several related, yet separable functions (Miyake et al., 2000; Ridderinkhof et al., 2004). Cognitive control is apparent in top-down processes such as shifting between two task sets, error monitoring, or maintaining a specific, non-automatized response set even when other stimulus-response (S-R) mappings are strongly activated. The latter process is known as inhibitory control: maintenance of a non-automatized response set can be assumed to involve active inhibition of the prepotent, more automatized response. Inhibition plays a major role not only in "cool" cognition, but also in emotional adjustment, withstanding inadequate or even harmful impulses and tempations (alcohol and drug abuse, risky sexual behavior), and may even be linked to educational and professional achievement (Schmeichel & Baumeister, 2004; Tangney et al., 2004).

In the assessment of inhibitory control, tasks are employed where the manner of responding for a prepotent, i.e. automatized S-R mapping is compared with the manner of responding when the automatized reaction has to be inhibited. In go/no-go tasks, for example, participants are required to respond as quickly as possible to a large number of stimuli, but have to refrain from responding in case of the infrequent and irregular appearance of a small subset of stimuli. Another frequently employed inhibition task is the classic Stroop task: In this task, color words are printed in colored ink. For congruent trials, the color word is the same as the print color (e.g. the word "red" is displayed in red); for incongruent trials, word and color differ (e.g. the word "green" is displayed in red). Naming the color is assumed to involve inhibition of the automatized response to read the word; accordingly, naming the color is slower and more error-prone than reading the word, especially for incongruent trials, as has been demonstrated in literally thousands of studies (MacLeod & MacDonald, 2000).

Motivation and Goal of the Present Study

Mental fatigue has mainly been studied in extended time frames, with tasks that have to be carried out for at least two hours. In the literature on the loss of self-control, however, it has been shown that cognitive control can be impaired already after short and simple attempts at self-control. Another central difference of the two research approaches lies in the complexity of the experimental tasks: Studies of mental fatigue have mostly applied very easy tasks involving only a little amount of cognitive control.

In the present study, a Stroop color-word task is used with a large proportion of congruent trials, i.e. trials where color and word match. A large proportion of congruent trials encourages neglecting the goal of naming the color, since the more automatized response of reading the word can become active on congruent trials (Kane & Engle, 2003). Thus, a Stroop task with a large proportion of congruent trials requires not only to inhibit the automatized response (reading the word), but also to actively maintain the goal (naming the color) in working memory. We assume that having to execute a Stroop task with a large proportion of congruent trials for an intermediate duration ($\sim$ 15 minutes) gradually impairs cognitive control resources. This impairment of cognitive control resources should lead to failures of goal maintenance and error monitoring processes, so that more errors occur in later stages of the task. We also explore changes in response times (RTs), since the gradual impairment of cognitive control might lead to more effortful processing in later stages of the tasks. Effortful processing in later stages of the task might also lead to an increased variability of RTs, especially in the case of lapses of cognitive control, leading to errors.

In addition to the substantive goals we wanted to explore the benefits and additional insights of a time-course oriented and intra-individual analysis when studying mental fatigue and the depletion of cognitive control. Studies of the loss of self-control after a previous exertion of self-control have as yet only analyzed intraindividually and interindividually averaged responses (group-level approach). A goal of the present study is to explore the time evolution of errors, response times and intra-individual variability of response times (cf. Castellanos et al., 2005), thereby extending the analysis of the loss of control from simple before/after effects to the analysis of a gradual decrease of cognitive control. We assume that the Stroop task, which has already been shown to be sensitive to self-control exertion effects, can be used to study the loss of self-control intraindividually, time-oriented, and without the need for a second self-control task.

Method

Participants and Procedure

Participants were 21 undergraduate psychology students, 15 female, aged 19 to 36 years (mean = 22.9, sd= 5.1) who received course credits in exchange for participation. All participants were tested individually; the experimenter remained in the room for the entire session. Stimuli (color words) were presented on a computer screen, and participants had to name the colour the word was presented in. After a short practice session, 480 trials were performed. Each trial began with the presentation of a fixation cross (black on a silver background) for 400 ms. Then, the fixation cross was immediately replaced by one of four color words ("red", "blue", "green", or "yellow") presented in either red, blue, green, or yellow. The same pseudo-random sequence of trials was used for all participants; the trial sequence was constructed so that 50% of trials were congruent (i.e. word and color were the same), while all other (incongruent) color-word combinations were equally likely. The response time (RT) was measured as the time point a participant started to speak. Participants pressed a button in order to proceed to the next trial. Thus, total duration depended on participants' RT and varied from about 11

minutes to about 18 minutes. The experimenter recorded errors (reading the word instead of the color, then proceeding to the next trial) and corrected responses (starting to read the word or reading the word, then naming the color).

Statistical Analysis

Data Processing For each participant, we analyzed the number of errors and the number of corrected responses. We assume that corrected responses reflect a different kind of cognitive process than errors: In the case of correcting a false response, the cognitive control process of error monitoring becomes active with a small delay; in the case of an error, the participant proceeds to the next trial and the error monitoring process does not become active at all (cf. Boksem et al., 2006)

Analysis of Change A central goal of the present study is the intraindividual analysis of changes in the distribution of erroneous responses and of changes in RT distribution during the time course of the task. Consequently (cf. Rouder, Lu, Speckman, Sun, & Jiang, 2005), we employed hierarchical regression models (aka random effects or multilevel models) with random intercepts for participants [1].

Several kinds of models were analyzed for the number of errors, the number of corrected responses, RTs, and RT variability using the different kinds of data sets: Models differed with regard to the construction of the time effect. The time effect was modeled by including a predictor variable coding for blocks of subsequent trials. Two different ratios of number of trials per block/number of blocks were analyzed: (1) 12 blocks of 40 trials and (2) 4 blocks of 120 trials. For both kinds of blocking, polynomial contrasts were used to test for non-linear effects of time in addition to the linear effect. Since in no case any replicable different effect could be found for the two kinds of blocking, we will report only results for the analyses with 4 blocks of 120 trials.

Preprocessing in the Analysis of RT and RT Variability For the analysis of RT and RT variability, raw RTs were analyzed. Neither the exclusion of RTs from erroneous or corrected responses nor setting all RTs $< 200ms$ to a value of $200ms$ as well as setting RTs $> 3000ms$ to a value of $3000ms$ (cf. Miyake et al., 2000) yielded results that differed considerably from the analyses of raw RTs.

For the analysis of RT variability, the different kinds of raw and preprocessed RT data were logarithmized; then, for each data set, variances were computed for 12 blocks of 40 trials or for 4 blocks of 120 trials. These variability data were then also subjected to hierarchical regression models, testing for linear and non-linear effects of time using polynomial contrasts.

[1] A random intercept means that interindividual differences in the mean of the dependent variable independent of the predictors are accounted for in the model.

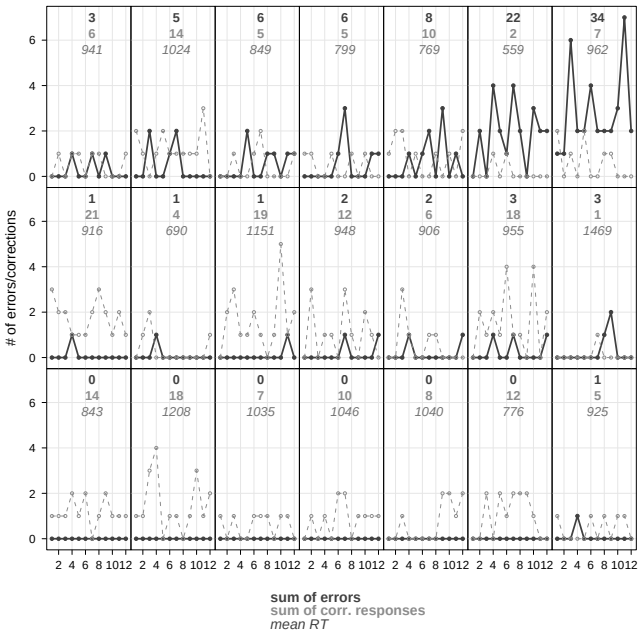

Figure 1: Errors and Corrected Responses per Subject for 12 Blocks of 40 Trials; Mean RT in Italics.

Results

Errors and Corrected Responses

Descriptive Analysis Altogether, participants produced very few errors ($98 \approx .97\%$) and corrected responses ($204 \approx 2.02\%$). Participants varied widely in the number of errors ($0-34$; $sd = 8.3$), with 6 participants without any errors, and less strongly in the number of corrected responses ($1-21$; $sd = 5.8$). The number of errors and the number of corrections were negatively correlated ($r = -.31$). Figure 1 presents errors and corrected responses tabulated by Subject for 12 Blocks of 40 trials, figure 2 shows the mean number of errors (grey bars) and mean response times (black dots) for 12 Blocks of 40 trials for all participants.

Errors and Time Course For the analysis of errors, hierarchical logistic regression models were analyzed[2]. As expected, there was a strong effect of congruency ($z = -6.43$, $p < .001$)[3], with the odds of committing an error being almost 20 times higher for non-congruent trials. For time course (block number), a test for polynomial contrasts revealed a linear effect of time ($z = 2.29$, $p = .03$) with the odds of committing an error increasing by a factor of 1.24 for every block of 120. Congruency and time course did not interact.

[2] Note that only results for the models with 4 blocks of 120 trials will be reported, since the kind of blocking did not change results; see above.

[3] One reviewer suggested to repeat these analyses excluding the participant with the largest number of errors (displayed in the upper right corner of all figures). This did not change the pattern of the results.

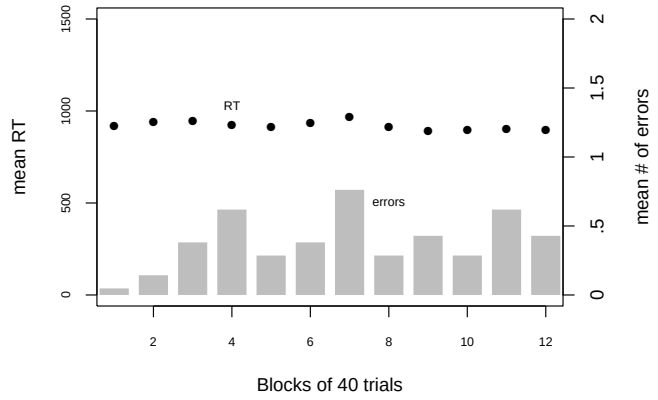

Figure 2: Mean Response Times (RT) (black dots) and Mean Number of Errors (grey bars) for 12 Blocks of 40 Trials.

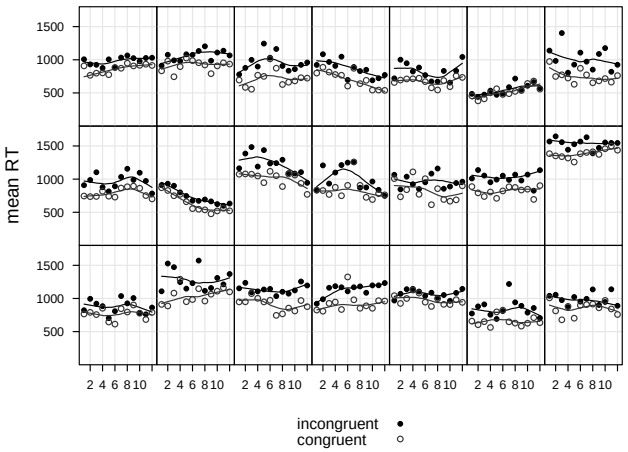

Figure 3: Mean raw response times per subject for congruent vs. incongruent trials across 12 blocks of 40 trials. In each panel, non-parametric regression lines are plotted for congruent vs. incongruent trials.

Corrected Responses and Time Course For corrected responses, there was an even stronger effect of congruency, with the odds of producing a corrected response being 78.5 times higher for incongruent trials. No significant effect of time course was found for corrected responses. However, there was a significant ($z = 2.14$, $p = .03$) interaction of congruency and time course: with each block of 120 trials, the odds ratio for the congruency effect decreased by a factor of .55; this means that for later blocks, the probability of producing a corrected response for congruent trials slightly increased.

Response Times

None of the analyses revealed any systematic pattern of RT change over time. Only in some of the analyses, a small decrease of RTs was apparent, but this decrease was not apparent for all participants, as indicated by the need to incorporate random slopes for the time effect. Also, the small decrease might be due to a smaller post-error slowing effect at later stages of the task (see below).

As expected, RTs for congruent trials were faster with a strong effect (mean difference for raw RTs $= 164ms$), but there was no interaction with time course. Figure 3 displays mean RTs (raw) for congruent vs. incongruent trials for 12 Blocks of 40 trials tabulated by subject together with a non-parametric regression line for each subject. Mean RT (raw) correlated positively with the number of corrections ($r = .19$) and negatively with number of errors ($r = -.28$).

RT increased for trials following an error (post-error slowing; raw mean increase = 465ms) and following a corrected response (raw mean increase = 476ms). For trials following an error, this effect slightly decreased with time course, but this interaction effect failed to reach significance ($z = -1.10$, $p = .14$ for raw data), which might be due to the fact that only few errors were produced on the whole.

RT Variability

In the hierarchical regression models for RT variability, the linear effect of time course showed a significant ($z = 3.32$, $p < .01$ for variances of logarithmized RT) increase of RT variability with time. This effect remained for all kinds of models. Figure 4 displays variances of logarithmized RT for 12 Blocks of 40 trials tabulated by subject together with both linear (solid) and non-parametric (dashed) regression lines for each subject.

Discussion

In the present study, a Stroop task had to be carried out with a large proportion of congruent trials. This large proportion of congruent trials paradoxically increases working memory load (Kane & Engle, 2003), since congruent trials encourage goal neglect such that the goal of naming the color has to be actively maintained in working memory and can not be automatized during the time course of the task. Due to this complication, the task was more cognitively demanding than tasks used previously in the analysis of mental fatigue; in addition, since the Stroop task has also been employed in studies of self-control loss, an analysis of the time evolution of this loss of cognitive control was possible.

Time Evolution of Errors and Corrected Responses

As expected, the amount of errors increased during the time course of the Stroop task, indicating that the participants' ability to inhibit the automatized response of reading the word instead of naming the color decreased over time. Errors in the Stroop task can be viewed not only as failures in inhibitory control, but also as failures in executive monitoring and behavioral adjustment, when participants proceed to the next trial without noticing the error. The finding of a decrease in

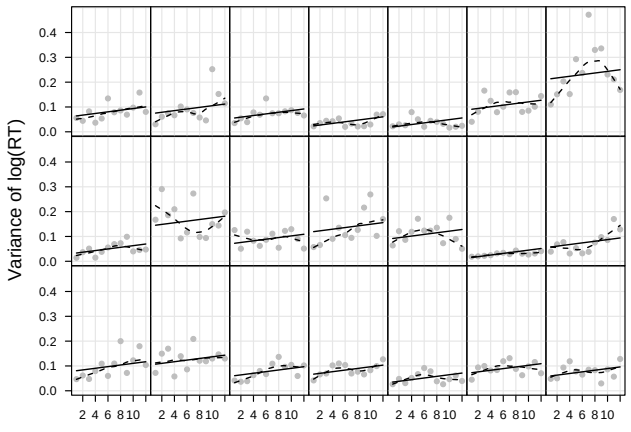

Figure 4: Variances of logarithmized RT per Subject across 12 Blocks of 40 Trials. In each panel, linear (solid) and non-parametric (dashed) regression lines are plotted.

error monitoring fits into results obtained in studies of mental fatigue (Boksem et al., 2006; Lorist et al., 2005), even if in the present study the duration was much shorter and the total number of trials much smaller than in studies of mental fatigue.

Interestingly, the number of corrected responses was not systematically related to the time course. This lack of a main effect however does not attenuate the general conclusion too much: the interaction of congruency and time course for the number of corrected responses means that during later stages of the task, participants sometimes started to name a color that was neither displayed as a word nor as a color [4]. Thus, it seems that repeated execution of the task generally impairs participants' cognitive control with regard to maintaining the goal of naming the color: During the first stages of the task, congruent trials were processed correctly, while some errors and some instantly corrected errors occurred for incongruent trials. During the later stages, even congruent trials were sometimes processed incorrectly. Because such a wrong processing is far more easy to detect for congruent trials, it could be instantly corrected.

Response Times and RT Variability

Unlike in studies of mental fatigue (e.g. Lorist et al., 2005), RTs did not increase systematically over the time course; instead, there was even some small evidence for a slight decrease of RTs during the time course. The lack of a systematic pattern of RT change might be due to interindividually different response strategies; the negative correlation of mean RT and number of errors at least hints that participants differed in terms of a speed-accuracy trade-off. The only participant with a clear increase in RT (see figure 3, second-to-last panel in the first row, upper right corner) was the one with the smallest mean RT and the one with the second largest number of errors. Anyhow, there were strong interindividual differences in mean RT, as evidenced by differences in mean RT (raw; $sd = 192ms$) being somewhat greater than the mean effect of congruency ($164ms$), just as there were strong interindividual differences in the number of errors. These interindividual differences in addition to the intraindividual differences evident in the time evolution of the number of errors and RT variability once more illustrate the need for an in-depth analysis of responses to cognitive tasks instead of just group-level comparisons of intraindividually averaged responses.

The increase in RT variability during the time course of the Stroop task, on the other hand, is consistent with the results of Boksem et al.'s (2006) analysis of mental fatigue. Increased RT variability can not be due alone to the combined effect of post-error slowing and increase of error rates, since the post-error slowing effect slightly decreased with time. Instead, increased RT variability was visible even when only correct responses were analyzed. An explanation for increased variability might be the impaired capacity for goal maintenance (see above) and action monitoring as in mental fatigue: On some trials at later stages, participants seem to have actively "struggled" to produce a correct response, increasing their RT on these trials above the response speed obtained at the beginning of the task. This interpretation is strengthened by the observation of initially incorrectly processed congruent trials in later stages of the task.

The increase of RT variability together with the results on the time evolution of errors and corrected responses hint at the explanation of a gradual impairment of goal maintenance and error monitoring with time on task, results that have already been obtained in the study of mental fatigue. An interesting result is the similarity of the performance pattern in the present study with the performance of children with ADHD (Johnson et al., 2007; Di Martino et al., 2008): Not only does the performance of children with ADHD decrease over time, their RTs exhibit a high intraindividual variability. However, for ADHD children RT variability is observable already from the beginning of a task, with simpler tasks and in shorter time frames. Despite this difference, the overall similarity of performance deficits in ADHD and impaired performance in mental fatigue hints at the possibility of common neural pathways of mental fatigue and ADHD.

Gradually Losing Control: Short-Term Mental Fatigue

In the present study mental fatigue was studied using a short-term approach: Instead of having to perform simple tasks over two hours or more, a slightly more complex task was employed for a much shorter time ($\sim$ 15 minutes). Some effects of mental fatigue were observable already after this short time course. Still, Boksem et al. (2006) and Lorist et al. (2005) have observed a decrease in RT after about an hour on task, an effect that could not be replicated in our study. Future studies might vary the time on task in order to explore these

[4] Unfortunately it was not recorded *which* color was wrongly named before the correct response was given.

phenomena more closely.

To our knowledge, this study was the first attempt to combine the approaches of research on mental fatigue with the ideas of research on self-control loss. While the underlying causes of self-control loss are as yet unclear (but see Gailliot & Baumeister, 2007), this study adds to the first attempts to integrate the results on self-control loss with the vast body of knowledge on cognitive control and executive functions. Just as in previous studies (Hofmann et al., 2007), we have shown that the exertion of cognitive control leads to an increase of automatic processing: with prolonged time on task, participants failed to maintain the goal of naming the color in working memory and thus failed to inhibit the tendency for automatized processing (reading).

Our intraindividually and change-centered analysis gives evidence that there is still something to learn even from a multiply employed task such as the Stroop. We believe that our results give some evidence for the possibility of a cross-disciplinary integration of the theories on mental fatigue and on self-control loss after previuous exertion of self-control.

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