



Mental fatigue and temporal preparation in simple reaction-time performance

Robert Langner^{a,*}, Michael B. Steinborn^b, Anjan Chatterjee^c, Walter Sturm^a, Klaus Willmes^a

^aNeuropsychology Section, Department of Neurology, RWTH Aachen University, Aachen, Germany

^bDepartment of Cognitive and Biological Psychology, University of Tübingen, Tübingen, Germany

^cCenter for Cognitive Neuroscience and Department of Neurology, University of Pennsylvania, Philadelphia, PA, USA

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ABSTRACT

Performance decrements attributed to mental fatigue have been found to be especially pronounced in tasks that involve the voluntary control of attention. Here we explored whether mental fatigue from prolonged time on task (TOT) also impairs temporal preparation for speeded action in a simple reaction-time task. Temporal preparation is enabled by a warning signal presented before the imperative stimulus and usually results in shorter reaction time (RT). When the delay between warning and imperative stimuli – the foreperiod (FP) – varies between trials, responses are faster with longer FPs. This pattern has been proposed to arise from either voluntary attentional processes (temporal orienting) or automatic trial-to-trial learning (trace conditioning). The former account suggests a selective RT increase on long-FP trials with fatigue; the latter account suggests no such change. Over a work period of 51 min, we found the typical increase in overall RT but no selective RT increase after long FPs. This additivity indicates that TOT-induced mental fatigue generally reduces cognitive efficiency but leaves temporal preparation under time uncertainty unaffected. We consider this result more consistent with the trace-conditioning account of temporal preparation.

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1. Introduction

Fatigue from prolonged mental work has been found to impair performance in a variety of cognitive tasks (e.g., Bills, 1931; Helton & Warm, 2008; Kraepelin, 1902; Lorist et al., 2000; Sanders & Hoo-genboom, 1970). The state of mental fatigue is characterized by the inability to allocate sufficient processing resources to the task at hand (Matthews & Desmond, 2002; Smit, Eling, & Coenen, 2004). Frequently, fatigued participants are still able to perform highly over-learned, automated tasks, whereas their performance significantly deteriorates when tasks require the voluntary allocation (i.e., top-down control) of attention (e.g., Boksem, Meijman, & Lorist, 2005, 2006; Lorist, Boksem, & Ridderinkhof, 2005; Lorist et al., 2000). Because top-down control processes are transient (Smallwood & Schooler, 2006; Steinborn, Flehmig, Westhoff, & Langner, 2008; Stuss, Murphy, Binns, & Alexander, 2003; West, 2001), maintaining performance at optimal levels requires a mechanism that

stabilizes control and ensures continuous task engagement. This stabilization is considered an effortful mechanism vulnerable to mental fatigue (e.g., Lorist et al., 2005; Sarter, Gehring, & Kozak, 2006; Smit et al., 2004; Wright, Stewart, & Barnett, 2008).

Our study examined effects of mental fatigue on speeded performance in a forewarned simple reaction-time (RT) task. Various studies have demonstrated that simple RT performance substantially deteriorates over time (e.g., Buck, 1966; Lisper & Ericsson, 1973; Lisper, Melin, & Sjöden, 1973; Sanders, Wijnen, & van Arkel, 1982; Van den Berg & Neely, 2006). It is not yet clear, however, whether this effect only results from an overall effect of fatigue on response speed or whether it also involves more specific fatigue-related changes in the timing behaviour under temporal uncertainty.

1.1. Strategic accounts of temporal preparation in variable-foreperiod designs

Preparation enhances performance, for example, by speeding up responses to an imperative signal in simple and choice RT tasks (Jennings & Van der Molen, 2005). Here, we only deal with purely temporal (i.e., nonspecific) preparation, which is based on the temporal

* Corresponding author. Address: Neuropsychology Section, Department of Neurology, RWTH Aachen University, Pauwelsstr. 30, 52074 Aachen, Germany. Tel.: +49 241 80 35959; fax: +49 241 80 82598.

E-mail address: robert.langner@rwth-aachen.de (R. Langner).

contingencies between experimental events. In tasks involving non-specific preparation, participants use temporal information to optimise performance by anticipating the imperative moment (i.e. the moment of target occurrence) (Coull, 2004). Typically, a warning signal (WS) precedes the imperative stimulus (IS), enabling nonspecific preparation for the impending IS. This usually improves RT substantially (e.g., Hackley & Valle-Inclan, 2003; Los & Schut, 2008).

The delay between WS and IS is called foreperiod (FP). When FP duration is variable within a block of trials, participants remain uncertain about the exact moment of IS occurrence on any given trial and thus cannot exactly synchronize their preparation with IS occurrence. In this variable-FP setting, responses are typically found to be relatively slow at early imperative moments but to become faster at later imperative moments during the FP interval (cf. Los, Knol, & Boers, 2001; Niemi & Näätänen, 1981; Woodrow, 1914). This phenomenon, termed the variable-FP effect, has been traditionally explained by assuming that participants exploit the gradual increase in conditional probability of IS occurrence during the FP and transform them into a state of preparation (Niemi & Näätänen, 1981, p. 137).

To illustrate this point, consider an RT experiment in which the IS is presented with an equal a priori probability at three imperative moments, say 1000, 3000, and 5000 ms after the WS. At the first imperative moment (i.e., 1000 ms after the WS), the probability of IS occurrence is 33% (and 66% that the IS will be presented later). In trials where the first imperative moment is bypassed, the probability that the IS will occur at the next one (i.e., 3000 ms after the WS) increases to 50%. When this moment is also bypassed, participants will then have full certainty that the IS will be presented at the latest imperative moment (i.e., 5000 ms after the WS). In this situation, the typical finding is a decrease in RT with increasing FP length. That is, the fastest responses in this example occur with FPs of 5000 ms. The resulting downward-sloping FP–RT function has traditionally been taken to reflect a strategic process by which participants convert the objective increase in the conditional probability of IS occurrence into a subjective expectation. This strategic account assumes that participants actively track the flow of time after the WS and intentionally monitor the changing conditional probability to use this information for top-down regulation of their preparatory state (e.g., Näätänen & Merisalo, 1977). This top-down control of preparation is considered an effortful process since it arises from voluntarily orienting attention to specific moments in time after the WS (e.g., Correa, Lupiáñez, & Tudela, 2006; Coull, Frith, Büchel, & Nobre, 2000; Lange, Krämer, & Röder, 2006; Nobre, 2001). The degree to which attention is directed to a specific time point during the FP is assumed to be directly related to the subjective probability (expectancy) of IS occurrence at this time point (e.g., Baumeister & Joubert, 1969; Karlin, 1966). Furthermore, studies have shown that a state of peak preparation can hardly be maintained for long, which underscores the importance of exact temporal predictions for being optimally prepared at the right time (e.g., Gottsdanker, 1975; Näätänen, 1972).

This strategic account, however, cannot explain sequential FP effects: Analyses that also considered FP length on the previous trial (FP_{n-1}) as a determinant of RT revealed that responses are relatively *fast* when the previous trial's FP was *short* but are relatively *slow* when the previous trial's FP was *long*. (e.g., Alegria & Delhaye-Rembaux, 1975; Karlin, 1959; Steinborn, Rolke, Bratzke, & Ulrich, 2008, 2009; Vallesi & Shallice, 2007; Van der Lubbe, Los, Jaskowski, & Verleger, 2004; Woodrow, 1914). These sequential FP effects are usually asymmetric, since RT is more strongly affected in trials with short FPs compared to trials with longer FPs, producing a typical $FP_{n-1} \times FP_n$ interaction (see Fig. 1). To explain these asymmetric sequential FP effects within the traditional account (e.g., Alegria, 1975; Drazin, 1961; Klemmer, 1957), it has been argued that individuals expect a repetition of FP_{n-1} on the current trial,

so that optimal preparedness is reached at the same moment as on the preceding trial. If FP_n is shorter than FP_{n-1} , then optimal preparedness will not yet have been reached at IS occurrence, and RT will be relatively slow. If instead FP_n is longer than FP_{n-1} and the repetition-expectancy-based moment of optimal preparedness is bypassed without IS occurrence, then it is assumed that individuals extend the period of optimal preparedness or cyclically re-prepare at later moments. Thus they achieve relatively fast responses in long- FP_n trials even after short- FP_{n-1} trials (i.e., in non-repetition trials), which accounts for the asymmetry in the sequential effects (cf. Vallesi & Shallice, 2007; Van der Lubbe et al., 2004, for a discussion). This asymmetry, in turn, has the potential to also explain the FP_n effect, although it is as yet unclear to what extent. The assumption of two different processes for explaining the FP_n effect and the asymmetric sequential FP effect is, however, a general disadvantage of the strategic account.

1.2. The Conditioning account of temporal preparation in variable-foreperiod designs

Los and co-workers (e.g., Los & Heslenfeld, 2005; Los & Van den Heuvel, 2001; Los et al., 2001) have recently challenged the strategic view by proposing a unified and parsimonious account for both effects. They argued that response-related temporal preparation is driven by trace conditioning, a nonstrategic process of trial-to-trial associative learning that determines preparatory behaviour across subsequent trials (see also Gallistel & Gibbon, 2000; Machado, 1997). The conditioning account of temporal preparation maintains that the FP_n and the asymmetric FP_{n-1} effects are two outcomes of one process. Specifically, it is assumed that the asymmetry of the sequential effect drives the FP_n main effect. That is, the $FP_{n-1} \times FP_n$ interaction is considered responsible for the negatively accelerating slope of the FP_n –RT function.

Thus, the asymmetric $FP_{n-1} \times FP_n$ interaction is at the core of the conditioning model, and it is explained as follows: In cases where FP is repeated, fast responses occur, because responding was just previously reinforced at the same imperative moment. In cases where FP alters from long on the preceding trial to short on the current one, slow responses occur, because the imperative moment was just previously bypassed. This bypassing without response is thought to extinguish previous moment–response associations or at least to reduce the strength of their association. Finally, in cases where FP alters from short to long, again fast responses occur, because later imperative moments were not just previously bypassed, and, thus, their response associations were not extinguished or loosened. As a result, responses in trials with the longest FP_n s are predicted to be consistently fast and not subject to sequential effects. In sum, the conditioning account predicts asymmetric sequential FP effects, since a long FP_{n-1} slows RT on a short- FP_n trial but not on a long- FP_n trial. A short FP_{n-1} , however, should not produce any slowing, neither on short- nor on long- FP_n trials. According to this model, the strength of the association between any given imperative moment and a response should increase with increasingly long FP_n s and should be maximal at the latest imperative moment. The strength of this moment–response association is assumed to be directly related to the preparatory state at this moment, which, in turn, is thought to facilitate responding (Los & Heslenfeld, 2005; Van der Lubbe et al., 2004).

1.3. Present study

As mentioned above, mental fatigue from prolonged time on task (TOT) has been shown to impair simple RT performance. Previous research, however, mainly focussed on the effects of TOT on overall RT performance. To our knowledge, only one study has investigated TOT modulations of FP effects so far: Björklund

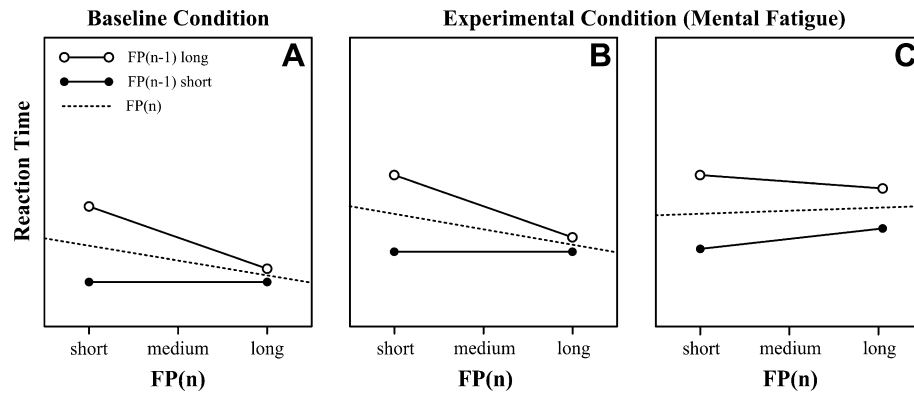


Fig. 1. Idealized hypothetical effects of time on task on the pattern of response timing in a simple reaction-time (RT) task with two variable foreperiods (FPs): panel A displays the baseline condition (non-fatigued state) at the beginning of the task; panel B displays the RT pattern at the end of the work period (fatigued state) as predicted from the conditioning view of temporal preparation; panel C displays the RT pattern at the end of the work period (fatigued state) as predicted from the strategic view of temporal preparation (see text for details).

(1992) reported that RT after long FP_n s increased more over 80 ms than did RT after short FP_n s. Unfortunately, he did not analyse sequential FP effects. Here we explored whether TOT-induced mental fatigue affects the complex sequential dependencies within RT patterns, which are typical of temporal preparation in variable-FP designs. Based on the premises (1) that TOT-induced mental fatigue mainly impairs tasks involving top-down attentional control, (2) that the processes underlying temporal preparation according to the strategic view *do* involve top-down attentional control, and (3) that the processes underlying temporal preparation according to the conditioning view *do not* involve top-down attentional control but rather bottom-up learning, we derived the following hypothesis: If the typical RT pattern in variable-FP experiments were mainly based on strategic, top-down attentional processes, it should suffer from mental fatigue, whereas if it were mainly based on trace conditioning, it should remain rather unaffected by fatigue.

Specifically, from a strategic view of temporal preparation (e.g., Näätänen & Merisalo, 1977), one would predict that mental fatigue reduces or even eliminates the FP_n effect and subtly changes the asymmetric sequential FP effect: regarding the FP_n effect, a strategic view would predict that TOT impairs the ability to increase preparation with an increase in the conditional probability of IS occurrence in long- FP_n trials, since this requires an effortful process of conditional probability monitoring during the FP interval (cf. Vallesi & Shallice, 2007, for a recent discussion). As a result, RT in long- FP_n trials would increase, and the typical downward slope of the FP_n -RT function would dwindle or even vanish. This prediction is consistent with the results of Björklund (1992). Analogously, regarding the asymmetry of the sequential FP effect, a strategic view would predict that TOT impairs the maintenance or restoration of a prepared state when imperative moments occur later than expected (in long- FP_n trials following a shorter FP_{n-1}). Further, it can be reasonably assumed that the FP-repetition expectancy does not change with TOT, since expecting a repetition appears to be the rather effortless default option. In sum, TOT-induced fatigue should bereave later imperative moments of their benefit from increased preparation after FP repetitions or maintained/restored preparation after shorter FP_{n-1} s, whereas it should spare the benefits of a short-FP repetition as well as the costs of an earlier-than-expected imperative moment (see Fig. 1, Panel C, for an idealized visualization of the predicted outcome pattern). In contrast, from the perspective of the trace-conditioning model (Los & Van den Heuvel, 2001; Los et al., 2001), no significant changes in the RT pattern with TOT would be predicted, since the mechanisms assumed to underlie temporal preparation in this model do not involve top-down control processes. Instead, the model is solely based on the

associative learning of temporal contingencies between warning signals and imperative stimuli. Accordingly, both the FP_n effect and the asymmetry of the sequential FP effect result from effortless, automatic processes and should not be affected by fatigue (see Fig. 1, Panel B, for an idealized visualization of the predicted outcome pattern).

To summarize, we investigated whether or not TOT-induced mental fatigue influences temporal preparation under time uncertainty. We derived two competing predictions based on two different explanations for the RT pattern typically found in variable-FP tasks: the traditional, strategic account, assuming top-down guidance of preparation, would predict a pronounced TOT-related RT increase at late imperative moments (in long- FP_n trials); the conditioning account, assuming bottom-up trial-to-trial learning, would predict no such interaction with TOT. To test these predictions, we conducted an experiment in which a warned simple RT task with variable FPs was performed over a time period of about 50 min.

2. Method

2.1. Participants

Thirty students (24 females and six males; mean age = 22.6 years, $SD = 3.3$) took part in the experiment in return for course credits. All participants but one were right-handed and all of them had normal or corrected-to-normal vision.

2.2. Apparatus and stimuli

The experiment was run in a dimly lit and noise-shielded room. It was controlled via a standard personal computer with colour display (19", 150 Hz refresh rate) and programmed in Matlab (The MathWorks, Inc., Sherborn, MA, USA) using the Psychophysics Toolbox extension (Brainard, 1997). Participants were seated at a distance of about 60 cm in front of the computer screen. A dot ($0.5 \times 0.5^\circ$ visual angle) in the middle of the screen served as fixation point and was constantly present throughout the experimental session. A 1000-Hz tone (70 dB SPL), presented binaurally via headphones, served as WS. The letter "X" ($1.14 \times 0.86^\circ$ visual angle), displayed in blue (7.1 cd/m^2) at the centre of the screen, served as the IS.

2.3. Task and design

Participants performed a forewarned simple RT task and were required to respond as quickly as possible to the IS by pressing

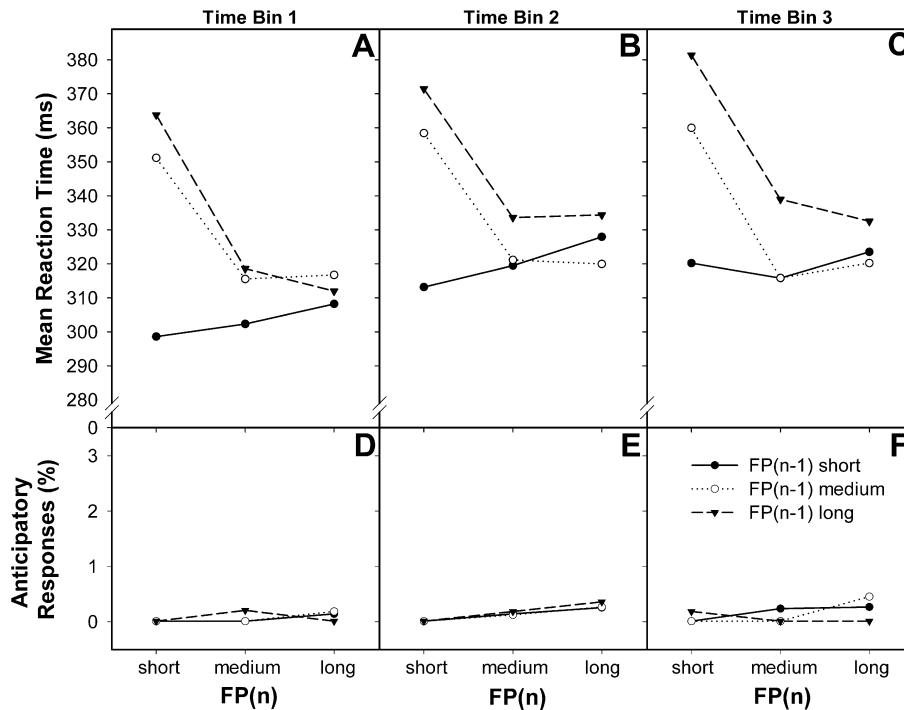


Fig. 2. The effects of time on task (TOT), preceding foreperiod length (FP_{n-1}), and current foreperiod length (FP_n) on task performance. The upper panels (A, B, and C) display the effects on reaction time (RT); the lower panels (D, E, and F) display the effects on the percentage of anticipatory responses. Connecting lines were added for illustrative purposes.

the right Shift key with their right index finger. A trial started with the presentation of the WS for 200 ms, followed by a blank FP interval, after which the IS occurred. We used FPs of 1000, 3000 and 5000 ms length, which were randomly chosen with equal probability for each trial. The IS was terminated either by response or when the response interval expired after 2000 ms. Subsequent trials were separated by a constant intertrial interval of 1500 ms. Feedback was given only when the response interval had expired without response; then the German phrase “zu langsam” (“too slow”) was presented for 300 ms. Participants performed 48 practice trials and 600 experimental trials, amounting to about 51 min of testing time. Reaction time was computed as the temporal distance between IS onset and response. We used a $3 \times 3 \times 3$ within-subject design with the factors time on task (TOT: first 17 min vs. second 17 min vs. last 17 min), previous FP length (FP_{n-1} : short vs. medium vs. long) and current FP length (FP_n : short vs. medium vs. long), and RT as the main dependent measure.

2.4. Self-report measures

Two subjective measures of mental fatigue were available from 15 participants: The Short Questionnaire for Current Strain (KAB; Müller & Basler, 1993) was administered before and after the experimental session to assess subjective perceptions of strain and fatigue. This self-report measure comprises eight pairs of adjectives on 6-point Likert-type rating scales describing opposite endpoints of different strain dimensions (e.g., stressed vs. relaxed; languid vs. fresh). Task-induced mental fatigue was assessed by comparing the KAB total scores from before and after the session.

Subjective state was further assessed by means of three scales of the Dundee Stress State Questionnaire-Short Version (DSSQ-S; Matthews, Emo, & Funke, 2005; Matthews et al., 2002): Energetic Arousal, Task Engagement, and Distress. The questionnaire consists of 30 items, which assess different facets of mental fatigue on 5-point Likert-type rating scales. The DSSQ-S was administered be-

fore and after the session; changes in subjective state were assessed by comparing pre- with post-task scores.

3. Results

Responses with an RT between 100 and 1000 ms were considered correct and used for computing mean RT. Responses slower than 1000 ms (0.3% on average) were considered outliers and were discarded from the analysis. Trials with premature responses (button presses between WS and IS or earlier than 100 ms after IS onset) were used to compute the percentage of anticipatory responses. Trials without response within 2000 ms after IS onset were counted as errors of omission. For a more fine-grained description of the overall TOT effect on response speed, we averaged individual mean RT of six successive 8.5-min time bins (containing 100 trials each), yielding the following values: 312, 331, 334, 332, 332 and 337 ms. That is, overall RT slowed over time by 25 ms. Note that the statistical analysis of TOT effects was based on three successive 17-min time bins (containing 200 trials each). Group averages of RT and percentage of anticipatory responses for the three time bins of all experimental conditions are depicted in Fig. 2. Additionally, group averages including standard deviation and standard error of mean RT are given in Table 1. Trials with missing responses were extremely rare (0.1% on average) and were not further analysed.

3.1. Standard RT analysis

Repeated-measures analyses of variance (ANOVAs) were performed on RT and percentage of anticipatory responses. When necessary, the Greenhouse–Geisser correction was used to compensate for violations of sphericity. The ANOVA results are listed in Table 2. As expected, all three factors had significant main effects: RT increased significantly with TOT [$F(2, 58) = 8.0, p = .001$, partial $\eta^2 = 0.22$] and FP_{n-1} length [$F(2, 58) = 67.1, p < .001$, partial

Table 1

Group averages, standard deviations, and standard errors of the mean of individual mean reaction time (in ms) as a function of current foreperiod length (FP_n), previous foreperiod length (FP_{n-1}), and time on task (successive 17-min periods).

Foreperiod	Time Bin 1			Time Bin 2			Time Bin 3		
	M	SD	SE	M	SD	SE	M	SD	SE
Short FP_{n-1}									
Short FP_n	299	56	4.8	313	64	5.1	320	66	6.0
Medium FP_n	302	46	3.8	320	55	4.7	316	50	5.8
Long FP_n	308	47	5.2	328	60	5.3	324	47	6.5
Medium FP_{n-1}									
Short FP_n	351	71	7.5	358	74	6.6	360	64	5.9
Medium FP_n	316	57	4.6	321	49	2.7	316	47	4.4
Long FP_n	317	56	5.0	320	57	4.3	320	66	6.0
Long FP_{n-1}									
Short FP_n	364	70	6.0	371	83	8.1	381	77	8.3
Medium FP_n	319	47	4.0	334	55	3.9	339	47	4.8
Long FP_n	312	52	4.5	334	55	5.1	333	51	4.7

Note: Standard errors of the mean are adjusted for within-subject designs (cf. Cousineau, 2005).

Table 2

Results of the analyses of variance for mean reaction time and percentage of anticipatory responses.

Source	Reaction time				Anticipatory responses		
	dfs	F	p	η^2	F	p	η^2
1 TOT	258	8.0	.001	0.22	0.3	.780	0.01
2 FP_{n-1}	258	67.1	.000	0.69	3.7	.045	0.11
3 FP_n	258	15.7	.000	0.35	1.0	.383	0.03
4 $TOT \times FP_{n-1}$	4116	4.1	.009	0.12	1.6	.196	0.05
5 $TOT \times FP_n$	4116	0.9	.405	0.03	1.7	.176	0.06
6 $FP_{n-1} \times FP_n$	4116	28.7	.000	0.49	1.2	.331	0.04
7 $TOT \times FP_{n-1} \times FP_n$	8232	0.4	.818	0.02	1.6	.178	0.05

Note: Effect size: partial η^2 ; factors: time on task (TOT: Time Bin 1 vs. Time Bin 2 vs. Time Bin 3); previous foreperiod (FP_{n-1} : short vs. medium vs. long); current foreperiod (FP_n : short vs. medium vs. long). Effects of interest are denoted in bold.

$\eta^2 = 0.69$]; it decreased significantly with FP_n length [$F(2, 58) = 15.7, p < .001$, partial $\eta^2 = 0.35$]. Also, there was the typical asymmetric $FP_{n-1} \times FP_n$ interaction [$F(4, 116) = 28.7, p < .001$, partial $\eta^2 = 0.49$], revealing that the increase in RT after a long FP_{n-1} trial was greatest in short FP_n trials. Crucially, there was no interaction of FP_n or $FP_{n-1} \times FP_n$ with TOT (all $F < 1$; see Table 2). There was, however, a significant interaction of FP_{n-1} with TOT [$F(4, 116) = 28.7, p < .001$, partial $\eta^2 = 0.50$].

3.2. Post-hoc RT analysis

Simple post-hoc contrasts were computed for significant TOT-related effects. They revealed that the main effect of TOT was mainly driven by a significant RT increase between the first and second time bin [$F(1, 29) = 12.3, p = .001$, partial $\eta^2 = 0.30$]; the increase between the second and third time bin was not significant [$F(1, 29) < 1$]. Further, the $TOT \times FP_{n-1}$ interaction was shown to be driven by a smaller RT increase between time bins 1 and 2 on trials with a preceding FP of medium length compared to trials with a short preceding FP [$F(1, 29) = 6.1, p = .019$, partial $\eta^2 = 0.17$] or with a long preceding FP [$F(1, 29) = 6.2, p = .019$, partial $\eta^2 = 0.18$].

3.3. Extreme-group analysis

To further test whether the non-modulation of the FP_n effect or the $FP_{n-1} \times FP_n$ interaction by TOT is because of an insufficient increase in mental fatigue over time, we repeated the ANOVA but

only included the participants with the largest performance decrement. To this end, we did a median split of the sample according to the individual mean RT increase over time (i.e., the difference between mean RT of time bins 1 and 3) and selected the 15 participants above the median. For descriptive comparison, we averaged individual mean RT of six successive 8.5-min time bins, which yielded: 291, 320, 320, 326, 325 and 337 ms. That is, in the subsample of strong decremeters, overall RT became slower over time by 46 ms. As expected, the ANOVA yielded significant main effects of TOT [$F(2, 28) = 13.7, p < .001$, partial $\eta^2 = 0.49$], FP_n [$F(2, 28) = 5.7, p = .026$, partial $\eta^2 = 0.29$] and FP_{n-1} [$F(2, 28) = 38.2, p < .001$, partial $\eta^2 = 0.73$] as well as the typical $FP_{n-1} \times FP_n$ interaction [$F(2, 28) = 14.0, p < .001$, partial $\eta^2 = 0.50$]. However, the analysis revealed no effect of TOT on FP_n , FP_{n-1} or $FP_{n-1} \times FP_n$ (all $F < 1.1$). Thus, the previously found $TOT \times FP_{n-1}$ interaction did not show in the subsample (partial $\eta^2 = 0.07$). The results are depicted in Fig. 3, which provides additional visual evidence that there is absolutely no TOT effect on the latest imperative moment, as would be predicted from the strategic account of temporal preparation.

3.4. Analysis of anticipatory responses

Premature button-presses were generally rare and therefore arcsine-transformed before submitting them to an ANOVA. The only significant effect was an increase in the percentage of anticipatory responses with increasing length of FP_{n-1} [$F(2, 58) = 3.7, p = .045$, partial $\eta^2 = 0.11$]. Notably, the analysis did not yield any significant interactions with TOT (all $F < 1.8$; see Table 2 for details).

3.5. Subjective measures

The questionnaire pre- and post-task scores were compared by means of paired t -tests. The KAB score after the session ($M = 26.3, SD = 6.1$) was significantly higher than before the session ($M = 20.5, SD = 7.1$) [$t(14) = -4.4, p = .001$]. The analysis of the three DSSQ-S scale scores revealed that energetic arousal decreased significantly [$t(14) = 3.4, p = .004$] from pre-task ($M = 6.1, SD = 3.2$) to post-task ($M = 2.9, SD = 2.6$). Further, there was a significant decrease [$t(14) = 4.1, p = .001$] in task engagement (pre-task: $M = 19.6, SD = 6.2$; post-task: $M = 11.9, SD = 5.5$) and a significant increase [$t(14) = -4.2, p = .001$] in distress (pre-task: $M = 9.0, SD = 3.5$; post-task: $M = 13.9, SD = 4.5$).

4. Discussion

Our study investigated whether mental fatigue from prolonged work affects temporal preparation under time uncertainty in a simple RT task. To this end, we examined potential interactions of TOT with the effects of the current and previous FPs on RT, using a variable-FP paradigm with three equiprobable FPs of 1000, 3000 and 5000 ms. The significant changes in subjective-state measures indicate that our TOT manipulation was successful in producing mental fatigue. The increase in the KAB score demonstrates that the cognitively little demanding simple RT task elicited perceived strain over the course of the session. This corresponds to the results of a previous study, which revealed higher levels of subjective strain after performing a monotonous low-demand condition of a simulated driving task compared to a high-demand racing condition (Fischer, Langner, Birbaumer, & Brocke, 2008). Our DSSQ-S findings match those of previous studies assessing subjective-state changes during vigilance tasks using the long version of the DSSQ (Helton & Warm, 2008; Temple et al., 2000). Participants reported feeling less energetic after the session than before its start; simi-

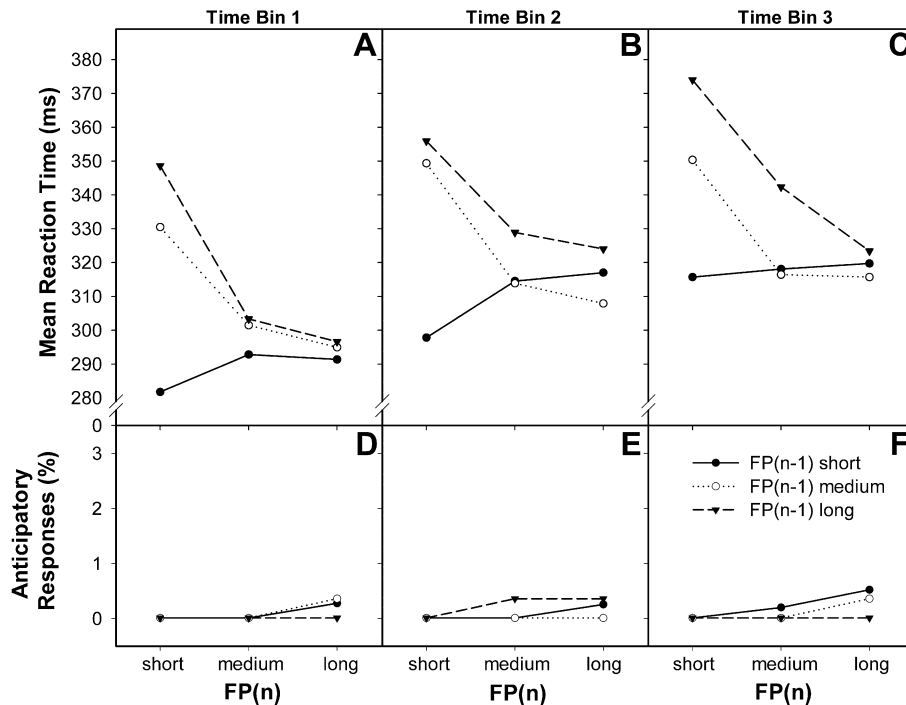


Fig. 3. Separate results for the 15 participants with the largest overall performance decrement. The effects of time on task (TOT), preceding foreperiod length (FP_{n-1}), and current foreperiod length (FP_n) on task performance. The upper panels (A, B, and C) display the effects on reaction time (RT); the lower panels (D, E, and F) display the effects on the percentage of anticipatory responses. Connecting lines were added for illustrative purposes.

larly, task engagement was perceived to be higher before the session than at its end. Decreasing energetic arousal and decreasing task engagement indicate mental fatigue or resource depletion. The elevation of distress is consistent with studies demonstrating that participants perceive long-duration monotonous RT tasks as stressful (Hancock & Warm, 1989; Szalma et al., 2004).

As expected, we found a significant slowing of mean RT over the course of 51 min of task performance. There were, however, no specific effects of TOT on indices of temporal preparation: neither the effect of FP_n nor the asymmetrical $FP_{n-1} \times FP_n$ interaction was modulated by TOT. It should be noted that the non-significance of the $TOT \times FP_n$ and $TOT \times FP_{n-1} \times FP_n$ interactions can hardly be explained by a lack of statistical power, since their effect sizes were very small (partial $\eta^2 = 0.03$ and 0.02 , respectively). Fig. 2 confirms visually that the RT pattern remained about the same over time. An extreme-group analysis, which included only the 15 participants with the largest TOT decrement, also did not demonstrate any modulation of FP effects by TOT (cf. Fig. 3). Also, the $TOT \times FP_{n-1}$ interaction found for the whole sample was not present in the subsample of TOT decremeters, which suggests that this effect was not due to an increase in mental fatigue. This reasoning is supported by the fact that in decremeters a larger RT increase over time corresponded to a reduction of this interaction's effect size (whole sample: partial $\eta^2 = 0.12$; decremeters: partial $\eta^2 = 0.07$).

4.1. Mental fatigue affects overall processing speed but not temporal preparation

The significant overall RT slowing with TOT replicates previous results (Björklund, 1992; Lisper, Melin, Sjöden, & Fagerström, 1977; Lisper et al., 1973) and provides further evidence for the impact of energetic variables on performance efficiency in elementary cognitive tasks. A shift of the speed-accuracy trade-off towards a stricter criterion can be excluded as an explanation, since no concomitant decrease in the number of errors (anticipatory responses or errors of omission) was observed. If anything, the number of

anticipatory responses tended to increase over time (cf. Fig. 2). Previous research supports the notion that mental fatigue may be a major cause for this performance deterioration (e.g., Boksem et al., 2005; Smit et al., 2004; Wright et al., 2008), but a decrease in arousal may also play a role, especially in highly repetitive, monotonous situations like simple RT tasks (Dirnberger, Duregger, Lindinger, & Lang, 2004). Although the effect of TOT on overall RT was modest (i.e., on average ca. 25 ms RT increase across six 8.5-min time bins), our study is one of the first to report a clear-cut performance decrement in a variable-FP experiment.

We suggest that the use of a WS may have contributed to the rather small decrement with TOT, since a WS may somewhat counteract the time-related performance decline typically found in unwarned simple RT tasks (cf. Lisper & Ericsson, 1973; Sanders et al., 1982). This assumption is supported by earlier studies using a paired-stimulus paradigm (Lisper et al., 1973, 1977), which reported a smaller time-related RT increase to the second (and therefore forewarned) stimulus than to the first one of a pair. Lisper et al. (1973) suggested that different rates of habituation to the two stimuli of a pair were responsible for their differential RT increase, but other explanations are possible as well: For instance, the individuals might get some relief from short relaxation pauses that are possible during the intertrial interval, that is, the time between response and next WS (cf. Wilkinson, 1990). Also, the WS provides additional stimulation that might be beneficial for maintaining arousal in monotonous tasks (Hackley et al., 2009). In addition, the WS event might act as a memory cue that reactivates the task goal (Steinborn et al., 2009).

In contrast to the overall slowing, temporal preparation (i.e. the effects of FP_n or the asymmetrical $FP_n \times FP_{n-1}$ interaction) was not modulated by TOT. Thus, according to our reasoning that only processes relying on top-down control should be affected by mental fatigue (see Introduction), the purely additive effect of TOT on performance speed is more consistent with the view that temporal preparation under time uncertainty results from a bottom-up trace-conditioning process rather than from top-down-guided con-

ditional probability monitoring and voluntary temporal (re)orienting. From the perspective of the strategic account of temporal preparation, RT would be expected to especially increase at late critical moments during the session. Obviously, this was by no means the case in this study. According to the trace-conditioning view, FP effects result from trial-to-trial reinforcement or extinction of moment–response associations. This learning process generates (and continuously updates) representations of temporal contingencies between WS and IS and its associated response. We consider this forming of representations an automatic, effortless process that does not suffer from a decline of top-down attentional control processes due to TOT-induced mental fatigue.

As mentioned in the introduction, there is one earlier study (Björklund, 1992) that reported an interaction between the effects of FP and TOT. This seemingly contradictory finding might be related to differences in the FP distribution: Björklund used five different FPs (500, 889, 1581, 2812, and 5000 ms). That is, a higher number of different FPs with a wider range was used, and FPs were spaced logarithmically rather than symmetrically. All these factors might have contributed to Björklund's finding the typical FP effect on RT only for the shorter FPs, which may be due to a relatively less precise time estimation at remote critical moments. This, in turn, might have rendered Björklund's FP distribution sensitive to TOT in that the already compromised time estimation at late critical moments became even more impaired by fatigue than that at early critical moments. Also, unlike in our study, Björklund used a double-response paradigm to measure movement time between two button presses. This more complex motor response probably evokes more preparatory activity, which might have somehow interacted with temporal factors and mental fatigue.

4.2. Sources of the time-related response slowing in simple RT tasks

One question remains to be answered: What processes in simple RT performance are slowed by mental fatigue? Although temporal preparation is an integral part of any simple RT task, there must be distinct subprocesses other than the ones subserving timing aspects that are sensitive to mental fatigue. According to our rationale, it should be processes relying on top-down control. Hence, the additive RT increase over time could be interpreted as less efficient information processing that results from a reduced allocation of attentional resources to task-relevant cognitive processes. Effortful top-down control is needed to “stay on the job,” that is, to maintain attention to the task over time, enabling the efficient processing of task-relevant information (Sarter et al., 2006; Stuss et al., 2005). Recent models of controlled attention argue that it is the cognitively little demanding tasks (in contrast to more demanding, intrinsically interesting ones) that most require the active control of attention when their performance needs to be sustained over prolonged time. These models have been successfully applied to explain the high vulnerability of simple, monotonous tasks to fatigue from sleep deprivation (Pilcher, Band, Odle-Dusseau, & Muth, 2007; Walker, Muth, Odle-Dusseau, Moore, & Pilcher, 2009). This might similarly apply to the effects of fatigue from prolonged mental work.

Mental fatigue may affect all stages of information processing that receive modulatory top-down input, from stimulus processing to response execution. Of course, this study cannot determine the exact locus (or loci) of fatigue effects within a stage model of information processing, since this would require additional manipulations. Efficient simple RT performance has been shown to involve top-down control to facilitate stimulus detection and to specify and prepare the response in advance (Frith & Done, 1986; Goodrich, Henderson, & Kennard, 1989; Henderson & Dittrich, 1998). It is these top-down modulations that potentially are vulnerable to mental fatigue. This notion is supported by studies that exam-

ined the effects of mental fatigue on preparatory processes in different cognitive tasks. Boksem et al. (2006) reported a TOT-induced decrease in the amplitude of the contingent negative variation, which is a slow cortical potential that globally reflects preparatory activity. Lorist (2008) showed that the facilitation of performance by response-related advance information diminished with increasing mental fatigue. We interpret these and our findings as indicating that it was not the timing under temporal uncertainty produced by variable FPs but rather the efficiency of processing stimulus information and initiating the motor response that was affected by mental fatigue.

To be quite explicit, we propose a dissociation between nonspecific temporal preparation and specific, attentionally guided perceptual and motor aspects of preparation, the temporal aspect being insensitive, the attentional aspect being sensitive, to mental fatigue. Such a dissociation has been suggested before regarding choice RT performance (e.g., Brown & Robbins, 1991; Holender & Bertelson, 1975). A crucial question for future research concerns how both nonspecific and specific aspects of preparation combine to produce efficient processing at the imperative moment. We conjecture that the representational strength of different moment–response associations, as determined by previous experiences, forms a kind of temporal salience map that is unintentionally used to time the allocation of attentional resources to task-specific perceptual and motor processes. This idea is akin to the concept of exogenous temporal expectations (cf. Coull & Nobre, 2008).

4.3. Limitations of the study

A limitation of our study concerns the modest effect of TOT, which might not have been powerful enough to modify FP effects. This argument implies that top-down control processes potentially involved in temporal preparation might be less affected by fatigue than those processes that led to the observed decrement. This possibility cannot be completely ruled out. It is, however, made implausible by the results of the extreme-group analysis which showed that there was no modulation of the RT pattern (especially at the latest imperative moment), even when the effect of TOT on overall RT was almost twice as large. Future studies should test whether stronger fatigue-related decrements (e.g., with longer or attentionally more demanding tasks) produce different results. Furthermore, settings that encourage top-down strategies in temporal preparation (e.g., the use of explicit temporal cues or non-uniform, peaked FP distributions) may be used to contrast the sensitivity to mental fatigue of different mechanisms potentially contributing to temporal preparation.

Apart from the power issue, it cannot be excluded completely that an interaction between fatigue and temporal preparation was absent only because it was masked by either of two well-known factors opposing the effects of time-related performance decrements: practice and compensatory effort. Practice-related masking effects are unlikely, since simple RT tasks have been found insensitive to repeated administration, which is why they are a favourite tool to assess alertness/fatigue in neuropsychology (Sturm & Willmes, 2001) as well as in chronobiological (Blatter & Cajochen, 2007) and sleep-deprivation (Lim & Dinges, 2008) research. Also, any practice effects that selectively affect temporal preparation would imply that, over time, a preparation-related strategy shift occurs from controlled to automatic processing, i.e. from intentional, reparation-based to nonintentional, conditioning-based timing behaviour. This may not be impossible but it is improbable, since the main effect of both strategies cannot necessarily be assumed to be equal, which it is. A similar reasoning applies to potentially counteracting effects of compensatory effort: it seems highly unlikely that a time-related increase in effort exertion would selectively affect the timing of preparatory behaviour,

thereby masking fatigue effects only on indices of temporal preparation but not overall RT. Nevertheless, we would like to emphasize that our study was not undertaken to unequivocally “decide” between alternative accounts of temporal preparation phenomena. Rather, it was done to contribute a further piece of evidence and to broaden the basis for a future evaluation of these phenomena.

Finally, another limitation is the availability of subjective-state measures for only half the sample. For the other half, the subjectively perceived effectiveness of our TOT manipulation in producing mental fatigue can only be assumed. Since all participants were sampled from the same population, this assumption may be warranted.

4.4. Conclusions

In sum, we observed that TOT-induced mental fatigue did not influence the pattern of response timing in a variable-FP paradigm. Based on our assumption that mental fatigue primarily impairs cognitive processes relying on top-down control, we infer that temporal preparation under time uncertainty is primarily guided by bottom-up processes such as trace conditioning. This provides further support for the conditioning account of temporal preparation (Los & Van den Heuvel, 2001; Los et al., 2001), generalizing the body of evidence to a manipulation of TOT. Future studies should test whether this interpretation holds true for manipulations of other energetic variables such as sleep deprivation and circadian rhythms. By analysing intertrial sequential effects, we extend previous research on TOT-induced mental fatigue, which often only considered effects on overall RT performance. In general, the examination of sequential effects may provide a means to gain additional insights into how mental fatigue affects different cognitive processes underlying human performance.

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