Visually guided movement with increasing time-on-task: Differential effects on movement preparation and movement execution

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Abstract

Top-down cognitive control seems to be sensitive to the detrimental effects of fatigue induced by time-on-task (ToT). The planning and preparation of the motor responses may be especially vulnerable to ToT. Yet, effects of ToT specific to the different phases of movements have received little attention. Therefore, in three experiments, we assessed the effect of ToT on a mouse-pointing task. In Experiment 1, there were 16 possible target positions with variable movement directions. In Experiment 2, the layout of the targets was simplified. In Experiment 3, using cuing conditions, we examined whether the effects of ToT on movement preparation and execution were caused by an increased orientation deficit or decreased phasic alertness. In each experiment, initiation of movement (preparatory phase) became slower, movement execution became faster and overall response time remained constant with increasing ToT. There was, however, no significant within-person association between the preparatory and execution phases. In Experiments 1 and 2, we found a decreasing movement time/movement error ratio, suggesting a more impulsive execution of the pointing movement. In addition, ToT was also accompanied with imprecise movement execution as indicated by the increased errors, mainly in Experiment 2. The results of Experiment 3 indicated that ToT did not induce orientation and phasic alerting deficits but rather was accompanied by decreased tonic alertness.

Keywords

Time-on-task; mental fatigue; alertness; visually guided movement

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Introduction

Prolonged and effortful engagement in a cognitive task often results in compromised performance and is accompanied by a range of subjective feelings that can be labelled as "mental fatigue" (Ackerman, 2011; DeLuca, 2005). Such so-called time-on-task (ToT) effects are associated with deteriorated functioning of many cognitive operations and enhance the risk of failures, not only in laboratory experiments but also in everyday situations (Bener et al., 2017; Lal & Craig, 2001). Therefore, much research has been carried out to identify the cognitive functions and tasks that are particularly sensitive to fatigue induced by ToT.

Previous research clearly shows that perceptual judgements, sustained attention, and simple motoric tasks are particularly sensitive to ToT and induce declined performance even after a relatively short period of time (i.e., a few minutes; see e.g., Buckley et al., 2016; Epling et al., 2016). The decline in performance on such tasks is assumed to be due to the difficulties in upholding top-down cognitive control (Langner & Eickhoff, 2013; Langner et al., 2010; Pilcher et al., 2007; van der Linden et al., 2003). Cognitive control

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refers to higher-order cognitive processes that are able to orchestrate lower-level processes for adequate task performance. Examples of cognitive control processes are working memory (Hopstaken et al., 2015a), performance monitoring (Boksem et al., 2006), and inhibition (Guo et al., 2018). Overruling the tendency of diminishing cognitive control after ToT requires additional effortful processing that is able to redirect the focus to the task at hand (Sarter et al., 2006). Exerting such compensatory control or self-regulation (Langner et al., 2010), however, also makes one more prone to develop fatigue. There is evidence suggesting that adequate levels of cognitive control require a sufficient level of alertness, which conceptually and physiologically overlaps with arousal and vigilance. Alertness is fundamental to sustain attention on task goals and to control cognition and behaviour over the course of a prolonged period (Lim & Dinges, 2010). In line with this notion, psychophysiological studies showed that ToT is accompanied by reduced activation in the locus coeruleus norepinephrine (LC-NE) system, resulting in a lower norepinephrine output, which is associated with suboptimal alertness for the voluntary control of behaviour (Aston-Jones & Cohen, 2005; Howells et al., 2012).

Of the many facets of cognitive control, the planning and preparation of motor responses seem to be especially vulnerable to ToT (Langner et al., 2010). For example, Boksem et al. (2006) found evidence for a decline in response preparation under fatigue, based on the finding that the amplitude of the contingent negative variation (CNV) decreased with ToT. CNV is an EEG marker of arousal and response initiation (Nagai et al., 2004). Similarly, Lorist et al. (2008) suggested a ToT-related reduction in response preparation. They found that after a prolonged period of time, individuals relied less on advanced response-relevant information (i.e., cuing of the correct responses) to prepare their subsequent response.

Preparation of motor responses is highly relevant in goal-directed behaviour, and the above findings indicate that this preparation phase may be particularly vulnerable to ToT. The empirical evidence for this assumption, however, is limited, because while the effects of ToT on perceptual judgements or responses in simple reaction-time tasks have been extensively investigated, remarkably only a few studies have addressed the question of how goal-directed movements are modified by ToT. Yet, the notion of compromised movement preparation with ToT seems to be in line with studies showing that movement preparation is effortful and attention-demanding (see Janczyk & Kunde, 2010; Spiegel et al., 2012 for grasping movements, and Liu et al., 2008 for pointing tasks). Accordingly, we present three experimental studies testing how the various aspects of a specific visually guided action, namely pointing behaviour, are affected by ToT/mental fatigue.

It has been established that the preparation of visually guided movements is controlled by an extensive posterior–anterior network (Liu et al., 2008). This was supported by a clinical study investigating patients with Friedreich's ataxia, an inherited neurodevelopmental disorder (Corben et al., 2011). Compared to healthy controls, the patients had difficulties with the preparation and error correction aspects of aiming movements. This suggests that a disturbed cerebellar connectivity with anterior cortical and subcortical structures might result in impaired pointing movement.

Based on the assumption that movement preparation is cognitively demanding and effortful (Liu et al., 2008) and relies on cognitive control (Boksem et al., 2006), we expect that visually guided movement, particularly the preparatory phase of such movement, deteriorates with increasing ToT. The differential effects of ToT on the different phases of visually guided movements have so far received little attention. Therefore, in the three experiments presented here, we investigated the effect of ToT on a visually guided mouse-pointing task. Participants pointed to a peripheral target by moving the cursor from the centre to the target. We registered the participants' gaze position to control fixation and to measure saccadic latencies. Following the reasoning outlined above, our first hypothesis was that movement preparation assessed by initiation time, lasting from the presentation of the target to movement initiation, becomes slower as participants spend more time on the task (Hypothesis 1).

We also expected ToT-related changes in movement execution. The results of the few previous studies addressing the association between fatigue and the execution phase of visually guided movements have been contradictory. For example, Rozand et al. (2015) found an increased movement duration in an arm-pointing task when it was performed after another cognitively fatiguing task. In contrast, the findings in Solianik et al.'s (2018) study suggested that the execution of a reaching movement controlled by a handle towards a visual target was actually faster and less variable with increasing ToT (Solianik et al., 2018). The pointing task in the present set of studies was similar to that used by Solianik et al. (2018) in terms of the quickly reachable targets presented on a screen. Based on this similarity, we also expected to find faster movements as a function of time spent on the task. We did not, however, expect a similar improvement in movement accuracy. The reason is that in the execution of a fast and accurate pointing movement, the movement speed and accuracy are often inversely related (Smyrnis et al., 2000). There are indications that diminished top-down control as a consequence of increasing mental fatigue may alter the speed–accuracy criterion, which can become apparent in faster but more erroneous responses (Le Mansec et al., 2018; Smith et al., 2017). For example, using a card-sorting test, van der Linden et al. (2003) found that, compared to a control group, fatigued participants showed faster but more erroneous responses after a switch in the card-sorting criterion. This finding was interpreted as the result of less preparation or planning before an action was executed.

In Elliott et al.'s (2010) multiple-process model of goal-directed movements, the execution of movements was associated with an impulse response strategy (see also Elliott et al., 2017). The model states that a predominant period of movement execution is under the control of impulse regulation, which has an important role in the control of rapid movement corrections. We expect that ToT may deteriorate impulse regulation in visually guided pointing movements. More specifically, our second hypothesis is that, as ToT increases, participants will execute the pointing task more impulsively with faster but more erroneous movements (Hypothesis 2). To test this, participants' speed–accuracy trade-off on movement response (i.e., movement time/movement error ratio) was examined.

The hypotheses were tested in three experiments. In Experiment 1, there were 16 possible target positions with many variable movement directions. In Experiment 2, the layout of the target positions was simplified with only four target positions, and horizontal movements were required to point to the targets. With this simplification, the task became less demanding in terms of the spatial attention and movement planning. In visually guided pointing, there are many cognitive operations that need to be controlled, but the ability to allocate attentional focus to the stimulus-relevant area may be especially relevant for efficiently preparing the pointing. Therefore, in Experiment 3, with an auditory cuing paradigm (No cue, Orientation cue, and Central cue conditions), we examined whether attentional orientation changed with ToT. A No cue and Orientation cue condition was compared to assess attentional orientation ability (see, e.g., Fan et al., 2002). ToT may compromise the level of phasic alertness, which is the transient increase in response readiness (Oken et al., 2006; Schneider, 2017; Sokolov & Sokolov, 1963). By comparing a No cue with a Central cue condition, we also could test whether phasic alertness level changed as a function of ToT.

We used a vigilance-type paradigm in each experiment. Participants performed the task for at least 15 min without a break, and the targets were presented with a wide range of inter-target intervals. Vigilance paradigms put high demands on sustained attention and are widely used to measure the effects of cognitive fatigue and ToT-related changes (e.g., Lim et al., 2012; Matthews et al., 2017). Impaired performance in vigilance or sustained-attention tasks reflects compromised functioning of various frontal lobe processes (Demeter et al., 2011; Lim et al., 2010, 2012), including diminished top-down cognitive control (Langner & Eickhoff, 2013). A great advantage of the paradigm we used is that it is known to induce ToT-related changes after a relatively short duration and therefore allows minimising the potential confound of physical fatigue.

Although we postulated separate hypotheses on movement preparation and execution phases, it is relevant to note the potential interconnections between those phases. Previous studies revealed many differences in movement preparation versus execution-related brain signals and the underlying brain substrates (see, e.g., K.-M. Lee et al., 1999; Lee & van Donkelaar, 2002), which underlines the possibility for differential ToT effects. However, various studies also proposed how the two phases are linked. For example, the movement preparation phase may be cognitively monitored, and in case of any disruption, the execution is delayed until an adequate preparation is achieved (Churchland & Shenoy, 2007). Thus, there seem to be compensatory strategies aimed at maintaining the execution of movement at a constant level of performance, even if the planning process is disrupted (Churchland & Shenoy, 2007). Particularly in relation to ToT, compensatory strategies may be used to reduce the demands on cognitive control (Hockey, 1997). One possible strategy is that fatigued people invest less in cognitively demanding action preparation and start relying more on adjustments or corrections during the movement itself. Yet, if such a strategy is used, it can be expected to be associated with shorter preparation periods and longer movement time or execution. After all, more monitoring and corrections during the movement itself would be needed. Such a strategy, however, would cause an opposite trend in the movement performance measures (e.g., a longer movement time) as we hypothesised above.

Finally, it is possible that, after some time, people learn strategies to become more efficient or enhance performance. For example, in the pointing task, participants may learn that when they take longer for planning they can execute the movement faster. Learning or developing strategies are generally more pronounced in complex tasks compared to simple tasks. There are different ways to address these points. Regarding complexity, however, the pointing task was relatively simple as it only requires a speeded reaction to stimuli, without further selection or decision processes. However, the tasks may be considered complex because fast spatial orientation ability and visual-motor coordination were fundamental for efficient performance. A possible influence of complexity, however, can be assessed by comparing the first and second experiment. These two experiments differ in number of locations and spatial arrangement.

Regarding the learning of strategies, when participants would learn a trade-off between the preparatory and execution phase as mentioned above, it can be expected that these two phases would be inversely related. To take that possibility into account, we include tests of the trial-based associations (i.e., slope analysis) between movement initiation and the measures of the executive phase (i.e., movement time and movement error).

To summarise, in three experiments, we assessed the effect of ToT on a visually guided mouse-pointing task. We predicted that mainly the preparatory phase of the movement, assessed by initiation time, would become

slower with increasing ToT. Second, as an indication of an impaired impulsivity regulation under fatigue, we predicted finding more impulsive movement execution with faster but more erroneous movements.

Experiment 1

Methods

Participants. In total, 31 undergraduate students took part in Experiment 1, receiving extra course credits for participation. Data from five participants were dropped due to an insufficient proportion of trials with valid fixations ($<85\%$) or due to stability problems with the eye tracking, yielding a final dataset of 26 participants (18 females, aged between 18 and 26 years, $M=19.77$, $SD=1.58$). By self-report, none of them had a history of neurological disease or mental disorder and all of them had normal or corrected-to-normal vision. Three of the participants were left-handed but stated that they used the mouse with their right hand and were therefore asked to use their right hand during the course of the experiment.

Sample size was determined based on an a priori power analysis conducted by Gpower 3.1 (Faul et al., 2007). The minimum sample size to ensure the statistical power of the effect of ToT on pointing movement was estimated, based on recent studies that map closest to our pointing task in terms of task parameters, duration, and aims. These studies reported large effect sizes of the ToT effects (η_p^2: .27–.30; e.g., Massar et al., 2020; Steinborn et al., 2016; Zentai et al., 2015). By applying these effect sizes, the recommended minimum sample size was 18–20 participants to achieve a power level of 90% and alpha $<.05$. Thus, the final sample of 26 participants had the appropriate statistical power to detect the effects we aimed to examine.

Task and stimuli. Figure 1a schematises the sequence of a trial. Participants performed a visually guided mouse-pointing task programmed in PsychoPy 3 (version 3.1.5. for Windows; Peirce, 2007, 2009; a runnable source code is available at https://data.mendeley.com/datasets/6cnm4n3gdc/draft?a=bc6266f9-6b5c-43f7-9d99-af6dc19346f4). Target stimuli were displayed on an integrated monitor, Tobii TX300 with a resolution of 1920 × 1080 pixels, and a 60 Hz refresh rate. The viewing distance was ~60 cm with a mouse positioned for right-hand use. Standard Windows mouse sensitivity settings were used.

During the whole course of the task, a fixation cross (25 × 25 pixels) with a visual angle of 1.2° was presented on a grey background at the centre of the screen. The target stimulus was a white-filled circle (20 pixels in diameter) with a visual angle of 1.1° presented on one of the 16 possible locations. These locations were arranged along two (invisible) concentric circles (inner circle: diameter of 250 pixels, 6.71°; outer circle: diameter of 500 pixels, 13.37°) around the fixation cross. On each trial, participants were instructed to fixate and to keep the cursor on the fixation cross until the target stimulus appeared. If they initiated a mouse movement too early (before the target appeared), the fixation cross changed its colour to red and the target presentation was inhibited. The target was presented after a random interval ranging between 500 and 7,000 ms drawn from a continuous uniform distribution. Participants were asked to move the cursor onto the target as quickly and precisely as possible. Time and two-dimensional mouse coordinates were continuously recorded. The trial was deemed successful if the cursor reached the target and was maintained within the target area for 100 ms. If these criteria were fulfilled, then the colour of the target turned to black to provide visual feedback about the successful pointing performance. Then participants needed to move the cursor back to the fixation cross. When the fixation cross was reached, a 250 Hz tone was presented for 200 ms through standard loudspeakers, accompanied by visual feedback about the time from the target onset to the target reach (i.e., initiation time + movement time).

Procedure. Participants were asked to have adequate sleep in the night prior to the experiment and were instructed to abstain from caffeine-containing substances and alcohol on the day of the experiment. On arrival to the laboratory, participants provided written consent and their sleep duration was assessed by self-report (the mean sleep duration was 7.85 hr with an *SD* of 1.39).

Participants were seated in a dark, sound-attenuated room. Before the ToT period, participants performed 20 practice trials with parameters identical to those of the main task. Then a standard 5-point eye-tracking calibration was followed. A chin rest was used to ensure higher accuracy of recording eye movements. After the calibration, participants were asked to indicate their actual subjective fatigue on a visual analogue scale presented on the computer screen (100 mm; "no fatigue at all" was presented on the left and "very severe fatigue" on the right side of the scale).

The experimental task was divided into three ToT blocks. Each block consisted of 56 trials and lasted approximately 5 min, so the whole ToT period lasted about 15 min. Similar or shorter durations have frequently been used in studies with vigilance paradigms and have shown to reliably induce fatigue (e.g., Jones et al., 2018; Loh et al., 2004). In each block, the target positions were equally balanced; thus, the target stimulus was presented on both circles and both sides of the fixation cross in an equal number of trials. Trials were presented in a pseudo-random order. When the ToT period ended, participants indicated again their subjective fatigue.

After the experiment, participants were asked whether they perceived difficulties in using the mouse and whether they experienced physical discomfort or pain in their hands during the task. None of them reported such problems,
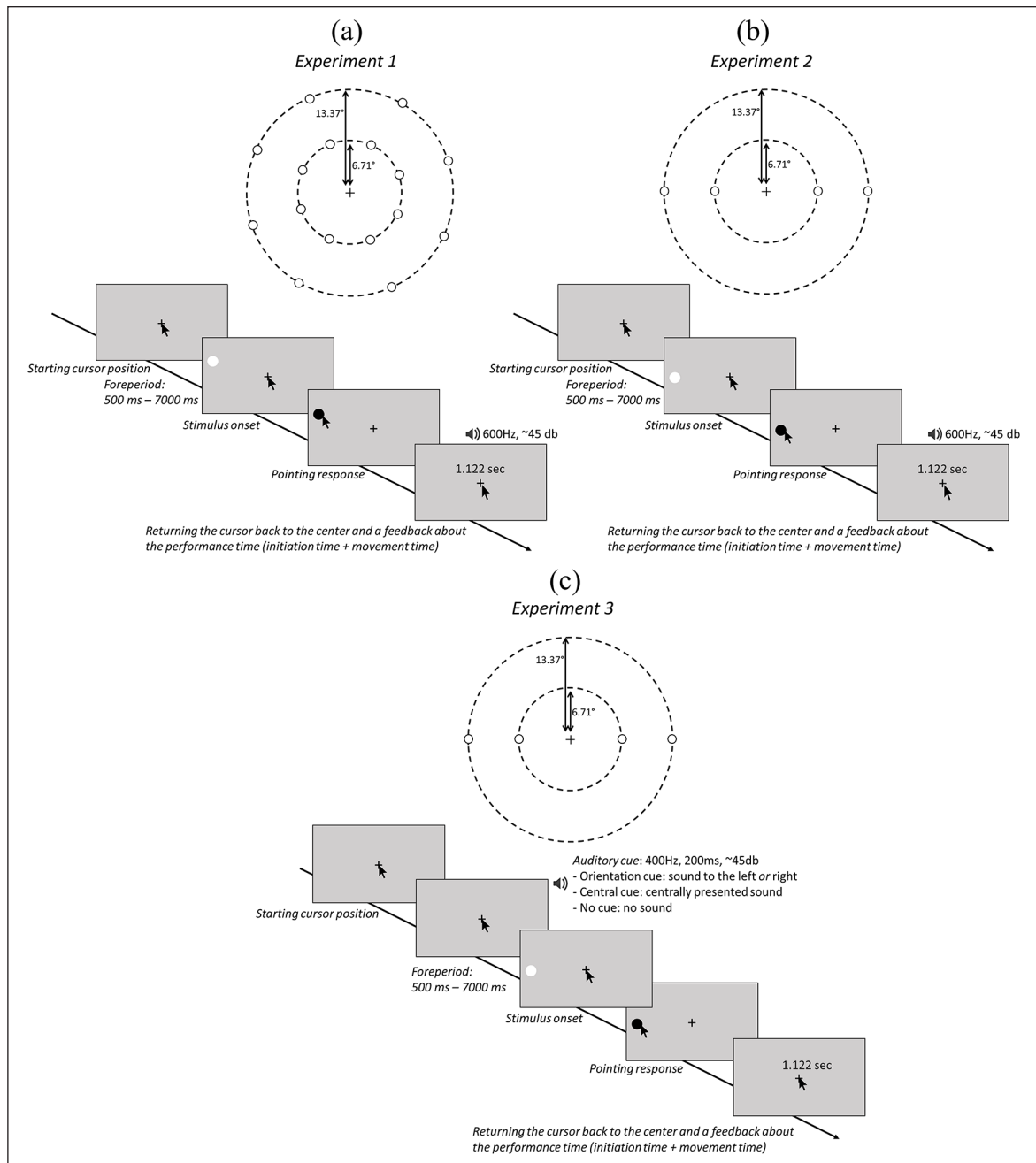
Figure 1. Schematised layout of the target positions and the sequence of trials in Experiments 1 (a), 2 (b), and 3 (c). On each trial, participants performed a visually guided mouse-pointing task, and in each trial, they pointed to a target dot by moving the cursor from the centre to the target. In Experiment 1, there were 16 possible target positions with many variable movement directions. In Experiments 2 and 3, there were four target positions only, and horizontal movements were required to point to the targets. In Experiment 3, The sequence of the trial was incorporated with three auditory cue conditions: Orientation cue, Central cue, and No cue conditions. For the Orientation cue condition, the cue was presented monaurally to either the left or the right ear and cued the side of the screen where the target was presented. For Central cue condition, the cue was presented binaurally, while for the No cue condition, the auditory cue was omitted.

suggesting that task performance was not confounded by serious physical factors.

Data analysis

Performance measures. In each trial, participants' data files contained the time stamps and x and y coordinates of the cursor. Cursor positions were sampled at 60 Hz. All movement trajectories were aligned to the same initial coordinates (0,0) (following Spivey et al., 2005). Euclidean distances travelled between consecutive cursor displacements and velocity for each movement trajectory were extracted. Trajectories of each participant were plotted

and then visually inspected for unusual patterns (e.g., large amounts of up and down movements, unusual movements resulting from slips of the hand). Only one such trajectory was identified and excluded from further analysis.

Several temporal and spatial (or accuracy-related) mouse-movement metrics were calculated. To assess the movement preparatory phase, initiation time was analysed. Initiation time (IT) was defined as the interval between the onset of target presentation and movement initiation (i.e., when the cursor left the fixation cross and thus had been moved by 3 mm).

To analyse participants' movement execution, we selected measures that characterise the temporal and spatial profiles of the movement trajectories. For the temporal profile, we calculated movement time (MT), defined as the interval between movement initiation and target reach. For the spatial profile, movement error (ME) was selected, which is one of the accuracy measures proposed by MacKenzie et al. (2001) and represents the average absolute deviation of the x and y coordinates from the task axis (i.e., the shortest path to the target). We also analysed the ratio of MT and ME (henceforth MT/ME ratio) as an index of speed–accuracy adjustments. In addition, we calculated the total response time (RT) as the sum of IT and MT.

Eye-movement analysis. Eye movements during the whole course of the experiment were recorded by a Tobii TX300 eye tracker with a sampling rate of 120 Hz. The recorded data were exported and processed offline. Missing data (i.e., validity codes higher than 1 provided by the eye tracker) due to blinks and artefacts were linearly interpolated. Fixations were defined using the default settings of Tobii. Trials where participants did not fixate on the fixation cross during stimulus presentation were excluded from further analyses of behavioural performance and eye movement metrics. For the analysis of saccadic latency, only trials with less than 33% of missing data were included. Saccadic latency was defined as the time (in milliseconds) from target onset to the initiation of the first valid saccade towards the stimulus. An eye movement was considered a valid saccade when velocity exceeded 30°/s, acceleration was higher than 8,000°/s², and distance was higher than 0.5° (Stigchel et al., 2011). Only saccadic latencies higher than 80 ms were included in the analysis.

The performance measures and saccadic latency data were analysed by repeated measures ANOVAs (rANOVA) with ToT (the three blocks of trials), target distance (near vs far distance). Follow-up rANOVAs were used to analyse significant interactions. When the ToT effect was significant, simple planned contrasts were used to test the differences between the first and the other two blocks of trials. If the violation of sphericity assumption was indicated by Mauchly's test, either the Greenhouse–Geisser correction (if epsilon was less than 0.75) or the Huynh–Feldt correction (if epsilon was greater than 0.75) was applied for the evaluation of the statistical significance of the F-value.

In addition, to explore the relationship between movement preparation and movement execution, a series of simple linear regression analyses was performed to estimate movement time slopes and movement error slopes as a function of initiation time, separately. For each participant, we estimated the slopes separately for each block and target distance (thus, for both measures, six individual slopes were estimated for each participant). The extracted slopes were then subjected to one-sample t-tests to compare the mean estimated slopes against zero. In addition, rANOVAs with Block as a within-subject factor were performed on the slopes to test the potential change in the magnitude and direction of the slopes over time.

Data of all three experiments are available to download from a public data repository: https://data.mendeley.com/datasets/6cnm4n3gdc/draft?a=bc6266f9-6b5c-43f7-9d99-af6dc19346f4.

Results

Descriptive statistics are presented in the supplementary materials (see Tables S1 and S2). Figure 2 depicts the results of the six variables analysed to assess the ToT-related changes in mouse-pointing movement. In addition, Table 1 presents the results of the main analyses. Here, we summarise the findings and report the results of the post hoc analyses.

The analysis of subjective fatigue ratings revealed significantly higher fatigue after the task than before, suggesting that the performance of the mouse-pointing task enhanced the participants' feelings of fatigue, $t(25) = -3.55$, $p < .01$, 95% CI = [−24.30, −6.47].

Importantly, in line with our first hypothesis, participants initialised their pointing movement significantly slower with increasing ToT. Simple planned contrast showed that initiation time significantly increased from the first to the second, $F(1,25) = 7.62$, $p < .05$, $\eta_p^2 = .23$, and third block of trials, $F(1,25) = 19.15$, $p < .001$, $\eta_p^2 = .43$. Initiation time was not affected by target distance. This latter finding remained unchanged with increasing ToT (see Table 1, no significant interaction of target distance × ToT). In contrast to initiation time, the initialisation of saccadic eye movements (i.e., saccadic latency) to the direction of the target showed no change over ToT. A significant main effect of the target distance indicated that saccadic eye movements were initiated slower if the target was presented at the far locations. The lack of ToT effect on saccadic latencies suggests that the slowing of movement initiation was not predominantly related to sensory processing deficits of the peripheral target. This conclusion is, however, not unequivocal because variance in saccadic movement is supposed to be modulated by a combination of perceptual and motor decision
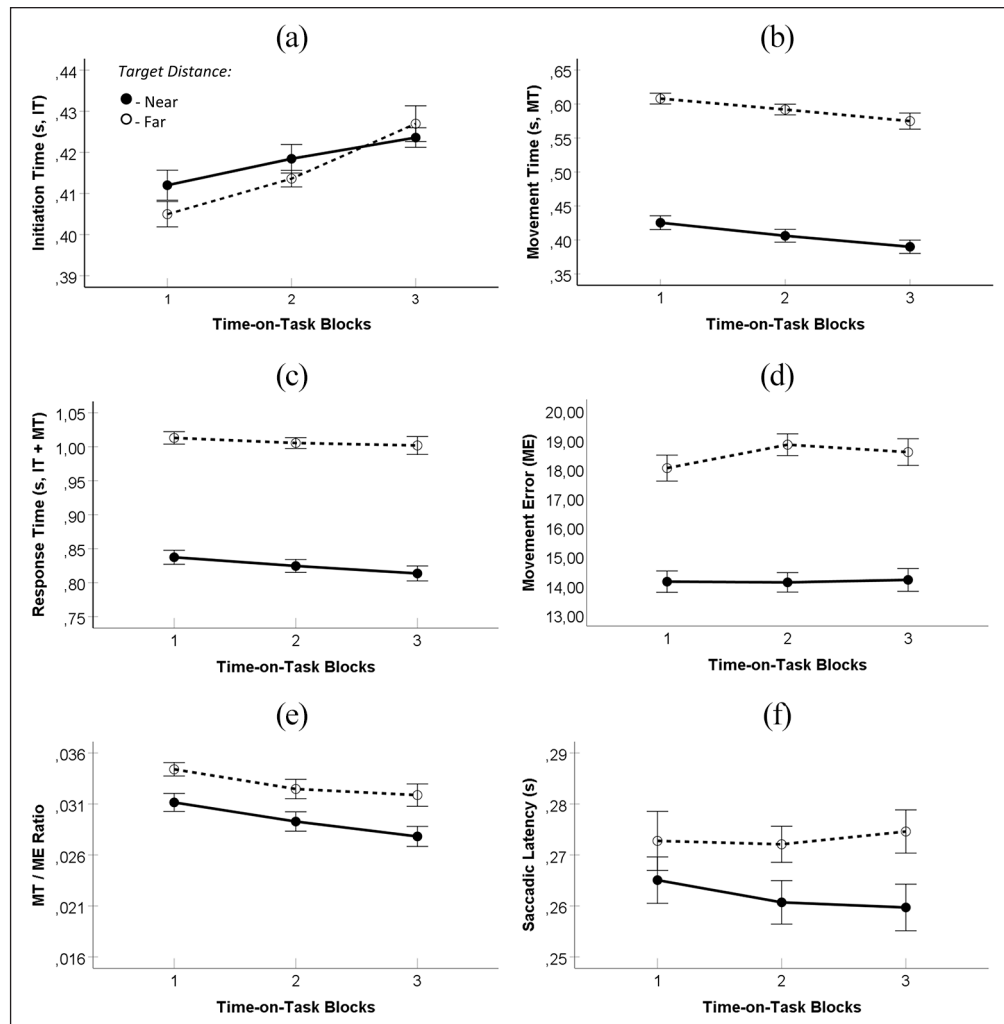
Figure 2. Results of for five pointing performance measures (a to e) and saccadic latency (f) in Experiment 1. Error bars represent within-subject error (Cousineau, 2005).

Table 1. Main effects and interactions yielded by rANOVA in Experiment 1.

Variables	Main effects and interactions					
	ToT		Target distance (TD)		ToT × TD	
	$F_{(2,50)}$	η_p^2	$F_{(1,25)}$	η_p^2	$F_{(2,50)}$	η_p^2
Initiation time	12.87***	.34	0.89	.03	1.74	.06
Movement time (MT)	5.98**	.19	487.16***	.95	0.02	.00
Movement error (ME)	0.41	.02	205.00***	.89	0.71	.03
MT/ME ratio	5.28**	.17	20.58***	.45	0.13	.00
Response time	1.44	.25	436.61***	.95	0.20	.01
Saccadic latency	0.12	.01	6.86*	.21	0.68	.03

ANOVA: analysis of variance.
*$p < .05$, **$p < .01$, ***$p < .001$, m: $p = .05$.

processes, and not only by the visual salience of the target (Liversedge et al., 2011).

For the execution phase, the movement time and the movement time/error ratio (MT/ME) were significantly related to ToT. As a function of ToT, participants executed the pointing movement faster without a significant change in accuracy. This was accompanied with a decreased MT/ME ratio, suggesting that ToT altered the speed–accuracy

criterion towards speed at the expense of accuracy. Simple planned contrast of the MT and the MT/ME ratio revealed that MT decreased from the first to third block of trials, $F(1,25) = 10.28$, $p < .01$, $\eta_p^2 = .29$, while the MT/ME ration decreased from the first to the second, $F(1,25) = 4.30$, $p < .05$, $\eta_p^2 = .15$, and third block, $F(1,25) = 9.88$, $p < .01$, $\eta_p^2 = .28$. This finding fits with our prediction (H2) that movement time becomes faster due to ToT. However, this finding does not directly indicate increased impulsivity because the increase in movement error was only minor and non-significant. Finally, total response time (initiation time + movement time) did not change significantly with ToT, suggesting that as a consequence of the differential trends in initiation time and movement time, the total duration of the pointing responses remained constant over ToT. The analyses of estimated movement error slopes, however, showed that there was no change in the association between initiation time and movement time, with increasing ToT suggesting that the opposite changes in these two performance measures were probably not due to a strategic shift (trade-off). Specifically, the estimated movement error slopes were not significantly different from zero ($p = .13–.93$), indicating no association between the time required for movement initiation and the accuracy of movement execution. Similarly, the estimated movement time slopes were not significantly different from zero ($p = .15–.72$), except for the far target condition in Block 3, where slower initiation times were significantly associated with slower movement times, $t(25) = 2.18$, $p < .05$, 95% CI = [.004, .145]. Importantly, the lack of association between movement initiation and execution remained constant with ToT: the rANOVAs showed that both the estimated movement error slopes, near target: $F(2,50) = 0.66$, $p = .52$, $\eta_p^2 = .03$; far target: $F(2,50) = 0.04$, $p = .96$, $\eta_p^2 < .01$, and the estimated movement time slopes, near target: $F(2,50) = 0.73$, $p = .47$, $\eta_p^2 = .03$; far target: $F(2,50) = .65$, $p = .53$, $\eta_p^2 = .03$, remained unchanged with increasing ToT. Thus, these results make it unlikely that the differential changes in initiation time and movement would have been driven by strategic changes.

Finally, target distance had a significant effect on movement execution and on response time. Obviously, movement time and response time were longer when the target was presented at the farther distance. In addition, participants pointed to the far target more erroneously and more impulsively (i.e., with higher MT/ME ratio) than to the near target. All these effects of the target distance were, however, unaffected by ToT: none of the ToT × target distance interactions reached significance.

Discussion

The findings of Experiment 1 supported Hypothesis 1. Specifically, the finding that initiation times became slower as a function of ToT suggests that the participants'

preparation of their visually guided movements was compromised by ToT. In line with Solianik et al.'s (2018) study, there was also evidence for a faster, but not more accurate movement execution under fatigue. This finding cannot be unequivocally interpreted as impulsivity because there was no significant increase in error over time, and, therefore, it does not directly support Hypothesis 2.

In Experiment 1, the spatial layout of the targets was complex, and the location of the targets was hardly predictable across the trials. Compared to Experiment 1, however, Experiment 2 had a simpler spatial layout: there were only four target locations, covering a smaller area, and the targets were all reachable by horizontal movements. Due to these simplifications, making predictions and plans on movement became potentially easier in Experiment 2 compared to Experiment 1. Thus, Experiment 2 tests whether the ToT effects found in Experiment 1 are replicable when the planning and preparation of movements are less demanding.

Experiment 2

Methods

Participants. In total, 30 undergraduate students participated for extra course credits. The data of five participants were excluded by applying the same exclusion criteria as in Experiment 1. The final dataset consisted of 25 participants (19 females, two left-handed, aged between 18 and 20 years, $M = 21.44$, $SD = 3.12$). Self-reported sleep duration had a mean of 7.92 hr ($SD = 0.96$). The statistical power was adequate to detect significant differences (see the a priori power calculation above).

Task and stimuli. The experimental procedure and the task were identical to that of Experiment 1, except that the number of target locations was reduced to four (two positions on each side and each circle; see Figure 1b). Importantly, each target was located on the horizontal axis ($y = 0$); thus, only horizontal movements were required to reach the target.

Data analysis. The data analysis procedures were identical to those described in Experiment 1.

Results

Descriptive statistics are presented in the supplementary materials (Tables S3 and S4). Figure 3 depicts the results, and Table 2 presents the results of the main statistical analyses. Below, we summarise the findings and report the results of the post hoc analyses.

Subjective fatigue significantly increased by the end of the continuous performance of the task, $t(24) = -4.48$,
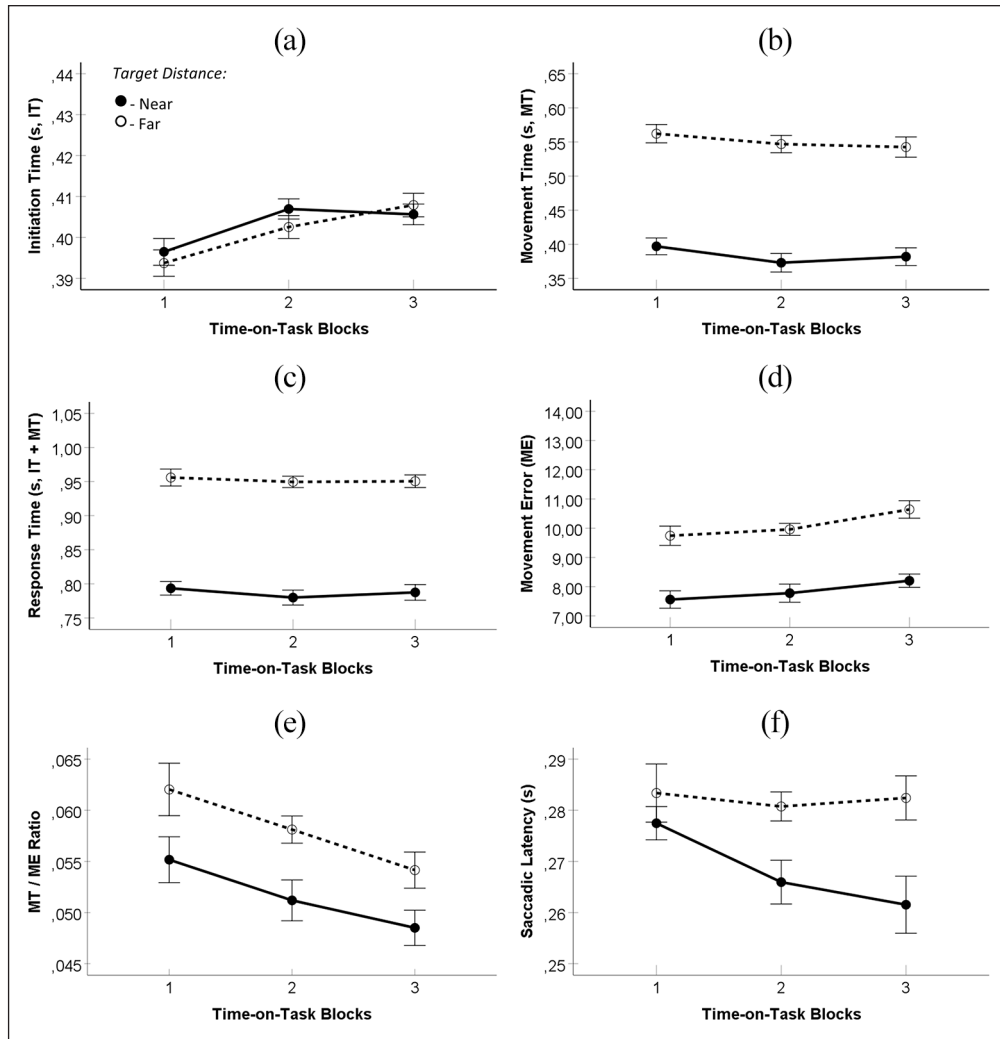
Figure 3. Results of for five pointing performance measures (a to e) and saccadic latency (f) in Experiment 2. Error bars represent within-subject error (Cousineau, 2005).

Table 2. Main effects and interactions yielded by rANOVA in Experiment 2.

Variables	Main effects and interactions					
	ToT		Target distance (TD)		ToT × TD	
	$F_{(2,48)}$	η_P^2	$F_{(1,24)}$	η_P^2	$F_{(2,48)}$	η_P^2
Initiation time	6.27**	.21	0.58	.02	1.24	.05
Movement time (MT)	2.97m	.11	340.21***	.93	0.27	.01
Movement error (ME)	3.48*	.13	64.18***	.73	0.23	.01
MT/ME ratio	7.11**	.23	9.02**	.27	0.10	.00
Response time	0.46	.02	277.61***	.92	0.09	.00
Saccadic latency	2.37	.09	7.16*	.23	2.35	.09

ANOVA: analysis of variance.
*$p < .05$, **$p < .01$, ***$p < .001$, m: $p = .06$.

$p < .001$, 95% CI = [−23.494, −8.665]. In addition and in line with Hypothesis 1, the initiation of pointing movements became significantly slower as a function of ToT.

This finding replicates that of Experiment 1. Simple planned contrast analysis showed that initiation time in the first block was significantly shorter than in the

second, $F(1,24)=6.37$, $p<.05$, $\eta_p^2=.21$, and in the third block, $F(1,24)=7.83$, $p<.05$, $\eta_p^2=.25$. The target distance had no significant effect on initiation times, which remained unchanged with ToT (i.e., no significant Target distance $\times$ ToT interaction). Similar to Experiment 1, saccadic latencies were faster for the near targets than for the far targets, but latencies showed no significant changes over ToT.

In the movement execution phase, movement error significantly increased, and movement time marginally significantly decreased with ToT ($p=.06$). The simple planned comparison indicated that movement execution was more erroneous in the third block compared to the first block, $F(1,24)=4.61$, $p<.05$, $\eta_p^2=.16$. In addition, we found a significantly decreasing MT/ME ratio as participants spent longer time on the task, and the simple planned contrasts analysis revealed a linear decrease in MT/ME ratio over time, Block 1 versus Block 2: $F(1,24)=4.28$, $p<.05$, $\eta_p^2=.15$; Block 1 versus Block 3: $F(1,24)=10.23$, $p<.01$, $\eta_p^2=.30$. That is, the results supported the second hypothesis on more impulsive movements with ToT. This more impulsive pointing performance was found to be independent from the distance of the target as indicated by the non-significant interaction of target distance with ToT. As in Experiment 1, although movement to the farther target was generally slower and more erroneous than to the near target, this difference was not further qualified by ToT.

Similarly to Experiment 1, overall response time (IT + MT) did not significantly change over time. In addition, similar to the first experiment was that the slope analysis did not indicate that the increasing initiation time and decreasing movement time are caused by a trade-off strategy. The one-sample tests conducted on the estimated slopes yielded no significant deviations from zero (movement error: $p=.25–.94$; movement time: $p=.26–.89$), except for the analysis of movement error slope for the far target condition in Block 1, $t(24)=-2.16$, $p<.05$, 95% CI=[−0.156, 0.004], where the estimated slope was significantly lower than zero, indicating that longer initiation times were associated with less erroneous movement execution. However, the rANOVAs yielded no significant Block main effects for both the estimated movement error slopes, target near: $F(2,48)=0.36$, $p=.70$, $\eta_p^2=.02$; target far: $F(2,48)=2.00$, $p=.15$, $\eta_p^2=.08$, and the estimated movement time slopes, Target near: $F(2,48)=0.85$, $p=.43$, $\eta_p^2=.03$; Target far: $F(2,48)=0.28$, $p=.76$, $\eta_p^2=.01$. Thus, in this experiment, we found no indication for a change in the association between movement preparation and execution as function of ToT.

Discussion

The results of Experiment 2 largely replicated the findings of Experiment 1 and supported Hypotheses 1 and 2. First, the findings confirmed that ToT induces a slower movement initiation. In addition, even more clearly than in Experiment 1, there was evidence for a more impulsive execution of the pointing movement with ToT: with increasing ToT, participants moved faster but more erroneously. This finding is in line with previous studies suggesting that one of the manifestations of mental fatigue induced by ToT is an impaired impulse regulation process (Le Mansec et al., 2018; Smith et al., 2017; van der Linden et al., 2003).

In Experiment 2, the spatial layout of the target locations was simpler and therefore less demanding regarding movement planning and movement execution. Relative to Experiment 1, this layout simplification indeed resulted in faster overall initiation times at both target distances. However, it did not eliminate the slowing trend of initiation time with increasing ToT. This finding implies that the spatial range of the attentional focus was probably not the main factor behind the initiation time slowing found in Experiments 1 and 2.

One possible process that may have contributed to the findings in Experiments 1 and 2 is a fatigue-related decrease in the participants' ability to orient their attention to the peripherally presented stimulus, resulting in a slower initialisation of the pointing movement (Hilt & Cardellicchio, 2020; Paneri & Gregoriou, 2017). Therefore, as introduced above, in Experiment 3, we added an auditory cuing paradigm (No cue, Orientation cue, and Central cue conditions) to examine the potential attentional orientation in ToT-related effects.

Experiment 3

Methods

Participants. In total, 27 undergraduate students participated for extra course credits. Applying the same gaze fixation criteria as before, three participants were excluded leaving a total of 24 participants (18 females, three left-handed, aged between 19 and 34 years, $M=23.92$, $SD=4.66$). Based on self-report, the mean sleep duration was 7.97 hr ($SD=1.18$). The statistical power was adequate to detect significant differences (see a priori power calculation above).

Task and stimuli. In Experiment 3, the same target positions were used as in Experiment 2 and the procedure of the experiment was identical to the procedures in the first two experiments. Experiment 3, however, was different in respect to the additional trial conditions (see Figure 1c). Specifically, three auditory cue conditions were used: Orientation cue, Central cue, and No cue conditions. The auditory cue was a 250 Hz tone presented for 200 ms through regular earphones. The cue-target interval was 200 ms. In the Orientation cue condition, the cue was presented monaurally to either the left or the right ear always on the side of the screen where the actual target would be
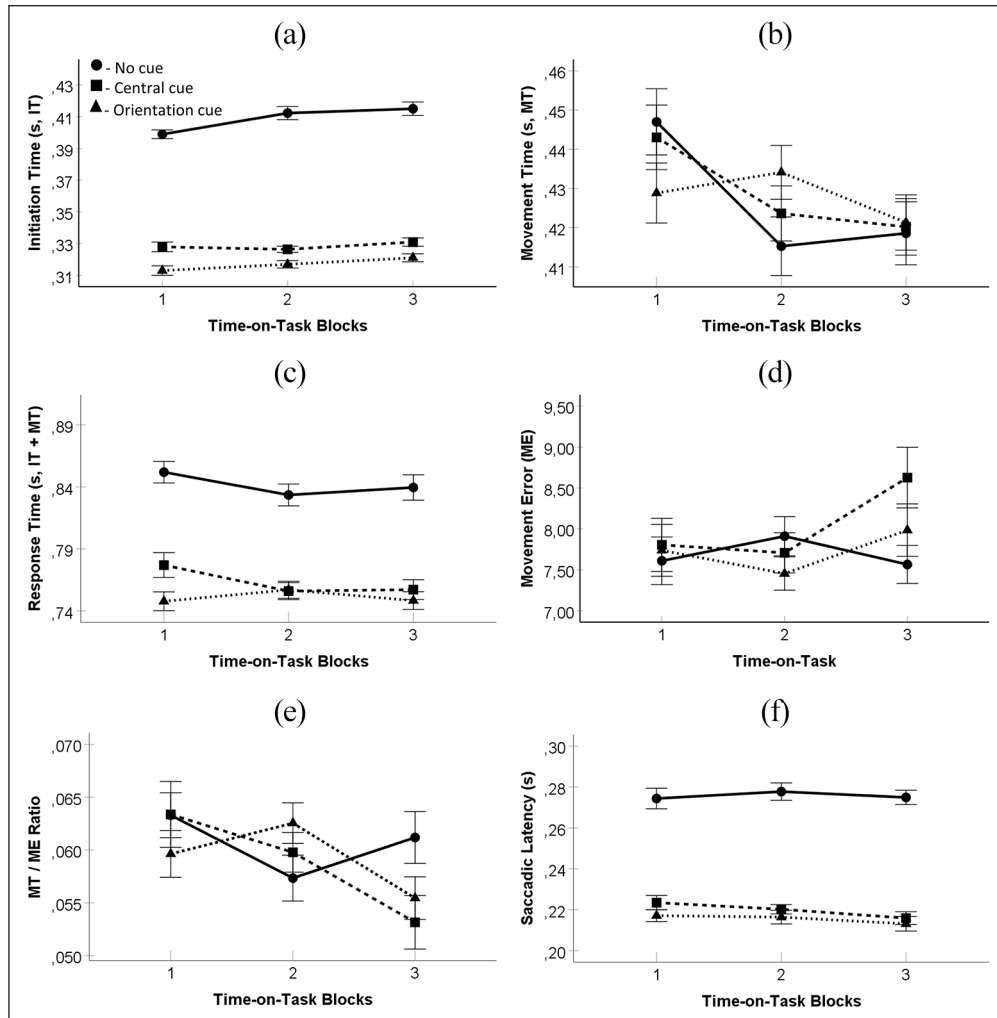
Figure 4. Results of five pointing performance measures (a to e) and saccadic latency (f) in Experiment 3. Error bars represent a within-subject error (Cousineau, 2005). Please note that the scale of figures is different to those used in the previous experiments (i.e., Figures 2 and 3).

presented. Participants were informed that the monaural cues indicated the side of the target location. In the Central cue condition, the cue was presented binaurally, while in the No cue condition, the cue was omitted. In this experiment, the auditory signal accompanied by the visual feedback in the first two experiments was omitted to avoid interference with the auditory cue. To ensure balance in the number of trials across conditions, there were 72 trials in each block. It should be noted that Experiment 3 included a higher number of trials than Experiments 1 and 2; therefore; this experiment lasted longer, about 20 min.

Data analysis. The data analyses were identical to those described in Experiments 1 and 2 except that, in addition to the factors of ToT and Target distance, the Cue (three auditory cue conditions) was also used as a within-subject factor in the rANOVA. Significant Cue main effects were followed by pairwise comparisons using a Bonferroni

correction. In addition, the analyses of movement error and movement time slopes were identical to the procedure described in Experiments 1 and 2, except that the slopes were also estimated separately for each cue condition (thus, for both measures, 18 slopes were extracted for each participant).

Results

Descriptive statistics are presented in the supplementary materials (see Tables S5, S6, S7, S8). Figure 4 depicts the result for each variable and Table 3 presents the main statistical analyses. Continuous performance of the task was associated with a significant increment in subjective fatigue, indicating that the pointing task remains subjectively fatiguing for the participants even if it is combined with a cuing paradigm, $t(23) = -3.42$, $p < .01$, 95% CI $= [-25.34, -6.24]$.

Table 3. Main effects and interactions yielded by rANOVA in Experiment 3.

Main effects and interactions		Initiation time	Variables				
			Movement time (MT)	Movement error (ME)	MT / ME ratio	Response time	Saccadic latency
ToT	$F_{(2,46)}$	4.27*	3.37*	0.62	2.36	0.83	0.47
	η_p^2	.16	.13	.03	.09	.04	.02
Target distance (TD)	$F_{(1,23)}$	3.29	663.08***	64.29***	12.67**	613.17***	16.52***
	η_p^2	.12	.97	.74	.35	.96	.42
Cue	$F_{(2,46)}$	575.93***	0.95	2.14	0.58	101.09***	210.03***
	η_p^2	.96	.00	.08	.02	.82	.09
ToT × TD	$F_{(2,46)}$	0.04	1.86	1.38	0.94	1.70	0.17
	η_p^2	.00	.07	.06	.04	.07	.01
ToT × Cue	$F_{(2,46)}$	2.84*	1.91	2.47*	3.22*	1.56	0.83
	η_p^2	.11	.08	1.00	.12	.06	.04
TD × Cue	$F_{(2,46)}$	1.36	1.82	0.75	0.88	2.48	1.35
	η_p^2	.06	.07	.01	.04	.10	.06
ToT × TD × Cue	$F_{(4,92)}$	0.31	0.31	0.23	0.44	0.21	1.03
	η_p^2	.01	.01	.01	.20	.01	.04

ANOVA: analysis of variance.
*$p < .05$, **$p < .01$, ***$p < .001$.

Initiation time. The analysis of initiation time yielded a significant main effect of ToT; initiation times became slower over time. Simple planned contrast analysis showed a significant difference between the first and the third block of trials, $F(1,23) = 5.30$, $p < .05$; $\eta_p^2 = .19$. There was a significant main effect of the Cue with significant differences between all cue conditions. Initiation times on trials following an Orientation cue were shorter compared to the other two cue conditions, Orientation versus Central cue: $t(23) = -6.70$, $p < .001$, 95% CI $= [-0.016, -0.007]$; Orientation versus No cue: $t(23) = -27.20$, $p < .001$, 95% CI $= [-0.100, -0.083]$, suggesting that the Orientation cues directed participant's attention towards the possible location of the target and reduced the time required to initiate the pointing movement. The Central cues also turned out to be advantageous. Initiation time on trials following a Central cue was found to be shorter than on trials without such a cue, Central versus No cue: $t(23) = -23.33$, $p < .001$, 95% CI $= [-0.089, -0.071]$, suggesting that after being presented by an auditory cue participants became generally more alert and reacted faster.

Pertinent in this study was that the ToT × Cue interaction on initiation time was significant. Follow-up analysis revealed a significant main effect of ToT for the No cue condition, $F(2,46) = 5.71$, $p < .05$, $\eta_p^2 = .20$, showing shorter initiation times in the first block compared to the third block of trials, $F(1,23) = 8.56$, $p < .01$, $\eta_p^2 = .27$. In contrast, there was no significant ToT effect on trials preceded by Central cues, $F(2,46) = .85$, *n.s.*, $\eta_p^2 = .04$, or Orientation cues, $F(2,46) = 2.32$, *n.s.*, $\eta_p^2 = .09$. These

findings suggest that participants' attentional orientation ability was not necessarily compromised as they became tired. Even in the last block they remained alert for fast, phasic initiations. In addition, importantly, the results in the No cue condition replicated the finding of the first two experiments and supported the first hypothesis, showing that the initialisation of mouse-pointing movements in the absence of auditory signals slows down with increasing ToT. This ToT effect was again not significantly affected by target distance.

Movement time and error. The time of the movement execution phase significantly decreased with ToT. Planned contrast comparisons showed that movement time was longer in the first block compared to the second, $F(1,23) = 4.97$, $p < .05$; $\eta_p^2 = .18$, and third block of trials, $F(1,23) = 4.93$, $p < .05$; $\eta_p^2 = .18$. We also found a significant Cue × ToT interaction for the MT/ME ratio. The MT/ME decrement over time was significant only for the Central cue condition, main effect of ToT; No cue: $F(2,46) = 1.72$, $p = .19$, $\eta_p^2 = .07$; Orientation cue: $F(2,46) = 2.83$, $p = .07$, $\eta_p^2 = .11$; and Central cue: $F(2,46) = 3.38$, $p < .05$, $\eta_p^2 = .13$; see also Figure 4. This disadvantageous effect of the Central cues was independent from the target distance and came mainly from the more erroneous movement execution with ToT, Block 1 versus Block 3: $F(1,23) = 4.33$, $p < .05$; $\eta_p^2 = .16$. More specifically, further analysis of the significant Cue × ToT interaction for movement errors revealed that, in the third

block, participants' movement execution on Central cue trials became significantly more erroneous compared to No cue trials, ME: $t(23) = -3.703$, $p < .01$, 95% CI $= [-1.654, -0.468]$, see also Figure 4. In sum, these findings suggest an alerting effect of the Central cues: this cue type may have alerted and urged participants to move, which, however, resulted in more erroneous movements as the participants spent more time on the task.

Finally, in line with the previous experiments, the overall response time did not significantly change as a function of ToT. A change in performance strategy seems, however, to be unlikely based on the results of the slope analyses. Specifically, the estimated movement time slopes were not significantly different from zero ($p = .07 - .93$). The one-sample t-test analyses of estimated movement error slopes showed that only one slope was significantly higher than zero, indicating that slower initiation times were associated with a more erroneous movement execution only in the second block if the target was presented on the far location and was preceded by an orienting cue, $t(23) = 2.30$, $p < .05$, 95% CI $= [0.015, 0.285]$. No other movement error slopes, however, differed significantly from zero ($p = .10 - .96$). Furthermore, the rANOVAs showed no significant changes in the movement error and movement time slopes with increasing ToT (all Fs < 2.93, $p = .07 - 1.0$) suggesting again that changes in the association between the preparatory and execution phases were unlikely to occur during task performance.

Response time and saccadic eye movements. The significant advantage of Orientation and Central cues over the No cue trials was observed for saccadic latencies and response time. Post hoc analyses showed that the initialisation of saccadic eye movements and the response time was significantly longer when No cue preceded the target, Saccadic latency: No cue versus Central cue: $t(23) = 15.45$ $p < .001$, 95% CI $= [46.46, 65.11]$; No cue versus Orientation cue: $t(23) = 15.37$, $p < .001$, 95% CI $= [50.01, 70.21]$; response time: No cue versus Central cue: $t(23) = 9.80$, $p < .001$, 95% CI $= [0.06, 0.10]$; No cue versus Orientation cue: $t(23) = 12.82$, $p < .001$, 95% CI $= [0.07, 0.11]$. Furthermore, both measures were found to be significantly higher when the target was presented at the farther distance.

Discussion

In accordance with Hypothesis 1, Experiment 3 provided additional evidence for a slower movement initiation with increasing ToT in the condition with no auditory cues. In this experiment, we included tests of orientation ability by comparing Central and Orientation cue conditions as a widely accepted marker of attentional orientation (e.g., Fan et al., 2002; Jennings et al., 2007). In general, initiation times and saccadic latencies in Orientation cue trials were faster than in Central cue trials, indicating that the

orientation cues successfully directed the participants' attention. Importantly, this difference remained constant over the whole duration of the task, implying that even after longer ToT, participants could still adequately utilise the information provided by the cues.

The robustness of orientation ability to ToT seems to be related to alerting characteristics of the cues. Participants' phasic alertness level was examined as the comparison of the Central cue and No cue trials (Fan et al., 2002). A constant advantage of Central cue trials over No cue trials was found with ToT indicating that fatigued participants were still able to increase their response readiness after being presented with a cue. Thus, to conclude, neither an impaired orientation ability nor a low level of phasic alertness can be considered as major factors behind the initiation time slowing as a function of ToT.

General discussion

Preparation of visually guided movements involves processes, such as the planning of the magnitude and timing of muscular forces and the forming of predictions about the consequences of the planned movement (Elliott et al., 2017). These processes are known to be influenced by top-down control and therefore may be potentially sensitive to the detrimental effect of ToT (e.g., Marchant, 2011; Wolpe et al., 2016). Accordingly, the present set of experiments systematically examined the vulnerability of visually guided pointing movements to ToT. In three experiments, mouse-pointing movement was tested with variables relating both to the pre-movement preparatory phase and the movement execution phase.

First, the overall speed (i.e., response time) of the pointing movement was insensitive to ToT. Thus, on average, participants did not become slower or faster overall during the task. Nevertheless, the two components of response time (initiation time and movement time) had opposite tendencies: while the initiation time increased with ToT, the movement time decreased. In addition, movement errors generally increased in the second experiment and in the Central cue condition in the third experiment. In line with our first hypothesis, the findings of all three experiments converged on the conclusion that the participants took longer to initiate their movement as they spent more time on the task.

The second hypothesis on movement execution also received support, albeit less consistently. In two experiments, we found a decreased MT/ME ratio, with ToT suggesting a time-related change in the speed–accuracy criterion towards speed at the expense of accuracy. This, however, cannot be considered clear support of our second hypothesis because although we found that participants moved faster, this was accompanied with significantly more errors in Experiment 2 only. In Experiment 3, participants reacted impulsively (i.e., faster, with more errors) in

the Central cue condition only. All in all, the experiments imply that ToT mainly induces a slower pre-motor planning, which is often accompanied by faster movement execution. Although initially this seems to indicate some sort of strategic trade-off, it appears to be a less adaptive one because the faster execution speed was often associated with more errors.

The ToT-related slowing in movement initiation did not show only in the more spatially complex target layout in Experiment 1 but also in the two experiments that adopted a simpler spatial layout (Experiments 2 and 3). This indicates that the complexity of the spatial layout may affect general pointing performance in terms of speed and errors but would not be the driving force behind the ToT effects on response initiation time.

One alternative explanation for the increased movement initiation time was that ToT compromised the participants' ability to orient their attention towards the targets. Attentional orientation is modified by both top-down and bottom-up processes, and so a ToT-related detrimental effect seemed plausible (Chica et al., 2016; Kolb et al., 1982; Paneri & Gregoriou, 2017). This possibility was examined by looking at the saccadic latencies. In each experiment, the results for the initiation of saccades suggested that participants' orientation ability remained insensitive to ToT. Consequently, the finding that saccadic latencies were not affected by ToT suggests that targets remained both sensory and attentional capturing even when the participants already became fatigued.

By comparing the Central and Orientation cue conditions, Experiment 3 confirmed in a more direct way that orientation ability remained unaffected by ToT. Initiation time and saccadic latencies were generally faster in Orientation cue trials than in Central cue trials, and this difference remained constant over the whole task duration. More generally, the central cues in Experiment 3 also provided a test of the participants phasic alertness. That is, the central cues (compared with No cue trials) were able to increase the participants' response readiness even after considerable ToT.

An interesting finding was that in Experiment 3, the increased movement-initiation time was replicated in only the No cue condition. This seems to suggest that instead of being the result of reduced phasic alertness, ToT seems to have had an impact mainly through a decreased tonic alertness. Tonic alertness, or intrinsic alertness, is related to top-down control of arousal in the absence of external cues and influences sustained attention and executive control (Degutis & Van Vleet, 2010; Posner, 2008; Weinbach & Henik, 2012). This notion fits nicely with previous studies stating that under ToT-induced fatigue, people are still able to marshal adequate levels of cognitive control when they are sufficiently externally alerted or motivated (Hopstaken et al., 2015a, b). Nevertheless, particularly the self-sustained maintenance of readiness seems sensitive to the detrimental effects of fatigue or ToT (van der Linden, 2011).

Throughout the three experiments, we also found some support for our second hypothesis, for more impulsive movement due to ToT. The evidence was less clear and consistent in comparison to the empirical support for Hypothesis 1, though. Specifically, due to ToT, participants consistently became faster in their movement execution, but that was not always accompanied by more errors. Moreover, in all three experiments, overall response time (initiation time plus movement time) did not significantly relate to ToT. The clearest evidence for impulsive movements was observed in Experiment 2, in which we found a marginally decreasing movement time, MT/ME ratio, and more errors as a function of ToT. Because of the relatively low cognitive demand of Experiment 2, fatigued participants may have felt less of the need to control their movements and may have disengaged from the task more than in Experiment 1, where the target layout was more complex, or in Experiment 3, where the variable cue conditions exogenously enhanced their alertness and attention.

The notion of more impulsive performance under fatigue fits with the model of Elliott et al. (2010, 2017). Their model emphasises the importance of continuous limb regulation during the executive phase of movement (or distance-covering phase). During this phase, impulse regulation can correct movement direction and velocity in case of discrepancies between the actual movement and the expectations derived from the movement phase. In the current set of experiments, we did not examine corrections within the movement trajectory. Therefore, we could not directly determine to what extent participants controlled and/or corrected their movement path. Nevertheless, we tend to interpret the faster and sometimes also more erroneous movement as indications of generally less controlled movement due to lowered tonic alertness or arousal.

The notion of impulsivity due to lowered arousal is also in line with the model of Howells et al. (2012), stating that hypo-aroused individuals with a suboptimal tonic firing rate in the LC-NE system are inattentive and impulsive in their responses. The model converges with studies showing that attention-deficit/hyperactivity disorder (ADHD) and its animal model (spontaneously hypertensive rat model, SHR) are accompanied by lowered arousal levels, accounting for an impulsive, reflexive behavioural style (Aron & Poldrack, 2005; Howells et al., 2009, 2010). Importantly, decreased alertness is also known to be related to enhanced task disengagement, which is found to be a major factor behind enhanced mental fatigue induced by ToT (see, e.g., Hopstaken et al., 2015a, b).

Finally, as mentioned above, it is plausible that performance strategies coordinating the initiation and execution phases may have occurred over the course of the tasks. Yet, the slope analyses showed no clear statistically tendentious change in the association between initiation time and the two execution measures over ToT (significant associations were found in only a very few cases). These results suggest

no strong interconnection between the preparatory and the execution phases of movements, therefore leaving relatively little room for the interpretation that the changes in movement preparation and execution belonged to a coordinated performance strategy.

In light of overall findings of the experiments, alternative interpretations also need to be discussed. First, a possible strategy raised was that with an increase in ToT, participants learn how to delay the initialisation of their movement to improve movement execution. This strategy would, however, require a strong, direct connection between the preparation and the execution of movements, which was not found in the three experiments. In addition, the movement error increased over ToT, suggesting that even if any learning process had taken place, it was not so successful, considering that response time remained constant with ToT.

Second, one may point to the possibility of a compensatory strategy in which fatigued participants pay less attention to movement preparation and instead focus more on the cognitively less demanding online adjustment of their movement path. However, such a strategy can be expected to be associated with longer movement execution times and, possibly, shorter movement preparation time. Thus, such a strategy seems less likely because that would lead to an actual mirror image of the findings that we reported in the three experiments.

To examine further the effects of ToT on pointing movements, future studies may want to consider examining ToT-related changes in the association of movement initiation and execution more systematically. More systematic analysis may be carried out by varying, e.g., the maximal duration of the initiation period or by displacing the targets after the movement was initialised, forcing the individuals to control more their movement path online.

To conclude, in three experiments, we found evidence that both the preparatory and the execution phases of pointing movements are affected by increasing ToT. The findings imply that participants' tonic alertness declined and compromised the cognitive control in a top-down manner, resulting in a slow initialisation and an impulsive movement execution. In contrast, the phasic alertness and the associated spatial orientation ability remained robust to the detrimental effects of fatigue.

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Data accessibility statement

The data and materials from the present experiment are publicly available at the Open Science Framework website: https://data.mendeley.com/datasets/6cnm4n3gdc/draft?a=bc6266f9-6b5c-43f7-9d99-af6dc19346f4

Supplementary material

The supplementary material is available at qjep.sagepub.com.

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