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Effects of mental fatigue on the capacity limits of visual attention

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The literature indicates that mental fatigue, due to Time-on-Task (ToT), compromises the ability to ignore distractors. The present study elaborates on this effect by testing whether perceptual load of the target stimuli moderates the ability to ignore distractors under fatigue. Participants (N = 27) performed a visual attention task (an Eriksen flanker task) for 2.5 hours without rest. Target letters were presented at three different perceptual loads and with a peripheral distractor letter. Three target-distractor conditions were tested: congruent, incongruent, and neutral. Results showed that, overall, error rates and reaction times increased with ToT. The detrimental effect of fatigue on performance was most pronounced in the high perceptual load condition. Importantly, however, we also found that fatigue-related ignorance of distractors was compromised in the low perceptual load condition, but not in the medium or high perceptual load condition. This finding is in accordance with the perceptual load theory and refines the knowledge about the declining cognitive performance under fatigue.

Keywords: Mental fatigue; Time-on-task; Visual attention.

It is a common phenomenon that after prolonged engagement in cognitively effortful activities, people experience a state that can be labelled as mental fatigue, or that is sometimes referred to as cognitive fatigue (Ackerman, 2010). Mental fatigue is a complex state that involves changes in motivation and mood (van der Linden, 2010). Moreover, mental fatigue has been associated with difficulties in sustained attention focused on a task, particularly when potentially interfering distractors are present (e.g., Boksem, Meijman, & Lorist, 2005; Lorist et al., 2000). Indeed, previous studies have shown that mental fatigue impairs attention in various ways. These attentional impairments are the consequences of numerous perceptual and cognitive mechanisms. One major effect that seems to occur under fatigue is a diminishing top-down control over cognitive processes (Boksem et al., 2005; Lorist et al., 2000; van der Linden, Frese, & Meijman, 2003). In other words, higher order mental processes controlling the adaptive regulation of basic cognitive and perceptual functioning are assumed to be disturbed by fatigue thereby leading to an “escape” of basic functions (e.g., van der Linden et al., 2003). When this happens, behavioural deteriorations are almost inevitable,
especially in complex tasks that require careful performance monitoring and adjustment of multiple functions (Boksem et al., 2005).

One way to test attentional control is by using distractors. More specifically, it has been shown that active attentional control is required to overcome the potential detrimental effects of distractors on performance (e.g., Chau, 2010; Peers & Lawrence, 2009). Previous studies that have used distractors in fatigue research do not show consistent findings. While an increased distractor effect was found in some fatigue studies (e.g., Boksem et al., 2005; Landsdown, 2001), other studies failed to find specific evidence for the increased interference of distracting information with fatigue (e.g., Lorist, 2008; Lorist, Boksem, & Ridderinkhof, 2005). Such inconsistencies seem to indicate that the ability to ignore distractors under fatigue may be moderated by other task characteristics. In the present study we argue that one characteristic that may play a role is the perceptual load of the stimuli. This idea is derived from the perceptual load theory of Lavie (1995, see later), which states that the effortful detection of a perceptually complex target might simply leave less spare attentional capacity to perceive task-irrelevant distractors. Thus, in case of a high perceptual load, the distractor will have a less disturbing effect (Lavie & de Fockert, 2003). This theory may provide valuable insight into the effects of fatigue on distractor processing and attentional capacity. Therefore, in the present study, we adopted the perceptual load theory to better understand the role of perceptual properties in distractor processing under fatigue. To our knowledge, the effect of perceptual load on distractor processing has not been systematically investigated before in fatigue studies. Our present study on the relationship between fatigue, distractors, and perceptual load was conducted in the context of the perceptual load paradigm as described by Lavie (1995), and Lavie and Cox (1997); we will briefly summarise that here. The perceptual load paradigm focuses on two main characteristics of the task, namely (1) perceptual load and (2) distractors. First, it is assumed that the perceptual load of the target affects the observers’ attentional capacity (e.g., Lavie, 1995, 2005). For example, the perceptual load of a target stimulus (e.g., a letter stimulus) is increased if the number of stimuli (a set of other letters) presented around the target is increased. An increase in perceptual load is usually associated with declined performance. The difficulty to detect the target stimulus under higher perceptual load might be intensified in situations that decrease the attentional capacity even more. Therefore, as fatigue is generally considered to have a detrimental effect on attentional capacity (Tops & Boksem, 2010; van der Linden, 2010), we predicted that the negative effects of high perceptual load become more pronounced with increasing levels of fatigue. In the present study fatigue is induced by Time-on-Task (ToT).

The second major characteristic in the perceptual load paradigm is the nature of the distractor. Distractors are known to put additional demands on attentional processing. This becomes apparent in, for example, the flanker task (i.e., Eriksen’s response–competition paradigm) where the target stimulus is flanked by a distractor stimulus in congruent, incongruent, or neutral identity to the target. Compared to trials with congruent distractors, participants typically show impaired performance on trials with incongruent distractors. The perceptual load theory refines the description of the relationship between performance and distractors by taking the perceptual load into account. More specifically, the theory proposes that the effect of distractor stimuli on target processing depends on the set size of the relevant items, that is, it depends on perceptual load. As Lavie (1995, 2005) argued, processing of target stimuli can prevent interference from distractors when the target stimulus has a so high perceptual load that it consumes most of the available attentional capacity. In that case, distractors are simply no longer fully processed. In contrast, when there is much spare attentional capacity, i.e., targets presented under low perceptual load, then this will result in the perception and further processing of distractors which will negatively affect performance. In the present study, we mimic the original design used by Lavie and de Fockert (2003) with similar stimuli and targets at various perceptual loads. In addition, distractor letters were displayed in congruent, incongruent, or neutral identity, which can reveal how much impact a distractor had on task performance.

It is relevant for the present research that several previous studies have suggested that low and high perceptual load are associated with different levels of attentional selection (e.g., Huang-Pollock, Carr, & Nigg, 2002; Lavie & Tsal, 1994). Under low perceptual load, late selection mechanisms are needed to actively ignore the effects of a perceived distractor on
performance (Lavie, 2000). In contrast, when target stimuli are presented under high perceptual load, early selection mechanisms are considered the bottle-neck of detecting the distractor. The effect of perceptual load on attentional selection has been confirmed by studies that found a reduction of distractor-related brain activity under high-load conditions. More specifically, functional imaging studies revealed that high load of the central task gates processing of peripheral task-irrelevant stimuli at a very early stage in the visual pathway. For example, Schwartz et al. (2005) found that visual cortex activity (i.e., activity in V1, V2, V3, and V4 areas) related to a task-irrelevant distractor was decreased when the central target stimuli (a stream of letter stimuli at fixation) were presented on high load. Similarly, reduced processing of peripheral distractors in visual system due to the increased perceptual load was found in O’Connor, Fukui, Pinsk, and Kastner’s study (2002). In a high load condition, when participants monitored for target letters among similar characters, the visual system activity related to a peripheral distractor was significantly decreased compared to a low load condition. This effect was shown to occur at a quite early stage of visual processing, in the lateral geniculate nucleus.

From the perceptual load paradigm as described previously it follows that any restriction in observers’ attentional capacity may lead to decreased distractor interference. This very specific expectation has already been confirmed in previous studies with participants who are presumed to have a reduced attentional capacity, namely elderly people and neuropsychological patients (e.g., Jansen & Keller, 2003; Makizako et al., 2010). For example, in line with the perceptual load theory it was found that, compared to younger participants, the elderly suffered from a greater distraction at very low perceptual load but were less impaired by the distractors in high perceptual load conditions. A quite similar pattern of results was found for patients having left hemineglect (Lavie & Robertson, 2001). These patients could be distracted by presenting stimuli in their right visual field, but, similarly to elderly people, they needed only a small increase in perceptual load to reduce distractor effect on target processing. The common point in these studies is that for elderly participants as well as for hemineglect patients the functional state of attentional top-down control is supposed to be impaired. This impairment in control might have deteriorating effects on the ignorance of distractors and on the attentional capacity to process the targets.

These findings in normal aging and in neuropsychological patient studies might be highly relevant to fatigue research because they clearly suggest that the functional state of observers’ attentional top-down control has a critical effect on target detection and distractor processing. It is often assumed that under fatigue attentional top-down control mechanisms are disturbed in a similar way. For example, the attentional effects of fatigue have been compared to these of elderly and frontal lobe patients (van der Linden & Eling, 2006). Consequently, we can expect that fatigued participants would display a similar pattern of results as have previously been reported in other populations with compromised top-down control. More specifically, we predict that mental fatigue (i.e., ToT) increases distractor effects at very low perceptual load, but decreases distractor effects at higher perceptual load conditions. In experimental settings this implies that our main prediction involves a three-way interaction between fatigue, perceptual load, and distractor. To our best knowledge, no other studies have tested the potential effects of perceptual load on distraction under fatigue. Yet, such test may refine our knowledge about the detrimental effects of fatigue on performance and may contribute to insight into the nature of mental fatigue.

To summarise, our aim is to investigate the effects of fatigue (i.e., ToT) on distractor processing with varying perceptual load of the task-relevant target stimuli. We expect that with increasing levels of fatigue, participants will perform worse on high versus low perceptual load trials, and will be less bothered by distractors in high perceptual load trials compared to low perceptual load trials.

**METHODS**

**Participants**

Twenty-seven under- and postgraduate students (12 females and 15 males aged between 20 and 29 years with a mean of 22 years, $SD = 2.54$) from the English Programme of the University of Pécs participated in this study. All participants were right handed and had normal or corrected to normal visual acuity by self-report. They were
naïve with regard to the purpose of the experiment and reported normal, medication-free health condition. All participants were paid and signed a written consent.

**Apparatus and stimuli**

A standard IBM-compatible computer with a calibrated 21-inch Silicon Graphics P/N monitor using a 1280 × 1024 pixel resolution with 90 Hz refresh rate presented the stimuli. The stimuli were displayed on a grey background with a 19.58 cd/m² luminance. The participants viewed the screen at 110 cm and a keyboard was used to record their responses.

![Figure 1](image_url)

**Figure 1.** Examples of test stimuli from each stimulus condition. Each stimulus consisted of a target letter and a distractor letter. A target letter, which could be either X or Z, appeared at one of the eight positions arranged in a circle, centred at 1.09° from the centre of the screen. The target letters subtended a visual angle of around 0.5° vertically and 0.42° horizontally. The distance between the target positions was 0.69°. Each of the target letters appeared equally often at each of the target positions. Three perceptual load conditions were produced: low, medium, and high loads. For the low perceptual load condition, the target letter was presented alone, and the other seven locations remained empty. For the high perceptual load condition, the other seven locations were
occupied by non-target letters (non-target set: N, S, G, Y, U, H, J). The non-target letters had no response association in the task. For the medium perceptual load condition, only three of the locations were occupied by three non-target letters randomly chosen from the non-target set. The non-target letters were identical to the target letters in size, and they appeared equally often at the locations.

The distractor identity could be congruent with the target letter’s identity (i.e., suggesting the same response as the target, e.g., a letter Z distractor when the target letter is Z), neutral (the distractor was a P suggesting neither an X or a Z response), or incongruent (suggesting the opposite response to the target; e.g., an X distractor when the target is Z). The distractor was always physically distinct from the target by being larger in size (0.74° vertically and 0.56° horizontally) and located in an irrelevant position. The distractors appeared randomly at one of the four positions above and below the circle. The distance between the distractor and the centre was about 2.56°. The distractor identities were each presented equally often.

Lavie and de Fockert (2003) investigated whether sensory degradation of task-relevant targets (i.e., decreased salience of the targets against the background) affects distractor processing. Their findings suggest, as they argued, that attentional capacity seems to remain unchanged for stimuli with degraded targets: Decreased attentional capacity to the targets should always be accompanied with a decreased processing of distractors. As it would be possible that our ToT manipulation also induces sensory fatigue we found it useful to introduce different levels of perceptual saliency. Note that any potential effects of saliency were not the main focus of the present study. Yet, we introduced different salience targets merely to check whether sensory fatigue processes have any effect on distractor processing for the current stimuli. We manipulated the perceptual saliency of the target and non-target letters varying the luminance contrast of the letters to the background. Three saliency conditions were produced with the Michelson contrast values of 0.23 (31.42 cd/m², low saliency), 0.47 (55.58 cd/m², medium saliency), and 0.67 (100.51 cd/m², high saliency). In each stimulus, the contrast of the distractor letters was identical to the contrast of the target/nontarget letters in the high saliency condition. The saliency conditions were randomly presented through the experiment.

Procedure

The experimental sessions lasted between 9:30 a.m. and 1:30 p.m. Participants were asked to abstain from alcohol and caffeine-containing substances at least 8 hours before the experiment. In addition, they were asked to have at least 7 hours of normal sleep during the night prior to the experiment. Each participant fitted to these criteria by self-report. Participants were not informed about the exact duration of the experiment, and they were also asked to hand over their watches after their arrival at the laboratory. Both verbal and written instructions were used to inform the participants about the task.

In order to get an indication of the pretask subjective fatigue level, participants were asked to indicate their agreement with the statement of “I feel tired” on a 5-point scale before the experiment. The scale consisted of five boxes and ran from agreement with the statement “yes, that is true” to disagreement “no, that is not true”. To measure the posttask subjective fatigue, this question was repeated right after the task ended. In addition to the subjective fatigue measurement, participants’ task-related motivation was also monitored before the experiment. Again on a 5-point scale, they had to indicate their agreement with the statement of “I will try to do my best on the forthcoming trials”. After the subjective measurements, the participants were given at least 30 practice trials. Reaction times and participants’ responses were recorded.

On each trial, before the stimulus appeared, a fixation cross was presented (700 ms) centred on the screen. Then, the stimulus appeared and remained on the screen with an SOA randomly varied between 150 and 250 ms. A mask (a number of lines with random orientation) was briefly presented (10 ms) after each stimulus to obliterate afterimages. The effect of potential afterimages was needed to be minimised because of the luminance contrast variation in our stimuli. After response or when 2500 ms had elapsed, participants were given a feedback about the correctness of their responses. The word of “correct”, “wrong”, or “no response” (in the case of no keypress) was displayed for 500 ms at the centre of the screen. The appearance of feedback was always accompanied by an auditory signal. Intertrial interval was also varied randomly between 500 and 700 ms. Figure 2 schematises a typical sequence of displays in a trial. The participants were instructed to determine the
target letter (x or z) by pressing the appropriate button on a keyboard. They were also instructed to ignore the flanker elements and to perform the task as quickly and accurately as possible.

Data analysis

In order to investigate the effect of ToT, the data were divided into three time intervals of 50 min each. Reaction time (RT) and accuracy data were analysed. The analysis of RTs was restricted to correct responses. Data were subjected to repeated measures of ANOVA. Initially we used a four factorial design that, as independent variables, included ToT interval (0–50 minutes, 50–100 minutes, 100–150 minutes), perceptual load (low, medium, high), congruency (congruent, incongruent, neutral), and also saliency (low, medium, high) because we had to check whether this latter variable interfered with the fatigue manipulation. Bonferroni adjustments were always performed for follow-up analysis of the significant main effects and interactions: The \( p \)-values were multiplied by the number of analyses to correct for the multiple comparisons. A corrected \( p \)-value of < .05 was considered statistically significant. Participants’ indication of their actual fatigue level before and after the task was also analysed.

RESULTS

Subjective fatigue ratings

First, we found that task-specific motivation before the task was high as the absolute mean score on the motivation question was \( M = 4.85 \) (\( SD = .45 \)) on a 5-point scale.

Second, we checked whether our manipulation had the intended effect on the participants’ subjective states. All participants reported significantly lower fatigue at the start of the task (pretask fatigue) than after the task (posttask fatigue). \( F(1, 26) = 109.16, p < .001, M_{\text{pretask}} = 2.11, M_{\text{posttask}} = 4.03, \eta^2_p = .8 \). So, in terms of subjective feelings, the ToT manipulation successfully induced mental fatigue.

Performance measures

General effects. Participants performed 2222 trials on average (\( SD = 78.92 \)) during the experimental session (2.5 hours). Reaction times on correct responses as well as accuracy data were subjected to repeated measures of ANOVAs (see Data Analysis).

Our main prediction involved the three way interaction between ToT, perceptual load, and congruency as predicted by the perceptual load theory in combination with previous research on the attentional effects of fatigue. However, in order to provide a general picture of how performance was affected by the different manipulations, we will first present the main effects and several second-order interactions. This will show that, overall, the manipulations of fatigue, perceptual load, and distractors had their intended effects.

First, each of the main effects reached significance both for accuracy and RTs, Specifically, accuracy and RTs were modulated by ToT: accuracy, \( F(2, 25) = 16.67, p < .001, \eta^2_p = .57 \); RTs, \( F(2, 25) = 9.08, p < .001, \eta^2_p = .42 \). Adjusted post hoc analyses revealed that participants performed relatively slowly with low accuracy in the first interval, followed by improved performance in the second interval (first vs. second interval), which indicates some learning effects: accuracy, \( t(26) = −5.29, p < .001 \); RTs, \( ns \). Finally performance declined again in the third interval indicating fatigue (second vs. third interval): accuracy, \( t(26) = 3.59, p < .01 \); RTs, \( t(26) = −4.18, p < .01 \). As both accuracy and RT seem to become worse in the last block, there was no sign of a speed–accuracy tradeoff.

The other main effects were also significant: perceptual load: accuracy, \( F(2, 25) = 97.81, p < .001 \); RTs, \( F(2, 25) = 103.39, p < .001 \); target
saliency: accuracy, $F(2, 25) = 8.86, p < .01$. RTs, $F(2, 25) = 11.17, p < .01$; congruency: accuracy, $F(2, 25) = 59.25, p < .001$; RTs, $F(2, 25) = 27.24, p < .001$. In sum, participants responded slower and less accurately with increasing perceptual load, at the presence of incongruent distractors, and decreasing target saliency.

In accordance with the perceptual load theory as described by Lavie (1995), we found a significant Perceptual load × Congruency interaction indicating that the effects of distractors depended on the level of perceptual load: accuracy, $F(4, 23) = 3.58, p < .05$; RTs, $F(4, 23) = 11.73, p < .001$.

For accuracy, the main source of this interaction was that for medium and high perceptual load conditions the congruent distractors had no facilitation effect on performance: medium load, $t(26) = -2.32, ns$; high load, $t(26) = -0.06, ns$. Facilitation here refers to findings in which congruent trials display an advantage, either in accuracy or RT, over neutral trials. In contrast to the medium and high load condition, we did find a facilitation effect for the low load conditions, $t(26) = -2.58, p < .05$.

For RTs, effects of the interaction between perceptual load and congruency did not become manifest in facilitation effects but instead revealed itself through distraction effects. That is, distraction here refers to cases in which incongruent trials lead to decreased performance compared to neutral trials. As the post hoc analyses of the Perceptual load × Congruency interaction revealed, participants performed slower on incongruent trials than on neutral trials for low and medium load conditions but not for the high load condition: low load, $t(26) = 7.09, p < .001$; medium load, $t(26) = 6.22, p < .001$; high load, $t(26) = 2.24, ns$.

**Interactions with time-on-task.** We found a significant ToT × Target saliency interaction for RTs, $F(4, 23) = 2.9, p = .04$, $\eta_p^2 = .33$. As the source of this interaction, the adjusted post hoc analyses revealed a significant increase in RT between the second and third ToT interval for each saliency condition with the largest effect size for the low saliency condition: high saliency, $t(26) = -3.65, p < .05, d = 0.7$; medium saliency, $t(26) = 3.1, p < .05, d = 0.61$; low saliency, $t(26) = 4.92, p < .01, d = 0.95$. In addition, in the last interval only, significantly slower RTs were found for the low target saliency condition compared to the medium, $t(26) = 4.28, p < .01, d = 0.82$, and high, $t(26) = 3.84, p < .05, d = 0.73$, target saliency conditions. These findings indicate that after a long duration of performance, participants had an increased difficulty in identifying low saliency targets. More importantly, however, was that target saliency did not show any interaction with perceptual load and congruency as a function of ToT: Congruency × Saliency: $F(4, 23) = 1.27, ns$; Perceptual load × Saliency × Congruency, $F(8, 19) = 0.94, ns$; ToT × Perceptual load × Saliency × Congruency, $F(16, 11) = 0.95, ns$. This suggests that sensory fatigue processes did not play a role in distractor processing in the current study, and so, they did not account for the interactions found between ToT and Congruency presented later.

In addition, the two-way interaction of ToT × Perceptual load was significant for accuracy and marginally significant for RTs: accuracy, $F(4, 23) = 11.72, p < .001$, $\eta_p^2 = .67$; RTs, $F(4, 23) = 2.32, p = .08$, $\eta_p^2 = .28$. For accuracy, the post hoc analysis suggested that participants had an increased difficulty in accurately performing the task during the third interval for high and medium load conditions but not for low load condition: second vs. third interval for low load, $t(26) = 0.81, ns$; second vs. third interval for medium load, $t(26) = 2.79, p < .05, d = 0.66$; second vs. third interval for high load, $t(26) = 4.56, p < .01, d = 0.75$ (see Figure 3). After having established these findings we can now continue to test our main prediction. That is, we found a significant three-way interaction of ToT × Perceptual load × Congruency for RTs. As this interaction is at the heart of our study it is summarised in separate paragraphs later. Before doing so, however, we first have to report that none of the other interactions in the present design reached significance, neither for accuracy nor for RTs. Table 1 shows descriptive statistics for the perceptual load and congruency conditions in each ToT interval.

**Time-on-task effect on the interaction of perceptual load and congruency.** Our main prediction was that ToT would increases congruency effects at low perceptual load, but decreases such effects at high perceptual load conditions. In line with this prediction, the three-way interaction of ToT × Perceptual load × Congruency was significant for RTs but not for accuracy: RT, $F(8, 19) = -2.88, p < .05, \eta_p^2 = .55$; accuracy, $F(8, 19) = 1.15, ns$. To elucidate the source of the complex interaction for RTs, subsequent ANOVAs were...
conducted. These ANOVAs yielded the following interpretation of the interaction.

Congruency was affected by ToT for low and high perceptual loads, but not for medium perceptual load: low load, $F(4, 23) = 2.66, p = .06, \eta_p^2 = .3$; medium load, $F(4, 23) = 0.74, ns$; high load, $F(4, 23) = 3.3, p < .05, \eta_p^2 = .36$. In addition, the Congruency $\times$ Load interaction, that is typical for the perceptual-load theory, was found to be significant in each ToT interval. Yet, these effects seem to be somewhat stronger in the first and the last interval: first interval, $F(4, 23) = 11.58, p < .001, \eta_p^2 = .66$; second interval, $F(4, 23) = 6.57, p < .05, \eta_p^2 = .42$; last interval, $F(4, 23) = 7.03, p < .01, \eta_p^2 = .53$.

Figure 4 depicts a clear difference in distraction (incongruent vs. neutral trials) between the low and high perceptual load conditions in the last ToT interval: Whereas for low load, the distraction effect increased from the second to the third interval, this distraction effect seems to show a clear decrease for high load. In the line with this, adjusted post hoc analyses of the three-way interaction showed that the distraction effect for high perceptual load (i.e., incongruent vs. neutral trials) increased in the second interval relative to the first interval and decreased in the third interval relative to the second interval: distraction in the first interval, $t(26) = 1.36, ns$, distraction in the second interval, $t(26) = 3.08, p < .05, d = 0.59$; distraction in the third interval, $t(26) = .09, ns$ (see Figure 4) indicating that fatigue might weaken the effect of distraction effects under high perceptual load. The post hoc analyses revealed significant increase in RTs both for incongruent and neutral trials between the second and the third interval: second vs. third interval for the incongruent condition, $t(26) = -2.63, p < .05, d = 0.5$; second vs. third interval for the neutral condition, $t(26) = -6.01, p < .001, d = 1.1$.

For low perceptual load, although, the RT for the incongruent as well as the neutral trials increased from the second to the third interval—probably due to a general slowing caused by fatigue—the effect sizes of these increments were higher for the incongruent trials compared to the neutral trials: second vs. third interval for incongruent condition, $t(26) = -4.29, p < .001, d = 0.82$; second vs. third interval for neutral condition, $t(26) = -2.89, p < .05, d = 0.55$. In addition, the difference between the incongruent and neutral trials, that is the distraction effect, seems to be higher in the third ToT interval relative to the second interval, $t(26) = 4.63, p < .001, d = 0.89$.
distraction in the third interval, \( t(26) = 6.24, p < .001, d = 1.2 \). In general, these results might suggest that when participants became fatigued, they suffered more from distraction but only when the number of letters in the trials (i.e., the perceptual load) was low.

In the analyses, the specific fatigue-related changes in distractor processing seemed to be somewhat overshadowed by the many significant effects that are due to a general slowing effect of fatigue. Therefore, in order to clearly describe the distractor-specific effects we also calculated the RT difference between the incongruent and neutral trials for the high and for the low load conditions. This RT difference is a widely acknowledged index of distraction effect (e.g., Lavie & de Fockert, 2003; Lavie & Robertson, 2001; Wilson, MacLeod, & Muroi, 2008). Now, we were interested in changes from the second to the third interval only, therefore an ANOVA with two factors (perceptual load: low and high; ToT intervals: 50–100 minutes, 100–150 minutes) was performed on the difference scores. We found a significant main effect of perceptual load, \( F(2, 25) = 11.6, p < .01, \eta^2_p = .31 \), a non-significant main effect of ToT, \( F(2, 25) = 0.74, ns \), as well as a significant interaction of ToT x Perceptual load, \( F(4, 23) = 17.59, p < .001, \eta^2_p = .44 \). Separate ANOVAs and post hoc pairwise comparisons indicated that the source of this interaction is a significant increase in distraction effect for the low load condition, \( t(26) = -3.06, p < .01, d = .58 \), and a significant decrease in distraction effect for the high load condition, \( F(2, 25) = 5.37, p < .05, \eta^2_p = .2 \); second vs. third interval, \( t(26) = 2.31, p < .05, d = .44 \). That is, these results confirmed the findings of the analysis reported in the previous section and strengthen our conclusion that distraction under fatigue depends on the perceptual load.

Finally, we have to report that no differential effects of ToT and perceptual load were found for the congruent-neutral and congruent-incongruent differences.

Notably, the pattern of results for accuracy was generally in line with RTs in respect of the above findings (see Table 1). Although the Perceptual load x Congruency x ToT interaction was non-significant for accuracy, weak tendencies in the same direction were observable: The distraction effect from the second to the third interval decreased for the high load condition, increased for the medium load condition, and showed no
Figure 4. Reaction times for time-on-task intervals in each congruency condition on low, medium, and high perceptual load. Error bars represent the standard errors of mean.
change for the low load condition. Due to the nonsignificance we cannot make strong interferences from these results. Nevertheless, they are relevant because they suggest that there was no speed-accuracy tradeoff in the effects. Specifically, even in the three-way interaction we observed significant increases in RT due to ToT that were not accompanied with improved performance. So, there were no signs of speed-accuracy tradeoffs.

**DISCUSSION**

There is ample evidence that fatigue due to sustained mental effort has multiple effects on attentive mechanisms (Boksem et al., 2005; Sarer, Giovens, & Pruno, 2001; Summala & Mikkola, 1994; van der Linden et al., 2003; van der Linden, Massar, Schellekens, Ellenbroek, & Verkes, 2006). The main source of these effects seems to be a weakened top-down control on more automatic cognitive processing. Such an inefficiency of control and preparatory mechanisms usually results in a more stimulus driven and compromised cognitive processing (van der Linden et al., 2003). The most common behavioural manifestations of these effects are longer RTs, increased error rates, as well as the difficulty in ignoring distractors. Yet, as can be derived from the perceptual load theory that has been advanced by Lavie and co-workers (Lavie, 1995; Lavie & Cox, 1997; Lavie & de Fockert, 2003), distractor interference in a prolonged selective attention tasks might not only depend on attentional difficulties due to fatigue but also on the perceptual load. Here we examined effects of the perceptual load of targets on distractor interference with a ToT paradigm. The present findings lead to the following conclusions.

First, we found general effects of ToT on performance. More specifically, ToT was accompanied with longer RTs and decreased accuracy rates as participants went through the long duration of the task. The relationship between performance and ToT was, however, not just linear. During the first part of the experiment participants’ performance mainly improved. This likely reflects learning or automatisation of performance. Regarding this, Fine and Jacobs (2002) reviewed learning across a wide range of stimulus properties and task parameters and found that the presence of external noise (distractors) increased learning effects. This finding implicates that learning to suppress task-irrelevant stimuli is crucial in developing an optimal performance strategy in complex visual tasks. This idea was supported by psychophysical and neuroimaging evidence (Gál et al., 2009) showing that practice indeed weakens perceptual sensitivity for task-irrelevant distractors.

More important, however, is that we found the initial performance improvement was followed by a clear deterioration in performance over time. This finding indicates that after a certain amount of ToT, further learning or task optimisation decreased and was replaced by fatigue effects. Such pattern of results also confirms that our ToT manipulation did not only lead to subjective feelings of fatigue but also negatively affected performance.

The main prediction in the present study was that mental fatigue (i.e., ToT) increases distraction effects at very low perceptual load, but decreases distraction effects at higher perceptual load conditions. This hypothesis was supported by the finding of incongruent-neutral RT differences that we labelled distraction effect or distractor interference. This distraction effect showed a clear increase with increasing ToT for low perceptual load, but also showed a decrease for high perceptual load and did not show any change for medium load. These results suggest that fatigued participants have a declined ability to ignore the distractors at very low perceptual load. Yet, for high perceptual load, they seem to show an unchanged or even a decreasing interference of the task-irrelevant distractors. This finding contributes to fatigue research as it refines knowledge about the way cognitive processes are affected by mental fatigue. Previous studies had already indicated that fatigue is associated with attentional deficits and difficulties in ignoring irrelevant information (Boksem et al., 2005; Landsdown, 2001). However, the present study shows that the detrimental effects of fatigue on distractor processing depend on the perceptual load of the main task.

In discussing the results, it is necessary to also reflect on whether the learning effects that we found in the present study may have affected or caused some of the fatigue effects that we report. Regarding this, we first have to note that without extensive pretraining, some level of learning or task familiarity always occurs in studies that deploy a ToT manipulation (see, e.g., Boksem et al., 2005; Lorist et al., 2000, 2005). However, such learning effects almost always work in the
opposite direction of fatigue effects. So, if any detrimental effects of ToT are found they may be inferred that from a certain point in time the effects of fatigue have become stronger than any learning effects that occur. In the present study, learning effects on the interaction between perceptual load and distractors were also in the opposite direction to the fatigue effects. That is, in the second interval, it appeared that target detection was improved because accuracy and RTs were improved. This was particularly the case in the high perceptual load condition and not in the low perceptual load condition. This effect seems obvious as in the low perceptual load condition the task was so easy that learning effects could hardly have any effect. Hence, learning effects influenced the Perceptual load × Distractor interaction. The improved and presumably more automatic target detection would lead to more spare attentional capacity, which, according to the perceptual load theory, would lead to increased distractor interference. The results in the second interval of the high load condition indicated exactly that pattern. In contrast, in the third interval, fatigue caused compromised accuracy and RTs which suggest lowered attentional capacity. Consequently, distractor interference was lowered in the high perceptual load condition. Thus, also for the specific variables in the present study, any effects of learning could be expected to be in a direction opposite to our main expectation. Therefore, as we did find the expected ToT effects, we considered it unlikely to be the results of learning.

It is relevant to note that the effects of fatigue that we found seem to resemble the effects of distractor interference that are found in elderly people and in neuropsychological patients with frontal lobe deficits (Lavie & Robertson, 2001; Maylor & Lavie, 1998). The resemblance between cognitive effects of fatigue and cognitive effects in elderly and neuropsychological patients has been noted before in other studies. For example, van der Linden and Eling (2006) found fatigue-related attentional effects in a global/local task that also showed a similar pattern as found in elderly and frontal lobe patients. It is known that in elderly people as well as in certain populations of neuropsychological patients (e.g., frontal lobe patients), cognitive control is particularly compromised. Thus, the fact that the present fatigue effects are similar to those in elderly people and frontal lobe patients is in line with the notion that fatigue mainly poses problems with the voluntary regulation of cognitive processes (Lorist et al., 2000; van der Linden et al., 2003).

Although the present study mainly focused on behavioural effects, it may be useful to provide some ideas about what underlying biopsychological mechanisms may be involved in the results we found. Regarding this, the literature provides some interesting cues because it has been suggested that dopamine plays a central role in the occurrence of fatigue-related cognitive effects (Boksem et al., 2005; Boksem & Tops, 2008; Tops & Boksem, 2010; van der Linden et al., 2006). Under fatigue, dopamine levels may be altered, which has a pronounced effect of the functioning of the frontal lobes. The reduced dopamine levels may be the results of declining rewards of engaging in the task at hand with increasing ToT. This dopamine hypothesis of fatigue may also explain why the effects of fatigue resemble the cognitive effects found in elderly. More specifically, cognitive deficits in elderly have also been associated with decrease dopamine levels (Bäckman et al., 2000). In addition, dopamine has been found as an important neurochemical basis of top-down attentional control in several studies. For example, attentional control has been found to be dependent on dopamine level and dopamine genotype in healthy participants (Scholes et al., 2007) and also in groups of patients with Parkinson’s disease (Williams-Gray, Hampshire, Barker, & Owen, 2008), schizophrenia (Sarter, 1994), and ADHD (Lou et al., 2004). Future studies might want to investigate whether the specific cognitive effects that we found in the present study are indeed linked to changes in dopamine levels under fatigue. One way to examine this is by testing whether the negative effects of ToT on the perceptual task diminished when baseline dopamine level is artificially raised, for example by applying dopamine receptor agonists or inhibiting reuptake.

In general, the pattern of findings of the present study increases insight into the effects of mental fatigue by disentangling several basic perceptual and attentional problems. Following the present results, additional questions may arise of which some reflect fundamental issues in fatigue research, such as whether attentional capacity is really lowered under fatigue or whether fatigued participants no longer focus on the task. To the best of our knowledge there is no study (or set of studies) that have answered the fundamental question of focused attention under fatigue yet. So, additional studies on this
topic might be useful. Nevertheless, this study might provide an interesting building block in research on fatigue as it is the first to show in a theory-driven way that under specific circumstances fatigue may also lead to reduced distractor interference. In everyday life, mental fatigue can have a pronounced impact on performance and safety. For example, in many major incidents and accidents in industry and transportation fatigue has been identified as one of the major contributing factors. Therefore, knowing how fatigue may affect cognitive performance may be useful for taking countermeasures and preventing fatigue-related errors.

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