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EFFECT OF MENTAL FATIGUE ON SPEED–ACCURACY TRADE-OFF

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Abstract—The aim of this study was to investigate the effects of mental fatigue on the duration of actual and imagined goal-directed arm movements involving speed–accuracy trade-off. Ten participants performed actual and imagined point-to-point arm movements as accurately and as fast as possible, before and after a 90-min sustained cognitive task inducing mental fatigue, and before and after viewing a neutral control task (documentary movie) that did not induce mental fatigue. Target width and center-to-center target distance were varied, resulting in five different indexes of difficulty. Prior to mental fatigue, actual and imagined movement duration increased with the difficulty of the task, as predicted by Fitts' law. Mental fatigue task induced a 4.1 ± 0.7% increase in actual movement duration and a 9.6 ± 1.1% increase in imagined movement duration, independently of the index of difficulty. The trial-by-trial evolution of actual and imagined movement duration remained stable with mental fatigue. The control task did not induce any change in actual and imagined movement duration. The results suggested that movement was slowed in the presence of mental fatigue, maybe due to proactive changes occurring during the preparatory state of the movement, to preserve task success.

Key words: Fitts' law, cognitive task, physical performance, motor planning, arm movement, pointing task.

INTRODUCTION

Mental fatigue refers to the subjective feeling of ''tiredness'' and ''lack of energy'' that people may experience after or during prolonged periods of cognitive activity (Boksem and Tops, 2008). While it is now well established that mental fatigue impairs cognitive performances such as attention or planning (van der Linden et al., 2003a; Boksem et al., 2005; Cook et al., 2007), its effects on motor performances seem to depend on the type of physical activity. For instance, previous studies showed that endurance performance was reduced when subjects were mentally fatigued (Marcora et al., 2009; Pageaux et al., 2013, 2014; Graham et al., 2014). Mental fatigue did not induce any change in cardiorespiratory or neuromuscular parameters, but increased the subjective perception of effort, resulting in a reduced time to task failure (Marcora et al., 2009; Pageaux et al., 2013). In contrast, mental fatigue did not affect maximal force production capacity (Bray et al., 2008; Pageaux et al., 2013; Rozand et al., 2014a,b). Moreover, it has been shown that mental fatigue was not linked to central fatigue (i.e., the failure to maximally activate the muscles; Gandevia, 2001) suggesting that different brain areas are involved during mental exertion and central fatigue. Overall, mental fatigue has been well investigated in physical demanding tasks. However, daily activities involve fine motor skills to a greater extent. For example, grasping a cup of tea or tapping on a keyboard require a high level of cognitive process (Fischer, 1980). It is of general interest to assess whether mental fatigue influences the performance in fine motor skill tasks, as those combining precision and speed, involving both cognitive and physical processes.

The speed–accuracy trade-off is a remarkable illustration of the constraints applied to goal-directed arm movements. In this motor paradigm, an increase in movement speed induces a decrease in spatial accuracy and, conversely, an increase in spatial accuracy induces a decrease in movement speed. Therefore, when individuals have to reach a target as fast and as accurately as possible, they have to choose a compromise between speed and accuracy (Woodworth, 1899). The speed–accuracy trade-off has been mathematically described by Fitts' law, which predicts that movement time equals to: $a + b \log_2(2D/W)$, where a and b are empirical constants and $\log_2(2D/W)$ represents the index of difficulty that increases when the inter-target distance (D) increases and the target width (W) decreases (Fitts, 1954; Fitts and Peterson, 1964). Consequently, movement time increases linearly with the index of difficulty. Fitts' law has been validated and verified for a variety of movements and experimental conditions, e.g., movements in two or three dimensions, and imagined movements (Decety and Michel, 1989; Plamondon and Alimi, 1997; Bakker et al., 2007; Personnier et al., 2010). Kourtis et al. (2012) observed that the amplitude of the event-related potentials over parieto-occipital areas was correlated linearly with the index of difficulty, suggesting that neural activity highlights

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Abbreviations: ACC, anterior cingulate cortex; BB, biceps brachii; ID, index of difficulty; MEPs, motor-evoked potentials; MIQ-R, Movement Imagery Questionnaire; RMS, root mean square; RMT, resting motor threshold; TB, triceps brahchii; TMS, transcranial magnetic stimulation; VAS, visual analog scale.

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in part the integration of the task's spatiotemporal constraints in the central nervous system (CNS).

Previous studies suggested that the speed–accuracy trade-off is altered in specific cases, e.g., the patients with Friedreich ataxia that alter motor coordination but not cognitive functions (Corben et al., 2011) or the elderly (Sleimen-Malkoun et al., 2013). In these populations, movement duration was slowed compared to healthy young subjects, especially for higher difficulties. In the presence of muscle fatigue in healthy subjects, the movement duration was greater independently of the index of difficulty, suggesting an adapted strategy of the CNS to preserve movement precision and task success (Missenard et al., 2009).

It has been shown that the preparation processes involved in the planning for future actions, which can be adapted with muscle fatigue, can be negatively impacted by mental fatigue (Lorist et al., 2000). For example, reaction time increased and performance in a switch task decreased after two hours of a high demanding cognitive task (Lorist et al., 2000). Furthermore, event-related potentials indicated that preparation processes and maintenance of a prepared state were affected by mental fatigue. According to these findings, one could expect that mental fatigue would also lengthen movement duration.

In this context, the aim of the present study was determine whether mental fatigue would to increase the duration of goal-directed movements involving speed–accuracy trade-off. To test this hypothesis, we used both actual and imagined movements. Imagined movement shares common neural and cognitive processes with its actual counterpart (Jeannerod, 2001). The use of motor imagery is a classical paradigm to study motor representations or motor planning process (Jeannerod, 1994, 2001), by avoiding the trial-by-trial influence of sensory feedback occurring during actual movement production.

EXPERIMENTAL METHODS

Participants

Ten healthy male subjects (age = 23.6 ± 2.4 years; weight = 73.9 ± 12.2 kg; height = 176.3 ± 7.9 cm) volunteered to participate in this study. All participants had normal or corrected-to-normal vision, and none of them had history of neurological disorders. The participants gave written consents and the experimental procedures were conducted according to the Declaration of Helsinki, and were approved by the regional ethics committee of Burgundy. All subjects were given instructions describing the experimental protocol and procedures, but were naive to its aims and hypotheses.

Experimental design

Our study included a familiarization session, a main experiment, and two control experiments (see Fig. 1).

Familiarization session. First, participants completed the revised version of the Movement Imagery Questionnaire (MIQ-R, see *Imagery ability and psychological state evaluations* section for more details). Then, they performed 30 actual pointing movements to targets of varied widths (0.5, 1.5 and 2.5 cm), and imagined doing the same movement with a kinesthetic strategy (i.e., feel the contractions of the movement normally generated by the actual movement) to get used to the task. Finally, they were habituated to transcranial magnetic stimulation (TMS) at rest and while imagining the movements. TMS is a safe and non-invasive technique used to assess the corticospinal excitability (see *Transcranial magnetic stimulation* section).

Main experiment. Here, we tested the effects of mental fatigue on the duration of actual and imagined arm pointing movements. Specifically, participants performed 35 imagined pointing trials followed by 30 actual pointing trials before (pre-test) and after (post-test) a mentally fatiguing task lasting 90 min (see *Mental fatigue* section).

Control Experiment 1. This control experiment was designed to control whether a non-demanding cognitive task could induce any effect on the duration of actual and imagined arm pointing movements. Participants performed 35 imagined pointing trials followed by 30 actual pointing trials before (pre-test) and after (post-test) watching at a non-emotional documentary (''Home'', Y. Arthus-Bertrand, 2009) with the same duration as for the mental fatigue task, i.e., 90 min.

Control Experiment 2. In this experiment, we controlled whether the order of actual and imagined tests could influence the duration of actual and imagined pointing movements. The Control Experiment 2 was similar to the Main Experiment, with the difference that participants carried out first actual and then imagined movements in the pre and post-tests. Six out of the 10 participants (age = 24.5 ± 1.9 years; weight = 77.7 ± 14.5 kg; height = 176.3 ± 9.3 cm) took part in this experiment.

To avoid any time-of-day effect on movement duration, the three experiments were performed during a same half-day for each participant (Gueugneau and Papaxanthis, 2010). The familiarization session was performed 24 h before the Main Experiment, and a delay of one week was respected between each experiment. Participants did not have any feedback on their results until the end of the three experiments. Despite all these precautions, expectancy effects remain possible for the participants, who could implicitly influence their performance.

Arm-pointing tasks

Actual movements. From a sitting position, participants had to point between two targets as accurately and as fast as possible with a pencil held in their dominant hand. The targets were black squares designed on a graphic tablet (Intuos4 XL, Wacom, Krefeld, Germany) allowing recording movement duration and final precision. The targets were presented in a frontal axis, with the nearest target aligned with the

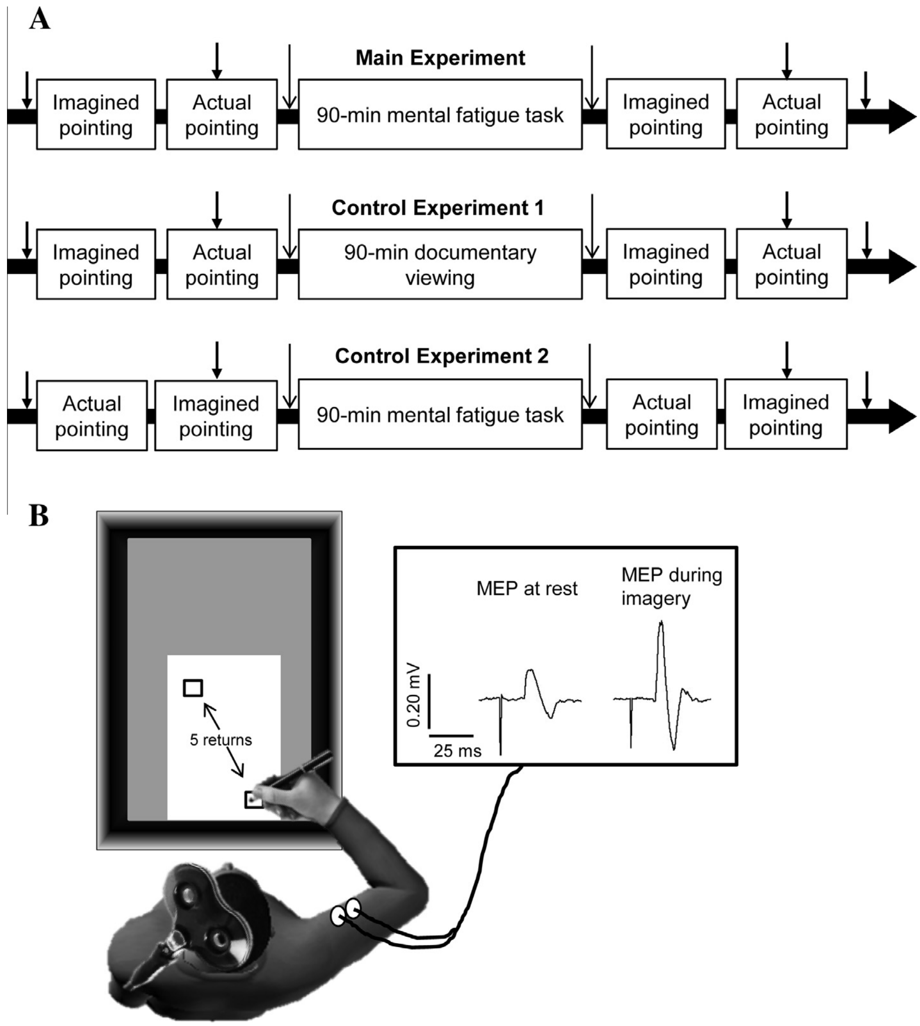

Fig. 1. Experimental protocol. Overview of the protocol for the Main Experiment, Control Experiment 1 and Control Experiment 2 (panel A), and of a schematic representation of the participants' position while performing actual and imagined trials (panel B). Broad arrows represent transcranial magnetic stimulation. Fine arrows represent Brunel Mood Scale and visual analog scale. The MEP recordings show typical traces of a subject at rest and when imagining, during the pre-test of the main experiment.

shoulder and the farther target shifted by 45° on the left. The distance between the participants' trunk and the graphic tablet was kept constant for all the tests throughout the sessions (15.4 ± 2.2 cm). Three widths (W = 0.5, 1.5 and 2.5 cm) and two center-to-center target distances (D = 15 and 25 cm) were used to manipulate the index of difficulty (ID), which was calculated by the formula: ID = $\log_2(2D/W)$. We used the combination of width and distance to create five different IDs: 3.6 (W = 2.5 cm × D = 15 cm), 4.3 (1.5 cm × 15 cm), 5.1 (1.5 cm × 25 cm), 5.9 (0.5 cm × 15 cm), and 6.6 (0.5 cm × 25 cm). One trial consisted in five cyclical pointing movements as accurately and as fast as possible between two targets of the same size, namely 10 arm movements. Participants always started from and finished to the nearest target. They carried out 30 trials (6 trials × 5 IDs) in a random order. A home-made software started the acquisition at the first pointing and stopped it at the last pointing, calculating automatically the total and the intermediate times at each pointing. When two consecutive targets were missed, the software stopped the acquisition and the trial was canceled and immediately repeated. The phase of actual pointing trials lasted approximately 8 min.

Imagined movements. Participants adopted the same initial posture as during actual movements, with their arm totally relaxed on the table. They imagined performing the five cyclical pointing movements as accurately and as fast as possible between the two targets. They were particularly instructed to feel pointing between the targets (kinesthetic imagery) as they would actually do (see Demougeot and Papaxanthis, 2011). A kinesthetic strategy was shown to maximally modulate corticospinal excitability compared to visual imagery (Stinear et al., 2006). Participants were free to move their eyes during the imagined movements, as it was previously demonstrated that eye movements did not influence the temporal equivalence between imagined and actual movements (Gueugneau et al., 2008). At the beginning and at the end of each imagined trial, they pressed on the graphic tablet (nearest target) with the pen to record the mental movement duration. Participants carried out 35 pointing trials (7 trials × 5 IDs). TMS was triggered for one trial per ID, to assess corticospinal excitability during the mental imagination of the movement. Motor responses were compared to rest to ensure that the motor system was activated while imagining (Kasai et al., 1997; Kiers et al., 1997). The trials during which the TMS pulse was delivered were not considered for analysis of imagined movement duration. Therefore, 30 pointing trials were kept for analysis. The imagery part lasted approximately 8 min.

Mental fatigue task

Mental fatigue was induced in the Main Experiment and the Control Experiment 2 by a modified incongruent version of the Stroop task (Stroop, 1992; Wallace and Baumeister, 2002) performed during 90 min. The modified Stroop task consisted in words of color (green, blue, red, yellow) presented in a mismatched color on the screen (e.g., the word ''green'' in blue). Participants had to press one of four colored buttons on the keyboard (green, blue, red, yellow), the correct response being the button corresponding to the color on the screen (e.g., for the word ''green'' in blue, they had to press the blue button). However, for words appearing in red, participants had to ignore the previous instructions and press the button corresponding to the written word (e.g., for the word ''yellow'' in red, they had to press the yellow button). Participants had to respond as accurately and as fast as possible. Twenty practice trials were done before the beginning of the mental fatigue task to ensure that they correctly understood the instructions. After each answer, response speed and accuracy, and percentage of correct responses from the beginning of the mental fatigue task were presented on the screen during 1 s. The mental fatigue task was implemented with the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, USA).

Electrical recordings

EMG signals of the biceps brachii (BB) and triceps brachhii (TB) muscles of the right arm were recorded with pairs of bipolar silver chloride circular surface electrodes (recording diameter of 10 mm, Controle Graphique Medical, Brie-Comte-Robert, France) positioned lengthwise over the middle of the muscle belly with an interelectrode (center to center) distance of 20 mm. The reference electrode was placed on the lateral humerus epicondyle of the left arm. The skin was shaved and cleaned to obtain low resistance between the two electrodes (< 5 kΩ). EMG signals were acquired with a MP150 (Biopac Systems Inc, Goleta, CA, USA; sampling frequency: 2 kHz, gain: 1000), and data were then analyzed using a software commercially available (Acqnowledge, Biopac Systems Inc., Goleta, CA, USA).

TMS

TMS pulses were delivered via a figure-of-eight-shaped coil (9-mm external wing diameter) attached to Magstim 200 stimulator (Magstim Co., Whitland, Wales, UK). The center of the junction of the coil was positioned over the left primary motor cortex to elicit the greatest motor-evoked potentials (MEPs) in the right BB muscle, and oriented to deliver anterior-posterior directed current into the brain. The coil was held tangentially to the scalp, with the handle pointing backward and 45° away from the midline of the skull. The optimal position, corresponding to the stimulus site providing the greatest amplitude for the BB evoked response, was marked and kept throughout the experiment. Resting motor threshold (RMT) of the right BB was determined as the intensity of stimulation eliciting a MEP of at least 0.05 mV in four of eight successive trials in the relaxed BB. The intensity of the stimulation was set to 120% of RMT (81.5 ± 11.5% output). The optimal position of the coil and the RMT were defined at the beginning of each experiment. Ten TMS pulses were delivered in pre-tests and post-tests, and five TMS pulses were delivered during the imagined pointing trials in pre-tests and post-tests.

Imagery ability and psychological state evaluations

Participants completed the revised version of the Movement Imagery Questionnaire (MIQ-R; Hall and Martin, 1997) during the familiarization session. Visual and kinesthetic imagery abilities are evaluated by this questionnaire. The MIQ-R consisted in four separate movement items (e.g., jumping, knee rising) actually performed then imagined (four visual, four kinesthetic). After each imagined movement, the subjects had to rate the vividness of their mental representation using a seven-point Likert scale (from 1 = ''very hard to see/feel'' to 7 = ''very easy to see/feel''). Mean MIQ-R score were 48.2 ± 3.5 (25.2 ± 1.9 for the visual modality, and 23.0 ± 1.7 for the kinesthetic modality). These results indicated that the participants were able to imagine the requested movement (Guillot et al., 2009).

The Brunel Mood Scale (BRUMS; Terry et al., 2003) was used to quantify current mood (''How do you feel right now?'') before and after the mental fatigue task and the documentary viewing. This questionnaire contains 24 items (e.g., ''do you feel angry, uncertain, miserable, tired, nervous, energetic'', etc.) divided into six respective subscales: anger, confusion, depression, fatigue, tension, and vigor. The items are answered on a 5-point scale (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, 4 = extremely), and each subscale, with four relevant items, can deliver a score between 0 and 16. Only scores for the Fatigue and Vigor subscales were considered in this study to define mental fatigue (Marcora et al., 2009).

A visual analog scale (VAS) was used by participants to estimate mental fatigue before and after the mental fatigue task and the documentary viewing. The VAS consisted in a line measuring 100 mm in length, with bipolar end anchors (0 mm = ''No mental fatigue''; 100 mm = ''Worst mental fatigue possible''). Participants were asked to place a mark along the line to indicate how they currently felt.

Data analysis

The root mean square (RMS) of the BB and TB EMG activity was analyzed at rest and during motor imagery.

The RMS was also calculated over 50-ms periods before the TMS pulses to ensure that MEPs were not contaminated by muscle activity.

The peak-to-peak amplitude of MEPs was calculated from EMG responses at rest and during motor imagery. MEP amplitude at rest was compared between pre-tests and post-tests to evaluate the effects of mental fatigue on corticospinal excitability. MEP amplitude was also compared between imagined pointing trials and rest condition to ensure that participants were actively engaged in the mental simulation of the movement.

For the actual pointing trials, the home-made software calculated the duration to reach each target. The duration of the 10 pointing movements was added to obtain the total duration of an actual pointing trial. The duration of the 6 actual pointing trials was averaged for each ID. For the imagined pointing trials, the home-made software calculated the duration between the first and the last pointing which were actually executed. The duration of imagined trials when TMS was triggered was not taken into account. The duration of the six imagined pointing trials without TMS pulse was average for each ID. The linear regression between movement duration and ID was calculated for each subject and then averaged.

To evaluate the change in movement duration between pre-test and post-test, we calculated the following ratio for actual and imagined movement duration and for each ID:

$$\frac{(\text{Movement duration in post test} - \text{movement duration in pre test})}{\text{movement duration in pre test}} \times 100$$

A positive value would indicate an increase in movement duration, whereas a negative value would indicate a decrease in movement duration at post-test.

Statistical analysis

Normal distribution (Shapiro-Wilk test, $p > 0.05$) and sphericity (Mauchly test, $p > 0.05$) for all variables were checked as appropriate.

The effects of mental fatigue (main Experiment and control Experiment 2) and the effects of the documentary viewing (Control Experiment 1) on movement duration were evaluated by means of two-way repeated measurements ANOVAs with *time* (pre-test and post-test) and *ID* (3.6, 4.3, 5.1, 5.9 and 6.6) as within-subject factors. This analysis was performed separately for each experiment and separately for the actual and the imagined movements.

To evaluate any change in the linear regression of movement duration and ID between pre-test and post-test, we compared the slope (*a*) and the intercept (*b*) by means of two-tailed paired *t*-tests for dependent samples. This analysis was performed separately for each experiment and separately for the actual and the imagined movement duration.

To test for any trial-by-trial modification in post-test movement duration, namely after the mental fatigue (main Experiment and control Experiment 2) and after the documentary viewing (Control Experiment 1), we carried out a one-way repeated measurements ANOVA analysis with *trials* (1–6) as within-subject factor. This analysis was performed separately for each experiment, separately for each ID, and separately for the actual and the imagined movement duration.

Comparison of rate of increase between actual and imagined movements was evaluated by two-way repeated measurements ANOVAs with *movement* (actual and imagined) and *ID* (3.6, 4.3, 5.1, 5.9 and 6.6) as within-subject factors. This analysis was performed for each experiment separately.

To test whether movement duration in the pre-test was similar between the Main Experiment and the Control Experiment 1, we performed two-way repeated measurements ANOVAs with *experiment* (Main Experiment and Control Experiment 1) and *ID* (3.6, 4.3, 5.1, 5.9 and 6.6) as within-subject factors. This analysis was performed for the actual and imagined movement duration separately.

Changes in MEP amplitude and in RMS EMG of BB and TB muscles were evaluated by two-way repeated measurement ANOVAs with *condition* (rest and motor imagery) and *time* (pre-test and post-test) as within-subject factors for the three experiments.

Results of BRUMS questionnaire, VAS, and number of canceled and repeated trials were compared in pre-test and post-test using two-tailed paired *t-test* for dependent samples. Partial eta squared was calculated for each ANOVA. Thresholds for small, moderate and large effects were set at 0.02, 0.13 and 0.26, respectively. Statistica software for Windows (Statsoft, version 6.1, Statistica, Tulsa, OK, USA) was used for statistical analyses. Data are presented as mean (± SE), and a significance level of $p < 0.05$ was accepted for all analyses.

RESULTS

Manipulation checks

The BRUMS questionnaire revealed that the sustained cognitive task significantly increased subjective feeling of mental fatigue in the Main Experiment (Fig. 2A, $t = 3.94$, $p < 0.01$) and the Control Experiment 2 (Fig. 2G, $t = 3.35$, $p < 0.01$). This increase in mental fatigue was associated with a decrease in the vigor score (Main Experiment: Fig. 2B, $t = 3.11$, $p < 0.01$; Control Experiment 2: Fig. 2H, $t = 3.61$, $p < 0.01$) and an increase in the VAS score (Main Experiment: Fig. 2C, $t = 6.24$, $p < 0.001$; Control Experiment 2: Fig. 2I, $t = 3.57$, $p < 0.001$). These results indicate that mental fatigue was successfully induced by the experimental manipulations. As expected, the documentary viewing did not induce any change in mental fatigue (Fig. 2D, $t = 1.40$, $p = 0.20$), vigor (Fig. 2E, $t = 1.18$, $p = 0.27$) and VAS score (Fig. 2F, $t = 1.37$, $p = 0.20$) in the Control Experiment 1.

Effects of mental fatigue on movement duration: Main Experiment

The aim of the Main Experiment was to test the effects of mental fatigue on the duration of actual and imagined arm pointing movements for different IDs.

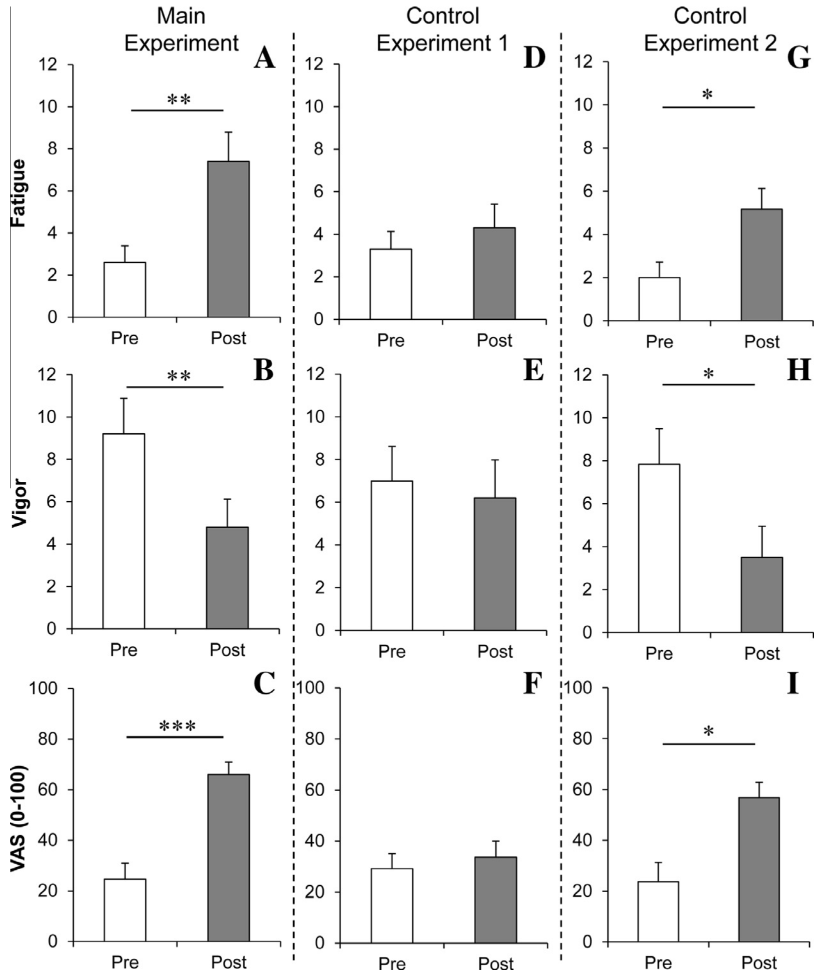

Fig. 2. Results for the BRUMS questionnaire and the Visual Analog Scale (VAS) score. Psychological state in pre (white) and post-test (gray) for the three experiments. Panel A, B, C: Fatigue, Vigor and VAS score for the Main Experiment. Panel D, E, F: Fatigue, Vigor and VAS score for the Control Experiment 1. Panel G, H, I: Fatigue, Vigor and VAS score for the Control Experiment 2. *, ** and ***: Significant difference between pre and post-tests ($p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively).

The mental fatigue task induced a 4.1 ± 0.7% increase in the duration of actual pointing trials (main effect of *time*, $F_{(1,9)} = 7.62$, $p < 0.05$, $\eta_p^2 = 0.46$) independently of the ID (Fig. 3A; no *time* × *ID* interaction, $F_{(4,36)} = 1.52$, $p = 0.22$, $\eta_p^2 = 0.14$). Movement duration progressively increased with ID, as predicted by Fitts' law (main effect of *ID*, $F_{(4,36)} = 196.71$, $p < 0.001$, $\eta_p^2 = 0.96$; post hoc analysis showed differences between all IDs, $p < 0.001$). The increase in movement duration after mental fatigue did not alter the slope of the relationship between ID and movement duration (pre-test: 0.97 ± 0.06 s.ID^{-1}, post-test: 1.02 ± 0.06 s.ID^{-1}; $t = 1.73$, $p = 0.12$); it only significantly increased the intercept (pre-test: 2.54 ± 0.30 s, post-test: 2.65 ± 0.28 s; $t = 2.38$, $p < 0.05$). The movement duration was not different for the six trials of each ID after fatigue, as the trial-by-trial analysis in post-test did not reveal any significant effect of movement duration (Fig. 4; no effect of *trial*, all $p > 0.40$; mean trial 1: 5.61 ± 0.27 s, mean trial 2: 5.43 ± 0.24 s, mean trial 3: 5.50 ± 0.27 s, mean trial 4: 5.51 ± 0.21 s, mean trial 5: 5.58 ± 0.25 s, mean trial 6: 5.60 ± 0.23 s).

Note that longer movement durations after the mental fatigue task were accompanied by a significant increase in the number of canceled and repeated trials, i.e., when two consecutive targets were missed (pre-tests: 1.6 ± 1.3 errors, post-tests: 2.7 ± 1.7 errors; $t = 2.70$, $p < 0.05$).

Imagined movement duration progressively increased with ID (main effect of *ID*, $F_{(4,36)} = 36.80$, $p < 0.001$, $\eta_p^2 = 0.80$; post hoc analysis showed differences between all IDs, $p < 0.05$), indicating that Fitts' law was preserved in motor imagery task. The duration of imagined pointing trials increased by 9.6 ± 1.1% after the mental fatigue task (main effect of *time*, $F_{(1,9)} = 14.31$, $p < 0.01$, $\eta_p^2 = 0.61$) independently of the ID (Fig. 3B; no *time* × *ID* interaction, $F_{(4,36)} = 1.86$, $p = 0.14$, $\eta_p^2 = 0.17$). As for actual movements, the slope of the relationship between ID and movement duration did not change after the mental fatigue task (pre-tests: $a = 0.62 ± 0.11$ s.ID^{-1}, post-test: 0.72 ± 0.09 s.ID^{-1}; $t = 1.62$, $p = 0.14$), only the intercept significantly increased (pre-test: 4.05 ± 0.42 s, post-test: 4.55 ± 0.43 s; $t = 2.32$, $p < 0.05$). Trial-by-trial evolution of imagined pointing duration after the

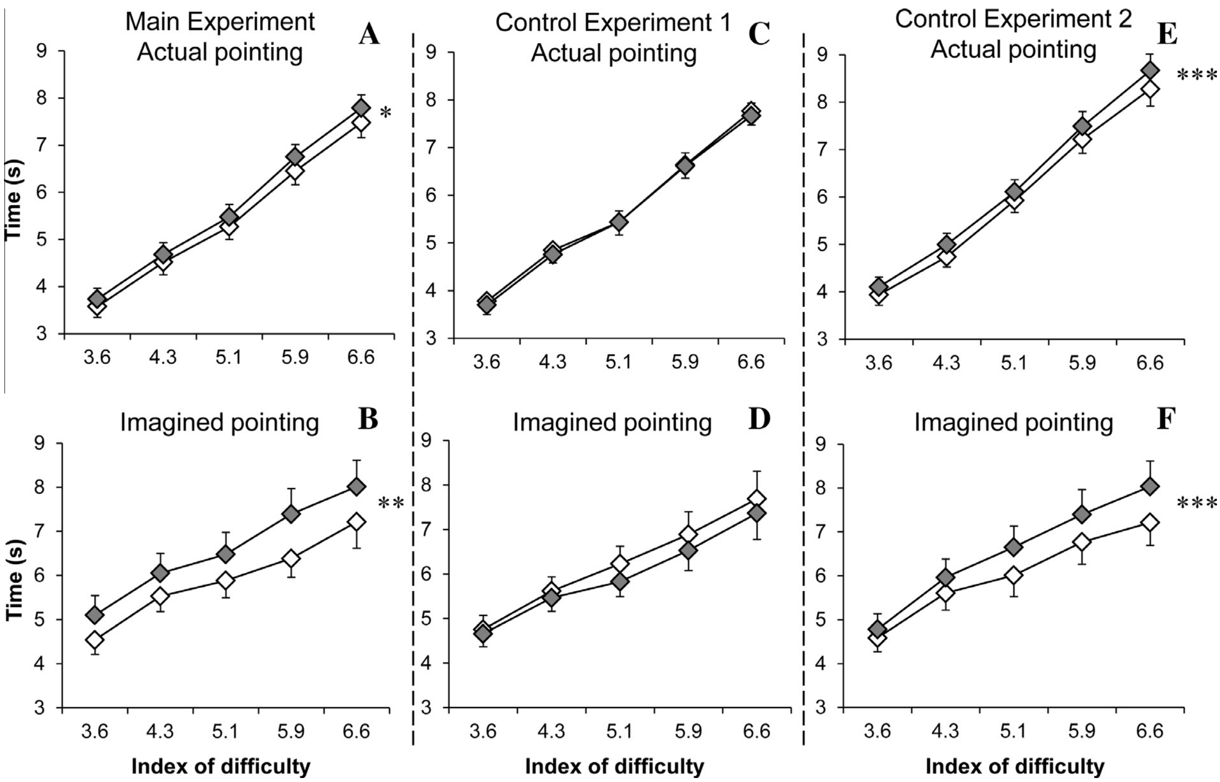

Fig. 3. Actual and imagined movement duration for the three experiments. Duration of actual pointing trials in pre (white) and post-test (gray) during the Main Experiment (A), the Control Experiment 1 (C) and the Control Experiment 2 (D), and duration of imagined pointing trials in pre (white) and post-test (gray) during the Main Experiment (B), the Control Experiment 1 (D) and the Control Experiment 2 (F). Duration increased with index of difficulty in all conditions (all, $p < 0{,}001$). *, ** and ***: Significant difference between pre and post-tests ($p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively).

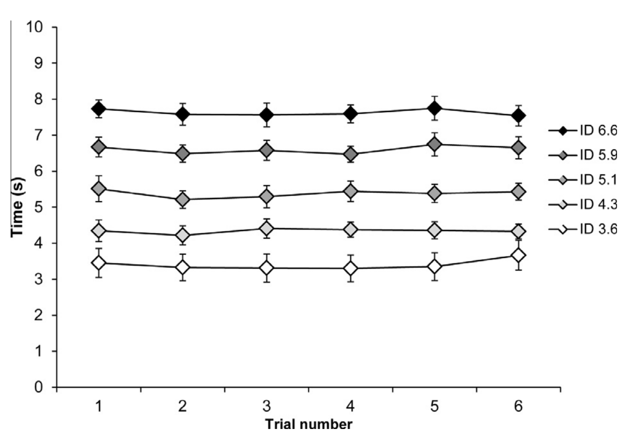

Fig. 4. Trial-by-trial evolution of movement duration in post-test. Duration of actual pointing trials for the five index of difficulty (3.6, 4.3, 5.1, 5.9 and 6.6) in post-test during the Main Experiment.

mental fatigue task was stable for each ID (no effect of *trial*, all $p > 0.15$).

The increase in the duration of imagined pointing movements (9.6 ± 1.1%) was greater compared to the duration of actual pointing movements (4.1 ± 0.7%; main effect of *condition,* $F_{(1,9)} = 6.88$, $p < 0.05$, $\eta^2_p = 0.43$), independently of the ID (no *condition* × *ID* interaction, $F_{(4,36)} = 0.51$, $p = 0.73$, $\eta^2_p = 0.05$).

Effects of documentary viewing on movement duration: Control Experiment 1

The aim of the Control Experiment 1 was to control that a non-demanding cognitive task did not induce any effect on the duration of actual and imagined arm pointing movements.

The duration of actual pointing trials did not change before and after the documentary viewing (Fig. 3C; no effect of *time*, $F_{(1,9)} = 0.52$, $p = 0.49$, $\eta^2_p = 0.05$). Movement duration of actual pointing trials progressively increased with ID (main effect of *ID*, $F_{(4,36)} = 173.79$, $p < 0.001$, $\eta^2_p = 0.95$; post hoc analysis showed differences between all IDs, $p < 0.01$). The slope of the relationship between ID and movement duration (pre-test: 0.98 ± 0.07 s.ID^{-1}, post-test: 0.98 ± 0.06 s.ID^{-1}; $t = 0.09$, $p = 0.93$) and the intercept (pre-test: 2.77 ± 0.34 s, post-test: 2.70 ± 0.25 s; $t = 0.43$, $p = 0.68$) remained constant after the documentary viewing. The number of canceled and repeated trials did not differ before and after the documentary viewing ($t = 0.80$, $p = 0.44$).

Similarly to actual pointing trials, the duration of imagined pointing trials was not different before and after the documentary viewing (Fig. 3D; no effect of *time*, $F_{(1,9)} = 4{,}56$, $p = 0.06$, $\eta^2_p = 0.34$). A trend to a decrease in imagined movement duration can be noticed, suggesting a possible learning effect with time, imagined movement duration becoming closer to actual movement duration. Movement duration of imagined pointing trials progressively increased with ID (main effect of *ID*, $F_{(4,36)} = 25.77$, $p < 0.001$, $\eta^2_p = 0.74$; post hoc analysis showed differences between all IDs, $p < 0.05$). Again, the slope of the relationship between ID and movement duration (pre-test: 0.71 ± 0.13 s.ID^{-1}, post-test: 0.65 ± 0.12 s.ID^{-1}; $t = 0.39$, $p = 0.39$) and the intercept (pre-test: 4.10 ± 0.33 s, post-test: 4.02 ± 0.30 s; $t = 0.37$, $p = 0.72$) did not change after the documentary viewing.

Note that the results of the Main Experiment and the Control Experiment 1 were not due to differences in the initial level in pre-test. Indeed, movement duration were not different for both actual (no effect of *experiment*, $F_{(1,9)} = 2.44$, $p = 0.15$, $\eta^2_p = 0.22$) and imagined movements (no effect of *experiment*, $F_{(1,9)} = 4.55$, $p = 0.06$, $\eta^2_p = 0.34$). No *session* × *ID* interaction was observed for both actual and imagined movements (Actual movements: $F_{(4,36)} = 0.36$, $p = 0.84$, $\eta^2_p = 0.04$; Imagined movements: $F_{(4,36)} = 1.54$, $p = 0.21$, $\eta^2_p =$ 0.15).

Effects of mental fatigue on movement duration: Control Experiment 2

The aim of the Control Experiment 2 was to control whether the order of actual and imagined tests could influence the duration of actual and imagined pointing movements.

The mental fatigue task induced a 4.1 ± 0.4% increase in the duration of actual pointing trials (main effect of *time*, $F_{(1,5)} = 120.10$, $p < 0.001$, $\eta^2_p = 0.96$) independently of the ID (Fig. 3E; no *time* × *ID* interaction, $F_{(4,20)} = 2.16$, $p = 0.11$, $\eta^2_p = 0.30$). The increase in the duration of actual pointing trials was similar in the Main Experiment and the Control Experiment 2 (no effect of *session*, $F_{(1,5)} = 0.08$, $p = 0.79$, $\eta^2_p = 0.02$). The duration of imagined pointing trials increased by 7.6 ± 0.9% after the mental fatigue task (main effect of *time*, $F_{(1,5)} = 48.78$, $p < 0.001$, $\eta^2_p = 0.71$) independently of the ID (Fig. 3F; no *time* × *ID* interaction, $F_{(4,20)} = 2.79$, $p = 0.06$, $\eta^2_p = 0.36$). The increase in the duration of imagined pointing trials was similar in the Main Experiment and the Control Experiment 2 (no effect of *session*, $F_{(1,5)} = 0.92$, $p = 0.38$, $\eta^2_p = 0.16$). The order of trial conditions did not influence the effect of mental fatigue on the duration of actual and imagined pointing tasks.

The increase in the duration of imagined pointing movements (7.6 ± 0.9%) was greater compared to actual pointing movements (4.1 ± 0.4%; main effect of *condition*, $F_{(1,5)} = 23.79$, $p < 0.01$, $\eta^2_p = 0.83$), independently of the ID (no *condition* × *ID* interaction, $F_{(4,20)} = 1.49$, $p = 0.24$, $\eta^2_p = 0.23$). This difference was also observed when imagined trials were performed before actual trials (Main Experiment).

Corticospinal excitability

MEP amplitude during imagined trials was significantly greater than that at rest for BB (Table 1, main effect of *condition*, Main Experiment: $F_{(1,9)} = 15.04$, $p < 0.01$, $\eta^2_p = 0.63$; Control Experiment 1: $F_{(1,9)} = 18.25$, $p < 0.01$, $\eta^2_p = 0.67$; Control Experiment 2: $F_{(1,5)} = 7.25$, $p < 0.05$, $\eta^2_p = 0.59$) and TB (Table 1, main effect of *condition*, Main Experiment: $F_{(1,9)} = 5.62$, $p < 0.05$, $\eta^2_p = 0.38$; Control Experiment 1: $F_{(1,9)} = 6.04$, $p < 0.05$, $\eta^2_p = 0.40$; Control Experiment 2: $F_{(1,5)} = 7.70$, $p < 0.05$, $\eta^2_p = 0.60$) muscles, indicating that subjects' motor system was actively engaged in the mental movement simulation.

ANOVAs did not reveal a main effect of time: MEP amplitude, both at rest and during motor imagery, remained stable before (pre-test) and after (post-test) the mental fatigue task in the Main Experiment (BB muscle: $F_{(1,9)} = 1.1$, $p = 0.32$, $\eta^2_p = 0.11$; TB muscle: $F_{(1,9)} =$ 0.23, $p = 0.64$, $\eta^2_p = 0.02$) and the Control Experiment 2 (BB muscle: $F_{(1,5)} = 0.27$, $p = 0.62$, $\eta^2_p = 0.05$; TB muscle: $F_{(1,5)} = 0.12$, $p = 0.75$, $\eta^2_p = 0.02$), as well as before and after the documentary viewing during the Control Experiment 1 (BB muscle: $F_{(1,9)} = 0.68$, $p = 0.43$, $\eta^2_p = 0.07$; TB muscle: $F_{(1,9)} = 1.17$, $p = 0.31$, $\eta^2_p = 0.11$). This result suggests that mental fatigue did not alter corticospinal excitability at rest and when participants imagined movements. There was no *condition* × *time* interaction for the three experiments for the BB (Main Experiment: $F_{(1,9)} = 2.21$, $p = 0.17$, $\eta^2_p = 0.20$; Control Experiment 1: $F_{(1,9)} = 1.10$, $p = 0.32$, $\eta^2_p = 0.11$; Control Experiment 2: $F_{(1,5)} = 0.03$, $p = 0.86$, $\eta^2_p = 0.007$) and TB muscles (Main Experiment: $F_{(1,9)} = 1.55$, $p = 0.24$, $\eta^2_p = 0.15$; Control Experiment 1: $F_{(1,9)} = 0.004$, $p = 0.95$, $\eta^2_p = 0.0004$; Control Experiment 2: $F_{(1,5)} = 0.01$, $p = 0.92$, $\eta^2_p = 0.002$).

RMS values of BB EMG activity was not different across the three experiments (no main effect of *time*, Main Experiment: $F_{(1,9)} = 4.16$, $p = 0.07$, $\eta^2_p = 0.25$; Control Experiment 1: $F_{(1,9)} = 1.16$, $p = 0.31$, $\eta^2_p = 0.10$; Control Experiment 2: $F_{(1,5)} = 1.14$, $p = 0.33$, $\eta^2_p =$ 0.19), as well as at rest and during imagined pointing trials (Table 1, no main effect of *condition*, Main

Table 1. Motor-evoked potential (MEP) amplitude and root mean square (RMS) values of the biceps brachii and triceps brachii muscles at rest and during imagery for the Main experiment, the Control Experiment 1 and the Control Experiment 2. * and **: Significant difference between rest and imagery conditions ($p < 0.05$ and $p < 0.01$, respectively)

	Main Experiment	Control Experiment 1	Control Experiment 2
MEP amplitude (mV)			
Biceps brachii			
Rest	0.24 ± 0.04	0.18 ± 0.03	0.23 ± 0.04
Imagery	1.08 ± 0.17**	0.76 ± 0.12**	0.54 ± 0.09*
Triceps Brachii			
Rest	0.26 ± 0.05	0.26 ± 0.05	0.14 ± 0.02
Imagery	0.37 ± 0.05*	0.38 ± 0.05*	0.25 ± 0.05*
EMG RMS values (10^{-3} mV)			
Biceps brachii			
Rest	4.10 ± 1.80	5.12 ± 5.14	3.88 ± 3.56
Imagery	5.84 ± 2.34	6.81 ± 6.22	4.05 ± 1.83
Triceps brachii			
Rest	4.33 ± 2.22	4.12 ± 1.16	4.40 ± 3.42
Imagery	5.06 ± 2.85	4.99 ± 2.10	3.83 ± 1.70

Experiment: $F_{(1,9)} = 0.01$, $p = 0.95$, $\eta^2_p = 0.0006$; Control Experiment 1: $F_{(1,9)} = 4.92$, $p = 0.06$, $\eta^2_p = 0.33$; Control Experiment 2: $F_{(1,5)} = 0.04$, $p = 0.85$, $\eta^2_p = 0.008$). No *condition* × *time* interaction was observed for the three experiments (Main Experiment: $F_{(1,9)} = 1.93$, $p = 0.20$, $\eta^2_p = 0.12$; Control Experiment 1: $F_{(1,9)} = 0.79$, $p = 0.40$, $\eta^2_p = 0.05$; Control Experiment 2: $F_{(1,5)} = 1.16$, $p = 0.33$, $\eta^2_p = 0.19$). RMS values of TB EMG activity did not present any difference in pre-test and post-test (no main effect of *time*, Main Experiment: $F_{(1,9)} = 0.81$, $p = 0.39$, $\eta^2_p = 0.08$; Control Experiment 1: $F_{(1,9)} = 3.31$, $p = 0.10$, $\eta^2_p = 0.27$; Control Experiment 2: $F_{(1,5)} = 0.69$, $p = 0.44$, $\eta^2_p = 0.12$), and between rest and imagined pointing trials (Table 1, no main effect of *condition*, Main Experiment: $F_{(1,9)} = 0.25$, $p = 0.63$, $\eta^2_p = 0.03$; Control Experiment 1: $F_{(1,9)} = 1.49$, $p = 0.25$, $\eta^2_p = 0.14$; Control Experiment 2: $F_{(1,5)} = 0.23$, $p = 0.65$, $\eta^2_p = 0.04$). No *condition* × *time* interaction was observed for the three experiments (Main Experiment: $F_{(1,9)} = 1.13$, $p = 0.31$, $\eta^2_p = 0.11$; Control Experiment 1: $F_{(1,9)} = 1.38$, $p = 0.27$, $\eta^2_p = 0.13$; Control Experiment 2: $F_{(1,5)} = 1.23$, $p = 0.32$, $\eta^2_p = 0.20$).

DISCUSSION

The aim of the present study was to investigate the effects of mental fatigue on the temporal features of actual and imagined arm movements involving speed–accuracy trade-off. The main results revealed that mental fatigue induced an increase in the duration of both actual and imagined pointing movements, independently of the difficulty of the task, suggesting that Fitts' law was qualitatively conserved despite mental fatigue.

Changes in actual movement duration after mental fatigue

In accordance with our hypothesis, actual movement duration increased after mental fatigue whatever the task difficulty. Fitts' law, expressed by the linear relationship between IDs and duration, was conserved after mental fatigue, but was upward shifted. The effects of mental fatigue on movement duration were also observed with physical fatigue. Indeed, Missenard et al. (2009) observed that physical fatigue induced an increase in movement duration independently of the ID. In their study, EMG activity and movement kinematic did not change after fatigue, revealing that the increase in movement duration was due to a global decrease in acceleration and deceleration movement phases. The authors used an optimal control model to explore the mechanisms that contributed to changes in Fitts' law with fatigue. They observed that motor command noise increased with muscle fatigue, resulting in an increase in variability of the final position of the pointing movement. Participants had to slow their movement to guarantee task success. According to the authors, the increase in movement duration with muscle fatigue was not due to a lack of force, but would reflect a strategy of the CNS that adapted motor planning and execution in order to preserve task success.

In the present study, the duration of the six trials did not change after mental fatigue for each ID, suggesting that the alteration of movement duration appears from the first trial and remained present until the sixth trial. Therefore, the effects of mental fatigue lasted during the whole duration of the post-test (~15 min). This finding suggests that the CNS planned a slower movement from the first trial to the last trial without adapting the motor command. The CNS seems to use the same strategy in presence of mental or physical fatigue in order to preserve task success. Indeed, we can speculate that mental fatigue would also increase noise in the motor command that should be integrated by the CNS. Slower movement is then an adaptation of motor planning to preserve task success (Harris and Wolpert, 1998). The increase in missed targets with mental fatigue showed an alteration in accuracy in addition to the increase in movement duration. We assume that during some trials the increase in movement duration was insufficient to counteract motor noise, resulting in missed trials (more than two consecutives missed targets). Participants may have slowed down more to succeed in the task. These results support the optimized-submovement correction model developed by Schmidt et al. (1979) and Meyer et al. (1982, 1988). This theory assumes that for a movement directed toward a target, the index of difficulty is integrated in the programming phase in order to reach the target. Consistent with this model, Heitz and Schall (2012) observed on monkeys that adjustments mediating speed–accuracy trade-off was characterized by shifts of baseline discharge rate of many neurons indicating proactive changes in the preparatory state. In summary, the increase in movement duration with mental fatigue indicates motor planning adaptation to preserve task success.

Effects of mental fatigue on imagined movement

As actual movement duration, imagined movement duration increased with mental fatigue. As previously defined, motor imagery is the mental representation of action without any corresponding motor output and afferent feedback (Jeannerod, 2001). Therefore, the increase in imagined movement duration was not due to afferent feedback, but confirmed that the CNS planned a slowed movement before executing or imagining the first trial.

An important finding in our study was that mental fatigue affected more the duration of mental than actual movements. Indeed, increase in movement duration was twice greater for imagined movements compared to actual movements. During motor imagery the brain monitors intentions and actions plans, but consciously retains them from overt execution. This involves a high temporal organization of the sequences of simulated actions, i.e., triggering and retention, which engage the activation of several brain areas and especially the frontal, prefrontal and parietal cortices (Decety, 1996; Sirigu et al., 1996; Jeannerod, 2001). The greater changes in the temporal processing of imagined actions compared to actual ones may suggest a greater influence of psychological bias, as mental fatigue effects, on imagined movements because of the absence of actual feedback.

Potential mechanisms to explain the effects of mental fatigue on movement duration

A possible explanation for the increase in movement duration with mental fatigue is that mental fatigue directly affects the cortical centers involved in the preparation of motor commands (Hallett, 2007). Mental fatigue tasks, such as Stroop task, are known to strongly activate the anterior cingulate cortex (ACC) and the lateral prefrontal cortex (Banich et al., 2000; MacDonald et al., 2000; Milham et al., 2002), especially due to unpredictable conflict, more than actual error (Carter et al., 1998, 2000). During the fatiguing mental tasks, the error-related brain activity, indexing performance monitoring by the ACC, is significantly attenuated (Lorist et al., 2005; Boksem and Tops, 2008). This induces an impairment in cognitive control, response preparation, planning process and action monitoring (Lorist et al., 2000; van der Linden et al., 2003b; Boksem et al., 2006). Furthermore, the ACC is implicated in motor control (Paus et al., 1998). Indeed, this brain area receives input from the primary motor cortex, premotor cortex and supplementary motor area (Dum and Strick, 1991; Morecraft and Van Hoesen, 1992), and gives rise to corticospinal projections that terminate in the intermediate zone of the spinal cord (Morecraft and Van Hoesen, 1992). Tanaka et al. (2014) observed that mental fatigue suppresses activities in the right ACC during physical performance. Therefore, the deactivation of ACC would induce an alteration of movement preparation and planning, in integrating greater errors in the performance. To compensate this phenomenon, the CNS would increase the movement duration, as seen when the index of difficulty of trade-off tasks increases. However, further neuroimaging studies are needed to better understand the role of the ACC in these alterations and to confirm these hypotheses.

Manipulation checks

As expected, the completion of the Stroop task for 90 min induced a subjective feeling of mental fatigue and a decrease in vigor. On the contrary, the documentary viewing did not induce any change in the psychological state of the participants. These results are consistent with previous studies on mental fatigue (Marcora et al., 2009; Pageaux et al., 2013) and ensure that we were successful in the expected change of the mental state.

The documentary viewing did not induce any change in actual and imagined movement duration in the Control Experiment 1. This result ensured that movement duration was not influenced by a non-demanding cognitive task or the simple passage of time. Furthermore, the order of the condition in pre-test and post-test did not influence the results regarding the duration of actual and imagined movements. Indeed, the changes in actual and imagined movement duration were not different following mental fatigue in the Main Experiment and the Control Experiment 2. This also suggests that in our study the effect of mental fatigue on movement duration lasted at least 15 min, i.e., the duration of the pointing tests.

MEP amplitude of the BB and TB muscles during the imagined pointing trials was greater than that at rest during the three experiments, reflecting an activation of the corticospinal track during motor imagery (Kasai et al., 1997; Kiers et al., 1997). This increase in MEP amplitude was not due to a slight contraction during motor imagery, BB and TB EMG activities remaining at the same level at rest and during the imagined pointing trials. This ensured that corticospinal modulation was not due to peripheral activation. Taking together, these results confirmed that the participants were well engaged in the imagined movement in the three experiments.

As predicted by Fitts' law (Fitts, 1954; Fitts and Peterson, 1964), movement duration progressively increased while IDs increased. Fitts' law was also held for the imagined movement. Indeed, imagined movement duration also increased with ID in the same manner as actual movement, in accordance with previous studies (Decety and Michel, 1989; Decety and Jeannerod, 1996).

CONCLUSION

The present study demonstrated that mental fatigue induced by a prolonged cognitive task increased actual movement duration, while maintaining Fitts' law. The increase in movement duration was also present for imagined task, suggesting that proactive changes occurred during the preparatory state of the movement. Our results attested that CNS adapted motor planning to preserve task success in presence of mental fatigue. This finding provides better insights into the role of the brain in regulating performance with mental fatigue, as previously suggested on endurance performance (Marcora et al., 2009). Although this study was performed on healthy subjects, the results may benefit to the comprehension of patients affected by chronic fatigue syndrome that is associated with slowed psychomotor and/or processing speed (Marshall et al., 1996; Davey et al., 2001). Future neuroimaging studies could help understand the regulatory mechanisms of motor task performance in the presence of mental fatigue.

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