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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. © 2015 IBRO. Published by Elsevier Ltd. All rights reserved.

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