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Physical Activity and Music to Counteract Mental Fatigue

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Abstract—Mental fatigue impairs both cognitive and physical performance. Bioactive substances (e.g., caffeine) have been used to counteract mental fatigue but could have side effects. The present study aimed to test two non-bioactive strategies to counteract mental fatigue: physical activity and listening to music. The participants first performed an arm-pointing task, then carried out a 32-min cognitively demanding task to induce mental fatigue (TLDB task), followed by another arm-pointing task at the end of the experiment. Between the end of the cognitively demanding task and the last arm-pointing task, 20 min went during which participants performed either 15 min of physical activity, of listening to music or of discussion (control). The subjective feeling of mental fatigue was assessed before each arm-pointing task and after the cognitively demanding task. For ''physical activity'' and ''listening to music'' groups, EEG was recorded at rest after each evaluation of subjective feeling of mental fatigue and during the cognitively demanding task. An increase in alpha power during the cognitively demanding task evidenced the presence of mental fatigue, without recovery during the following 20-min period. In the control condition, the arm-pointing task performance was deteriorated 20-min after the cognitively demanding task, while it remained stable after both physical activity and listening to music. Furthermore, recovery on the subjective feeling of mental fatigue was similar for both groups. The present results suggested that practicing physical activity and listening to music could be efficient strategies to counteract the negative effects of mental fatigue on motor performances.

Key words: mental fatigue, compensation, motor control, physical activity, music listening.

INTRODUCTION

Mental fatigue, which is defined as a psychobiological state caused by prolonged and/or intense periods of cognitively demanding activity and characterized by subjective feelings of ''tiredness'' and ''lack of energy'' (Boksem and Tops, 2008; Rozand and Lepers, 2016), could negatively impact daily life. A recent study conducted on the general population of Lausanne revealed that the prevalence of fatigue (defined as an unpleasant physical, cognitive, and emotional symptom) was 21.9% (Galland-Decker et al., 2019). Fatigue, especially mental fatigue, affects everyday life and can lead to a decrease in productivity (Ricci et al., 2007), medical errors (Tawfik et al., 2018), or road accidents (Dinges, 1995). Moreover, mental fatigue is also a prevalent symptom in many diseases, such as cancers (Chang et al., 2000), brain injuries (Cantor et al., 2013), Parkinson's disease (Stocchi et al., 2014), Lyme disease (Shadick et al., 1994), or more recently in COVID-19 (Del Rio and Malani, 2020). Improved understanding of the neurophysiological mechanisms underlying mental fatigue is important to counteract its negative effects in both healthy individuals and patients.

In a laboratory environment, it has been demonstrated that mental fatigue significantly impairs cognitive (Lorist et al., 2000) and physical performance (for reviews: Pageaux and Lepers, 2018). When experiencing mental fatigue, impaired attention (Boksem et al., 2005), emotion regulation (Grillon et al., 2015), decision making (Guo et al., 2018), or executive functions (Lorist et al., 2000) have been observed. Concerning physical performance, mental fatigue has been shown to impair sport-related decision making (Smith et al., 2016; Head et al., 2017), technical skills (Le Mansec et al., 2018), motor control (Rozand et al., 2015), and endurance (Marcora et al., 2009).

To attest to the presence of mental fatigue, several subjective and objective markers can be used. It has recently been indicated that the use of a visual analog scale (VAS) appears to be the most practical method for assessing mental fatigue (Smith et al., 2019). Nonetheless, it seems necessary to use electrophysiological

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Abbreviations: EEG, electroencephalography; ID, index of difficulty; RPE, rating of perceived exertion; TLDB, time load dual back; VAS, visual analog scale.

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markers in addition to a subjective scale to characterize mental fatigue. Studies using electroencephalography (EEG) have notably highlighted that mental fatigue induces changes in brain oscillations. A recent meta-analysis suggests that an increase in theta power would be the most reliable biomarker of the presence of mental fatigue (Tran et al., 2020). Moreover, mental fatigue also induces an increase in alpha power (Boksem et al., 2005; Arnau et al., 2017), interpreted as reflecting decreased attention.

Mental fatigue has negative impacts on both cognitive and physical performances; thus some studies have investigated different compensation strategies to counteract the effects of this fatigue. Previous research has shown, for example, that chicken extract could help to compensate for the deleterious effects of mental fatigue (Nagai et al., 1996; Yamano et al., 2013). This positive effect was attributed to the various amino acids, peptides, and proteins contained in the chicken extract and their effects on levels of several brain neurotransmitters. However, the exact mechanisms to explain this remain to be clarified. Although chicken extract is very popular in Asia, it is not the case in Western countries. Caffeine is also a common bioactive substance that has been shown to be efficient in counteracting the effects of mental fatigue (Azevedo et al., 2016). Franco-Alvarenga et al. (2019) showed that performance (20 km cycling time trial) in mentally fatigued cyclists was improved by 1.4% after ingesting caffeine (ingestion before the mentally fatiguing task). The beneficial effect of caffeine on endurance performance when mental fatigue is experienced could be attributed to the positive effect of caffeine on perceived effort (Doherty and Smith, 2005) and neuronal excitability (Davis et al., 2003). However, bioactive substances such as caffeine could also have side effects, such as abnormal heart rhythm, insomnia, shakiness, coronary heart diseases, arterial hypertension, arterial stiffness, or an elevation of cholesterol (Nawrot et al., 2003; Dworzański et al., 2009). To avoid these side effects, Van Cutsem et al. (2018) showed the effectiveness of rinsing the mouth with caffeine-maltodextrin to compensate for mental fatigue. However, although the use of a caffeine-maltodextrin mouth rinse is possible in laboratory settings, it is less practical in everyday life, especially at work for instance.

Other studies have chosen to use non-bioactive substances to compensate for the effects of mental fatigue. The intermittent release of certain odors (e.g., citral, green or menthol odor) (Kato et al., 2012) or listening to relaxing music (Guo et al., 2015) during mentally fatiguing tasks also appeared to be efficient strategies to limit the effects of mental fatigue on subsequent tasks. Finally, studies showed that other strategies such as taking a steam bath after mental effort (Mizuno et al., 2010), mindfulness (Axelsen et al., 2020), or auditory binaural beats (Axelsen et al., 2020) could also be efficient at counteracting the effects of mental fatigue. Nonetheless, these non-bioactive strategies proposed to counteract mental fatigue may be difficult to apply in the context of daily life (e.g., at the workplace), and present some limitations. For example, listening to music when performing a cognitive task can have a distracting effect and induce a decrease in performance (Dobbs et al., 2011). For its part, mindfulness requires practice to reduce mental fatigue effects and seems to be effective in fighting against mental fatigue only for experienced mindfulness persons (Axelsen et al., 2020).

The present study thus aimed to test two more user-friendly strategies to counteract mental fatigue. The first strategy was listening to pleasant music. One of the most common effects of listening to music is the "Mozart effect". Previous work showed that performance was better on spatial reasoning tasks after listening to a Mozart's sonata rather than silence or a relaxing sound (Rauscher et al., 1995). Levitin (2006) proposed that listening to music for 10–15 min before starting work would boost productivity. It is worth noting that the beneficial effects of listening to music on cognitive performance would be related more to changes in the listeners' emotional state than to the effects of the music itself (Schellenberg, 2012). Listening to music before completing an activity could also have a positive impact on physical exercise (Jarraya et al., 2012). In the present study and contrary to the study by Guo et al. (2015), listening to music was not proposed during the cognitively demanding task but after it, in order to counteract mental fatigue after its induction. It has been shown that music could be a distractor while completing a cognitive task and could lead to a decrease in performance (Dobbs et al., 2011). However, to induce a mental fatigue state, the participants needed to be engaged in the cognitively demanding task, without being disturbed.

The second compensation strategy tested in the present study was moderate physical exercise. An fMRI study evidenced that a 10-minute exercise session on a cycle ergometer at light intensity was sufficient to improve cognitive performance, and that this positive effect of physical activity was linked to an increase in arousal levels (Byun et al., 2014). In the literature, this beneficial effect of physical exercise has been largely reported for cognitive performance (Oberste et al., 2019), but also motor learning (Marin Bosch et al., 2020), or physical performance (Fradkin et al., 2010). In this context, conducting acute physical exercise could also be a promising and effective strategy to counteract mental fatigue.

We chose to evaluate the efficiency of these two compensation strategies on motor control (i.e., an arm-pointing task). Motor control is involved in many daily life activities such as writing, tapping on a keyboard, or grasping a cup of coffee, and has previously been shown to be impacted by mental fatigue. For instance, Rozand et al. (2015) showed that after 90 min of the Stroop task movement durations during an arm-pointing task were increased by ~4%, evidencing an impairment of motor control during mental fatigue. Our research group has shown that the effects of mental fatigue on motor control persisted during at least 20 min after the completion of a cognitively demanding task (Jacquet et al., 2021b). The persistent mental fatigue effects on a cognitive performance had also been observed during 12 min following a cognitively demanding task (Matuz et al., 2019). Besides these two recent studies demonstrating persistent effects of mental fatigue over time, we decided to perform a manipulation check in a first experiment to assert that mental fatigue persisted 20 min following the cognitively demanding task to, after that, test the compensation strategies proposed. The second and main objective of the present study was to evaluate the effectiveness of listening to music and acute physical activity to counteract the effects of mental fatigue on motor control. We hypothesized that both means could be efficient strategies to counteract mental fatigue. This effectiveness should be evidenced by maintaining performance on movement duration during an arm-pointing task after inducing mental fatigue followed by the compensation strategies. A possible recovery effect could also be evidenced on brain oscillations with a decrease in both theta and alpha power.

EXPERIMENTAL PROCEDURES

Participants

The study involved 37 healthy active adults, with normal or corrected-to-normal vision and no history of neurological disease (age: 20.6 ± 0.7 years; seven males and 30 females), divided into two experiments. All gave written informed consent to perform the experiment and were kept naïve from the aim and the hypotheses of the investigation. To check that they were all right-handed, participants completed the Edinburg questionnaire. All participants were given instructions to sleep for at least 6 h, not to consume alcohol, and not to practice vigorous physical activity the day before each visit. They were also instructed not to consume caffeine or nicotine for at least 3 h before testing and were asked to declare if they had taken any medication or had any acute illness, injury, or infection. The experiment was conducted in conformity with the latest version of the Declaration of Helsinki (1964).

Experimental design

For the two experiments, two sessions were performed: a familiarization and an experimental session. The familiarization session aimed to accustom the participants to the different questionnaires used and train them on both arm-pointing and Time Load Dual Back (TLDB) tasks (Borragan et al., 2016). The experimental session occurred between 48 h and 96 h after the familiarization session, at the same time of day.

Pilot experiment: validation of experimental conditions

The first experiment was a pilot experiment, which will serve as a control group for the main experiment, and aimed to validate experimental conditions. It included 14 participants (age: 21.1 ± 1.8 years; two males and 12 females). The participants started by completing the Saint Mary's Hospital Sleep Questionnaire. Then, they reported their level of mental fatigue on a visual analog scale (VAS), and they performed the arm-pointing task (Pre measurement). Participants then conducted the cognitively demanding task consisting of 32 min of the TLDB task (excluding rest periods between blocks). Immediately after the cognitively demanding task, they evaluated their level of mental fatigue on a VAS and repeated the arm-pointing task (Post measurement). The evaluation of the level of mental fatigue on a VAS and the arm-pointing task were repeated 10 min (Post 10 measurement) and 20 min (Post 20 measurement) after the completion of the cognitively demanding task (Fig. 1A). During rest periods following the TLDB task (i.e., between the Post and Post 10 measurements and the Post 10 and Post 20 measurements), the experimenter talked with the participants. During the conversation, the same topics were discussed in the same order and concerned their job (or education), their hobbies (e.g., sport, nature), and their perspectives for the future (e.g., studies, jobs).

Main experiment

The main experiment involved 11 participants for the "physical activity" group (age: 19.9 ± 0.8 years; 4 males and 7 females) and 12 other participants for the "listening to music" group (age: 20.8 ± 0.5 years; 1 male and 11 females). None of the participants of the main experiment took part in the pilot experiment. The session began with completing the Saint Mary's Hospital Sleep Questionnaire. After this completion, the EEG recording began and lasted throughout the whole experiment. To record the brain activity of participants at rest, they were asked to stare at a black screen in front of them, to relax, and to think about nothing for 2 min. Following this rest period, the participants' subjective level of mental fatigue was evaluated on a VAS, and they carried out the arm-pointing task (Pre measurement). Participants then performed the cognitively demanding task consisting of 32 min of the TLDB task (excluding rest periods between blocks), following their brain activity at rest was recorded for 2 min, and they completed a VAS to report their subjective level of mental fatigue (Post measurement). Because the results of a previous study (Jacquet et al., 2021b), supported by the results of our pilot experiment, indicated that performance on an arm-pointing task was not impaired immediately after the end of a cognitively demanding task, and in order to limit practice effects, in the main experiment we decided not to perform an arm-pointing task immediately after the cognitively demanding task. Participants then performed a compensation task, which consisted of either 15 min of moderate physical activity (i.e., cycling at a moderate intensity) or 15 min of listening to music. After the compensation task, brain activity was recorded for 2 min at rest, and then the subjective level of mental fatigue was evaluated on a VAS, followed by the arm-pointing task (Post 20 measurement; Fig. 1B).

Psychological measurements

The sleep quality of each participant the night before the experiment was assessed using the Saint Mary's Hospital Sleep Questionnaire (Ellis et al., 1981). Only the three

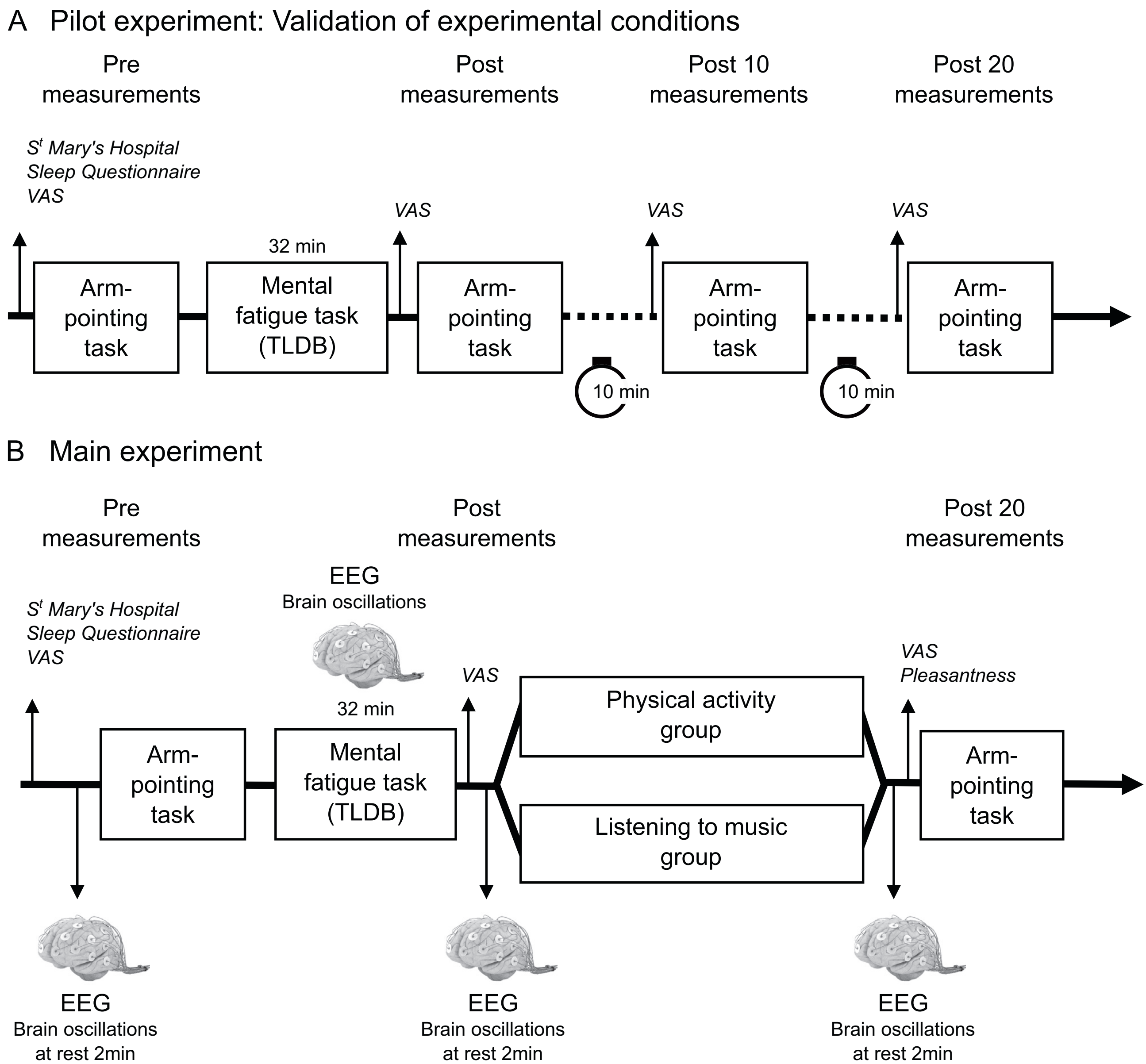

Fig. 1. Overview of the protocol for the validation of experimental conditions **(A)** and for the main experiment **(B)**. EEG: electroencephalography. TLDB: Time Load Dual Back. VAS: Visual Analogue Scale.

most relevant questions about sleep complaints were used in this study: "night sleep duration", "sleep quality" ranged from 1 (very badly) to 6 (very well), and "sleep satisfaction" from 1 (very unsatisfactory) to 5 (completely satisfactory).

The subjective mental fatigue level of participants was evaluated using a VAS of mental fatigue. The VAS was a 100-mm-long line with bipolar end anchors (0 mm = "Not mentally tired at all"; 100 mm = "Extremely mentally tired"), on which participants had to place a mark to estimate their level of mental fatigue.

The pleasantness of the compensation strategies (i.e., listening to music or physical activity) was evaluated using a VAS of pleasantness. The VAS was a 100-mm-long line, with bipolar end anchors (0 mm = "Not pleasant at all"; 100 mm = "Extremely pleasant"), on which participants had to place a mark to estimate the pleasantness of the activity performed.

Mental fatigue task: the time load dual back task

The Time Load Dual Back (TLDB) task is a dual-task combining a classical N-back working memory-updating task (Kirchner, 1958) and an interfering second task. Letters and digits were alternately presented on a screen. For the digits (1, 2, 3, 4, 6, 7, 8, or 9), which constituted the interfering task, participants had to press the key "1" on the numeric keypad with their right index finger if the digit was odd and the key "2" if the digit was even. For the letters (A, C, T, L, N, E, U, or P), participants were instructed to press the space bar with their left hand every time the displayed letter was the same as the previous letter (1-back task). Experiment Builder software (SR Research) was used to monitor stimuli presentation. Stimuli were presented in Arial font size 60, centrally on a 16-inch computer screen (60 Hz refresh rate). Stimuli were presented by blocks of 60 with a break of 30 s between blocks.

For the familiarization session, we followed the procedure of Borragan et al. (2016) and Borragan et al. (2017) to determine individual thresholds of presentation duration. All participants started the TLDB task with a duration of 1500 ms for each event (i.e., letters and digits) with an inter-stimulus interval set at 0. At the end of each block, performance accuracy was calculated. If it was equal to or greater than 85%, the duration of the presentation was reduced by 100 ms. When performance accuracy became less than 85%, participants performed two more blocks with the same duration to pursue familiarization. For the experimental session, the threshold of stimulus presentation was fixed at the last successful level.

The arm-pointing task

The arm-pointing task is a physical task used to evaluate motor control. This task aims to reach a target presented on a touchscreen as accurately and fast as possible. Participants were sitting on a comfortable chair with a pencil in their right hand. At the starting position, shoulder abduction was 90° and movements were direct at 45° to the left.

In the start position, their arm was aligned with their right shoulder and all targets to be reached were located on a 45° diagonal to the left to limit joint stress. The targets were black squares displayed on a touchscreen in front of the participant. The targets presented several indexes of difficulty (IDs), which were calculated using the formula $ID = \log_2(\frac{2D}{W})$, where D represents the center-to-center distance between the start point and the target and W represents the width of the target.

For the pilot experiment, 48 targets, each with a different ID between 2.75 and 6.25, were created using different distances (between 5 cm and 32 cm) and widths (between 1 cm and 2.5 cm). Then, seven ID classes were constituted: a ID 3 class [2.75 to 3.25[, a ID 3.5 class [3.75 to 4.25[, a ID4 [3.75 to 4.25[, a ID 4.5 class [4.25 to 4.75[, a ID 5 class [4.75 to 5.25[, a ID 5.5 [5.25 to 5.75[, and a ID 6 class [5.75 to 6.25[.

For the main experiment, to improve data collection (i.e., avoiding missing values) and statistical analyses, 42 targets were created with seven IDs ranging from 3 to 6 by steps of 0.5 using different distances (between 5 cm and 32 cm) and widths (between 1 cm and 2.5 cm). Each ID included six different targets with different sizes and distances from the starting point.

The time recorded for the pointing movement began when the participant took the pen off the starting position and stopped when he/she put it back on the touchscreen. If the participant landed on the target the trial was considered as "correct", otherwise, it was a missed trial. For each trial, the participant had to return to the starting position. The pointing task lasted approximately 1.5 min.

Compensation tasks proposed in the main experiment

Physical activity. The physical activity condition consisted of 15 min of exercise on an ergo-cycle. The intensity of the exercise was determined according to the Rating of Perceived Exertion (RPE) of each participant, and fixed at "moderate", corresponding to a level of 12–13 on the Borg's 6–20 RPE scale (Borg, 1998). The Borg's RPE scale ranges from 6 (Nothing at all) to 20 (Maximal exertion) and includes verbal anchors: No exertion at all (6), Extremely light (between 7 and 8), Very light (9), Light (9), Somewhat hard (13), Hard/Heavy (15), Very hard (17), Extremely heavy (19) or Maximal exertion (20). Perception of effort, which could be defined as the conscious sensation of "how hard, heavy and strenuous a physical task is" (Marcora, 2009), was assessed every 3 min by asking the following question to the participants: "How hard and intense is it for you to perform the exercise at this moment?". To avoid any distractions during the physical exercise, participants were placed in front of a wall on which only the scale of RPE was posted.

During the familiarization session, participants included in the "physical activity" group were accustomed to the RPE scale. In addition, they performed 15 min of cycling on the ergo-cycle, at an identical intensity to that of the experimental session, to feel the effort it required.

Listening to music. The listening to music phase consisted of spending 15 min, sitting in front of a black screen and listening to pleasant music. Music preference is personal (Hargreaves and North, 2010), therefore the participants themselves selected the songs used as stimuli. In this study, we were not interested in the characteristics of the music (e.g., musical genre, tempo, rhythm, or timbre) but only in its pleasant aspect for each participant. Participants brought their music playlist on the day of the familiarization session. In this way, the songs were assembled to form a single music track for the experimental session using Audacity software (Version 2.3.0 for Windows).

EEG recording and preprocessing for the main experiment

The Active Two BioSemi system from 64 electrodes was used to record the electroencephalogram according to the 10–20 International system. Horizontal eye movements were monitored with electrodes placed on the outer left and right canthi, while eye blinks were monitored with an electrode placed under the left eye. Two additional electrodes were placed on the left and right mastoids (A1, A2). During recording, the BioSemi system's common-mode sense electrode served as the reference electrode. Electrophysiological signals were digitized at a 2048 Hz sampling rate and acquired with ActiView software. Offline data analyses were performed using MATLAB (MathWorks, Natick, MA, USA) and the EEGLAB toolbox (Delorme and Makeig, 2004). Continuous data were down-sampled to 256 Hz, band-pass filtered at 0.01–100 Hz, and re-referenced to the average of A1 and A2. Noisy electrodes were identified with the *probability* and *spectrum* methods proposed in EEGLAB (threshold, $Z = 5$) and interpolated, when necessary, with a spherical method.

Data analyses

Pointing movement. Movement durations below 100 ms (0.1%) and above 1000 ms (0.4%) were excluded from the analysis. Movement durations beyond three standard deviations (SDs) of the mean were also excluded from the analysis (0.7%). For the pilot experiment, missing values were replaced by a value computed for each subject from the linear equation obtained from the other points of the corresponding task (i.e., Pre, Post, Post10, or Post20). This method reduced the variability of movement duration. For the main experiment, to avoid missing values, the arm-pointing task was adapted to have several trials for each ID.

Spectral analysis for EEG data. Spectral analysis of the EEG recording during the TLDB task and at rest before each arm-pointing task was performed with Fast Fourier Transform (FFT), using the *spectopo* function of the EEGLAB toolbox. EEG power was divided into five frequency bands: delta, 1–4 Hz; theta, 4–7 Hz; alpha, 8–12 Hz; beta 13–30 Hz; and gamma, 30–40 Hz. Nine regions of interest (ROIs) were constituted to perform analyses on both ERPs and spectral data (Arendsen et al., 2020; Jacquet et al., 2021a): Frontal Left (FL; mean of FP1, AF3, AF7, F3, F5, F7, FC3, FC5, FT7), Frontal Median (FM; mean of FPz, AFz, F1, Fz, F2, FC1, FCz, FC2), Frontal Right (FR: mean of FP2, AF4, AF8, F4, F6, F8, FC4, FC6, FT8), Central Left (CL: mean of C3, C5, T7, CP3, CP5, TP7), Central Median (CM: mean of C1, Cz, C2, CP1, CPz, CP2), Central Right (CR: mean of C4, C6, T8, CP4, CP6, TP8), Posterior Left (PL: mean of P9, P7, P5, P3, PO7, PO3, O1), Posterior Median (PM: mean of P1, Pz, P2, POz, Oz), and Posterior Right (PR: mean of P4, P6, P8, PO4, PO8, O2).

Statistics

All data are presented as means ± standard errors of the mean. Greenhouse-Geisser's correction to the degrees of freedom was applied when violations of sphericity were present (corrected *p*-values are reported). Only significant effects are reported, except when non-significance is relevant for the hypotheses being evaluated.

For the pilot experiment, mental fatigue effects on the VAS were evaluated using a one-way repeated-measures ANOVA with time (Pre, Post, Post 10, and Post 20) as the within-subject factor. The effects of mental fatigue on movement durations and errors during the arm-pointing task were evaluated using a two-way mixed-model repeated-measures 4 × 7 ANOVAs with time (pre, post, post 10, and post 20) and class of IDs (3, 3.5, 4, 4.5, 5, 5.5, and 6) as within-subject factors.

For the main experiment, participants of the pilot experiment were included in the statistical analyses as a control group. ''Night sleep duration'', ''sleep quality'', and ''sleep satisfaction'' were evaluated using one-way ANOVA with group (''Control'', ''Physical activity'', and ''Listening to music'') as between-subject factor. Mental fatigue effects on the VAS were evaluated using a two-way mixed-model repeated-measures 3 × 3 ANOVAs with group (''Control'', ''Physical activity'', and ''Listening to music'') as between-subject factor, and time (Pre, Post, and Post 20) as within-subject factor. The effects of mental fatigue on movement durations and errors during the arm-pointing task were evaluated using a three-way mixed-model repeated-measures 3 × 2 × 7 ANOVAs with group (''Control'', ''Physical activity'', and ''Listening to music'') as between-subject factor, and with time (Pre and Post 20) and ID (3, 3.5, 4, 4.5, 5, 5.5, and 6) as within-subject factors. For brain oscillations recorded during rest periods, a two-way mixed-model repeated-measures 2 × 3 ANOVAs with group (''Physical activity'', and ''Listening to music'') as between-subject factor, and time (Pre, Post, and Post 20) as the within-subject factor, were used. Brain oscillations during the TLDB task were analyzed using a two-way mixed-model repeated-measures 2 × 4 ANOVAs with group (''Physical activity'', and ''Listening to music'') as between-subject factor, and time-on-task (part 1, 0–8 min; part 2, 8–16 min; part 3, 16–24 min; and part 4, 24–32 min) as the within-subject factor. Only results about theta and alpha power, which are the power of interest, are reported in the Results section, the other brain oscillations are reported in supplementary data. Statistical analyses were performed independently for each ROI.

All analyses were performed using JASP (Version 0.13.1.0) [Windows software]. Significant main effects of time and significant interactions were followed up with contrast tests with Bonferroni correction, only adjusted *p*-values were reported. For each repeated-measure ANOVA, partial eta squared was calculated. Thresholds for small, moderate, and large effects were set at 0.01, 0.07, and 0.14, respectively (Cohen, 1988). Cohen's *d* was calculated for each *t*-test. Thresholds for small, moderate, and large effects were set at 0.2, 0.5, and 0.8, respectively (Cohen, 1988).

RESULTS

Pilot experiment: validation of experimental conditions

Visual analog scale. Fig. 2 shows the VAS scores. ANOVA revealed a significant time effect on the subjective feeling of mental fatigue ($F_{1.767, 22.973} = 15.420$, $p < 0.001$, $\eta_p^2 = 0.543$). Post-hoc

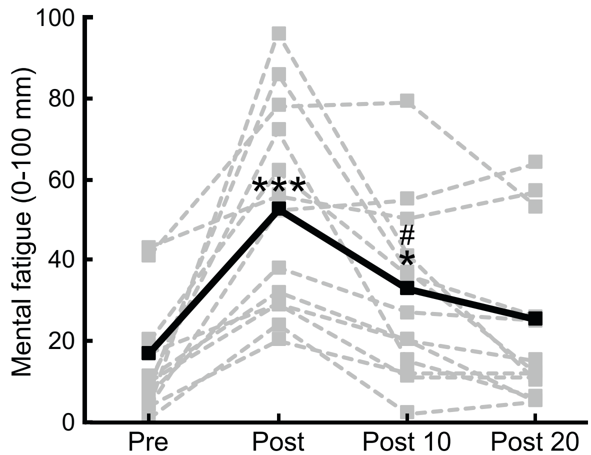

Fig. 2. Individual data for the subjective feeling of the mental fatigue for experiment aiming to validate experimental conditions. * and ***: Significant difference from precedent measurement, respectively $p < 0.05$ and $p < 0.001$. #: Significant difference from Pre measurement ($p < 0.05$).

analyses revealed that the cognitively demanding task (*Pre vs. Post*) induced an increase in the subjective feeling of mental fatigue ($t_{13} = -5.290$, $p < 0.001$, $d = -1.413$). A decrease in the subjective feeling of mental fatigue was observed between Post and Post 10 measurements ($t_{13} = 3.680$, $p = 0.014$, $d = 0.984$), but not between Post 10 and Post 20 measurements ($t_{13} = 2.235$, $p = 0.218$, $d = 0.597$). While the subjective feeling of mental fatigue was still higher 10 min after the completion of the cognitively demanding task (*Pre vs. Post 10*; $t_{13} = -3.736$, $p = 0.012$, $d = -0.998$), 20 min after the task it was no longer significantly different from its initial level (*Pre vs. Post 20*; $t_{13} = -2.039$, $p = 0.312$, $d = -0.545$).

Arm-pointing task. Fig. 3 shows the movement durations. Analyses performed on the arm-pointing task

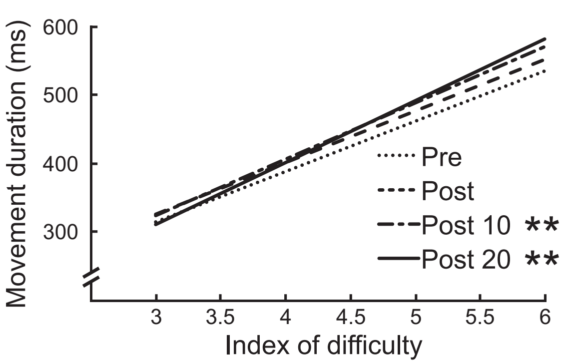

Fig. 3. Time course of the duration of arm-pointing movement at Pre, Post, Post 10, and Post 20 measurements for experiment aiming to validate experimental conditions, with a significant effect of the index of difficulty (ID; $p < 0.001$). ** = Significantly different from Pre ($p < 0.01$).

showed a significant class of IDs effect ($F_{6, 78} = 217.254$, $p < 0.001$, $\eta_p^2 = 0.944$), indicating that movement durations were slower with increasing of the class of IDs. A significant effect of time ($F_{3, 39} = 6.087$, $p = 0.002$, $\eta_p^2 = 0.319$) showed an increase in movement durations over time. While there is no difference in movement durations between Pre and Post measurements ($t_{13} = -2.339$, $p = 0.147$, $d = -0.625$) arm-pointing movements were slower in Post 10 ($t_{13} = -3.767$, $p = 0.003$, $d = -1.007$) and Post 20 ($t_{13} = -3.625$, $p = 0.005$, $d = -0.969$) measurements compared to Pre measurement. Finally, a significant class of IDs × time interaction ($F_{18, 234} = 3.982$, $p < 0.001$, $\eta_p^2 = 0.234$) revealed that the increase in movement durations over time was more pronounced for the targets with the higher class of IDs. Analyses on arm-pointing errors revealed a significant effect of class of ID ($F_{6, 78} = 7.196$, $p < 0.001$, $\eta_p^2 = 0.356$), indicating an increase in errors with increasing class of IDs.

Main experiment

Behavioral results. Sleep: Analyses performed on the Saint Mary's Hospital Sleep Questionnaire revealed that there are no significant differences in sleep duration (462.3 min ± 9.8), sleep quality (4.7 ± 0.2), or sleep satisfaction (3.9 ± 0.1) between the three groups.

Visual analog scale: Fig. 4 shows the VAS scores. A significant time effect was reported on the subjective feeling of mental fatigue ($F_{2, 68} = 52.153$, $p < 0.001$, $\eta_p^2 = 0.605$). Post-hoc analyses showed an increase in the subjective feeling of mental fatigue between Pre and Post measurements ($t_{36} = -9.972$, $p < 0.001$, $d = -1.639$), followed by a decrease between Post and Post 20 ($t_{36} = 6.897$, $p < 0.001$, $d = 1.134$). However, the subjective feeling of mental fatigue remained higher at Post 20 than at Pre ($t_{36} = -3.074$, $p = 0.009$, $d = -0.505$).

Pleasantness: A *t*-test showed that physical activity (56.6 ± 4.8) was perceived as less pleasant than listening to music (88.9 ± 2.2) ($t_{21} = -6.229$, $p < 0.001$ 0.05, $d = 2.600$).

Arm-pointing task: Fig. 5 shows the movement durations. Analyses performed on arm-pointing movements showed a significant ID effect ($F_{1.802, 61.282} = 514.419$, $p < 0.001$, $\eta_p^2 = 0.938$), qualified by a linear trend ($t = 55.075$; $p < 0.001$), indicating that participants' movements were slower with increasing IDs. In addition, a significant time × group interaction ($F_{2, 34} = 7.470$, $p = 0.002$, $\eta_p^2 = 0.305$) was observed. Post-hoc analyses indicated a significant increase in movement duration between Pre and Post 20 for the "Control" group ($t_{13} = -3.411$, $p = 0.025$, $d = -0.779$), whereas no significant differences were observed for the "Physical activity" group ($t_{10} = 2.033$, $p = 0.750$, $d = 0.687$), or for the "Listening to music" group ($t_{11} = 0.127$, $p = 1.000$, $d = 0.042$). Finally, a significant time × ID × group ($F_{5.892, 100.157} = 2.510$, $p = 0.027$, $\eta_p^2 = 0.129$) indicated that time effect was more pronounced for high IDs compared to low IDs for

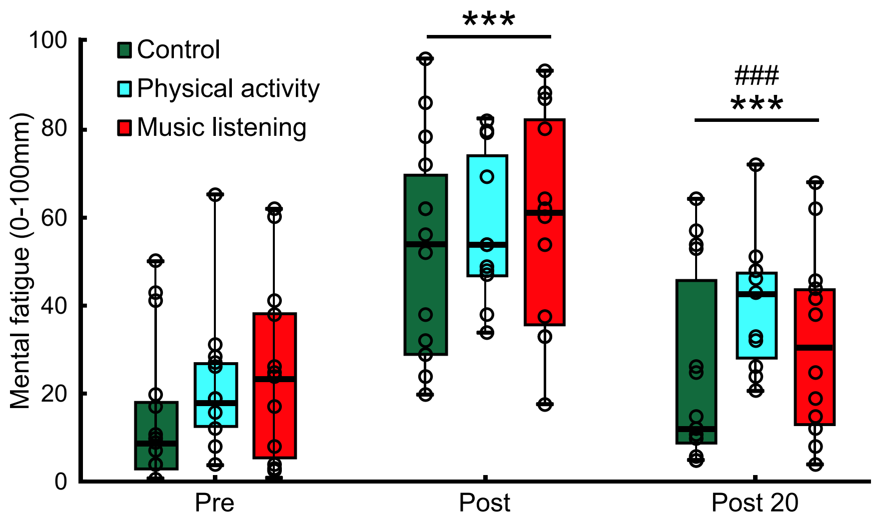

Fig. 4. Time course of subjective feeling of mental fatigue for the main experiment. ***: Significant difference from precedent measurement ($p < 0.001$). ###: Significant difference from Pre measurement ($p < 0.001$). Data are presented as median ± 25th and 75th quartiles.

the control group. Analyses on arm-pointing errors revealed a significant ID effect ($F_{3.532,\ 120.074} = 14.352$, $p < 0.001$, $\eta_p^2 = 0.297$), indicating an increase in errors with increasing IDs, and a group effect ($F_{2,\ 34} = 3.397$, $p = 0.045$, $\eta_p^2 = 0.167$), evidencing that the "Listening to music" group made slightly more errors than the "Control" group ($t_{25} = 2.539$, $p = 0.048$, $d = 0.418$).

EEG spectral analyses during the TLDB task.

Theta: Fig. 6.C shows theta power during the TLDB task. Analyses revealed a significant time-on-task effect for all brain regions excepted PL and PR regions (all *ps* < 0.005; $\eta_p^2 > 0.250$) with maximal effect in PM region ($F_{1.450,\ 30.456} = 10.477$, $p = 0.001$, $\eta_p^2 = 0.333$). Post-hoc analyses indicated a significant decrease in theta power for FL, FM, CL, CM, and PM regions between Part 1 and Part 2 (all *ps* < 0.21; $d > 0.634$), and for all the brain regions between Part 1 and Part 3 (all *ps* < 0.016; $d > 0.652$), and between Part 1 and Part 4 (all *ps* < 0.005; $d > 0.903$).

Alpha: Fig. 6.D shows alpha power during the TLDB task. Analyses revealed a significant time-on-task effect for all brain regions (all *ps* < 0.047; $\eta_p^2 > 0.148$) with maximal effect in PM region ($F_{1.815,\ 38.108} = 10.477$, $p = 0.003$, $\eta_p^2 = 0.253$). Post-hoc analyses indicated a significant increase in alpha power for all regions between Part 2 and Part 4 (all *ps* < 0.028; $d > 0.613$).

EEG spectral analyses at rest.

Theta: Analyses performed on brain oscillations revealed a significant time effect in PL region ($F_{2,\ 62} = 3.670$, $p = 0.034$, $\eta_p^2 = 0.149$). Post-hoc analyses indicated a significant increase in theta power between Post and Post 20 ($t_{23} = -2.696$, $p = 0.030$, $d = -0.562$).

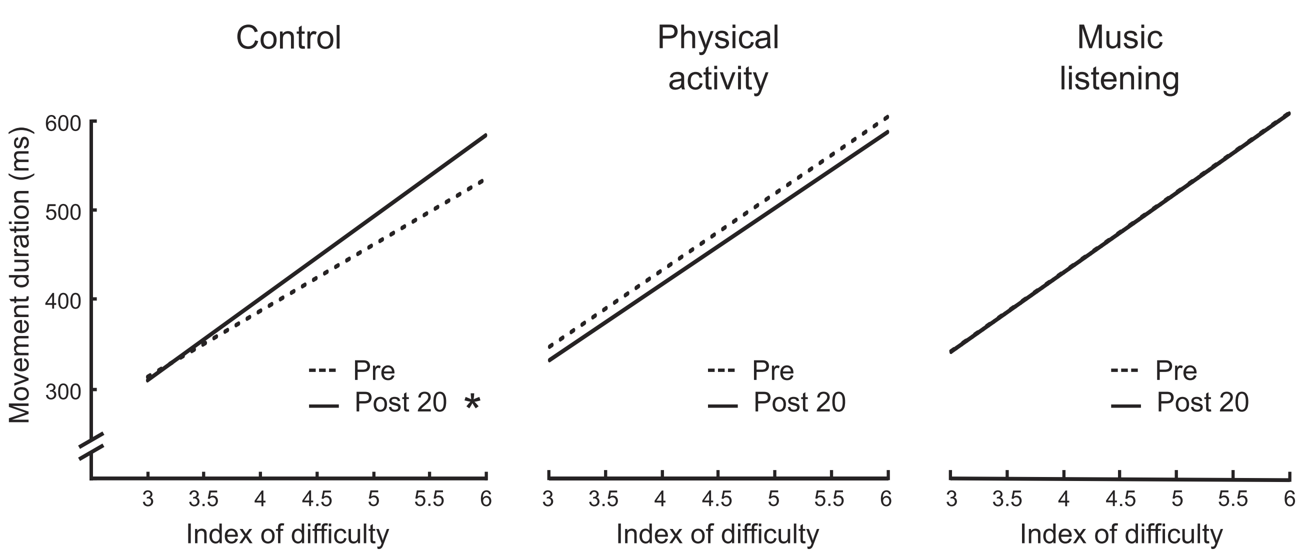

Fig. 5. Time course of the duration of arm-pointing movement at Pre (before mentally fatiguing task), and Post 20 (Post compensation), for the main experiment, with a significant effect on the index of difficulty ($p < 0.001$). *: Significant time effect ($p < 0.05$).

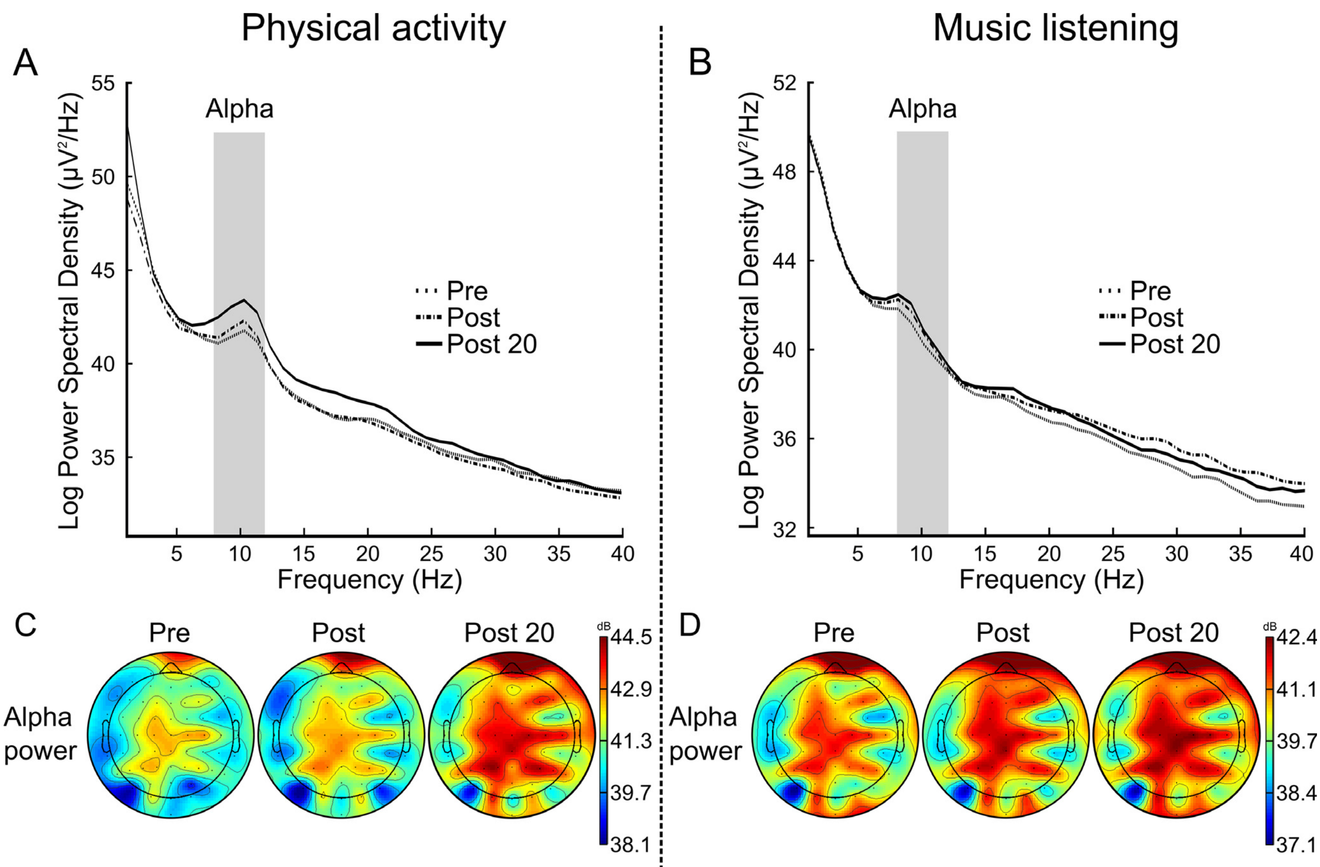

Fig. 6. Brain oscillations of brain power spectrum during the 2-min rest periods at Pre, Post, and Post 20 during the main experiment for both the ''physical activity'' **(A)** and ''listening to music'' **(B)** groups, with the specific time course of the alpha power for both the ''physical activity'' **(C)** and ''listening to music'' **(D)** groups.

Alpha: A significant effect of time was reported for all brain regions (all $ps < 0.013$; $\eta_p^2 > 0.210$), with a maximal effect in the CR region ($F_{2,\ 42} = 24.740$, $p < 0.001$, $\eta_p^2 = 0.541$). Post-hoc analyses revealed a significant increase in alpha power between Post and Post 20 for all regions except the FL and FM regions (all $ps < 0.031$; $d < -0.825$), and a significant increase in alpha power between Pre and Post 20 for all brain regions (all $ps < 0.006$; $d < -0.560$). Moreover, a significant time × group interaction was observed for FR, CM, CR, PL, and PR regions (all $ps < 0.031$; $\eta_p^2 > 0.165$) with a maximal effect in PL region ($F_{2,\ 42} = 5.302$, $p = 0.009$, $\eta_p^2 = 0.202$), indicating a greater increase in alpha power for the ''Physical activity'' group compared to the ''Listening to music'' group.

DISCUSSION

The present study aimed to (i) confirm the persistent effect of mental fatigue on arm-pointing task performance after a prolonged cognitively demanding task, and (ii) test two 15-min compensation strategies to counteract the negative effects of mental fatigue: listening to music and physical activity. Firstly, the results of the pilot confirmed that the effects of mental fatigue were persistent and increasingly pronounced over time on arm-pointing movements for at least 20 min, despite a progressive decrease in the subjective feeling of mental fatigue. Secondly, the main experiment evidenced that listening to music and physical activity were efficient to counteract the negative effects of mental fatigue on an arm-pointing task.

A 16-min TLDB task has already been used successfully to induce a feeling of mental fatigue (Borragan et al., 2016; Borragan et al., 2017). However, it has been shown that 32 min of the TLDB task were necessary to induce deleterious effects related to mental fatigue on an arm-pointing task as used in the present study (Jacquet et al., 2021b). In their study, Jacquet et al. (2021b) used both electrophysiological (EEG) and subjective markers (VAS of mental fatigue) to attest to the presence of mental fatigue. As expected, the 32 min of the TLDB task increased the subjective feeling of mental fatigue in the pilot experiment, as well as for both the ''Physical activity'' and ''Listening to music'' groups in the main experiment. Moreover, analyses performed on brain oscillations showed a significant increase in alpha power during the cognitively demanding task, a marker of mental fatigue presence despite some interindividual variability (for review: Tran et al., 2020). In this review, the authors suggested that the increase in theta activity was a stronger biomarker of mental fatigue. However, in the present study, and as observed in a previous study using the TLDB task to induce mental fatigue (Jacquet et al., 2021b), a decrease in theta power occurred during the cognitively demanding task. A recent study suggested that the increase in theta power occurred during the intertrial intervals and that, in contrast, the task-related theta activity declined with mental fatigue (Arnau et al., 2021). The TLDB task was designed to be as mentally demanding as possible, and the intertrial intervals were reduced as much as possible. In this context, it is not surprising to observe a decrease in theta power during the TLDB task, and this decrease could be considered as a biomarker of the presence of mental fatigue, which can be interpreted as a reduction of task engagement with increasing mental fatigue (Arnau et al., 2021). Altogether, these observations allow us to affirm that we succeeded in inducing mental fatigue with 32 min of the TLDB task.

The effects of mental fatigue on different physical performances are now well established in the literature (for review: Pageaux and Lepers, 2018), with motor control being one of the physical performances impacted. Rozand et al. (2015) evidenced that in the presence of mental fatigue, induced by 90 min of a modified Stroop task, the duration of arm-pointing movements increased by 4%, irrespective of the index of difficulty of the target. This result supporting impaired motor control with mental fatigue has been replicated with different cognitively demanding tasks (Rozand et al., 2016; Jacquet et al., 2021b). A possible explanation for this negative effect of mental fatigue on motor control is that an increase in noise in the motor command would lead to slower movements to maintain task success (Rozand et al., 2015), as also suggested in case of physical fatigue (Missenard et al., 2009).

A recent study evidenced that motor control impaired with mental fatigue was persistent and could last at least 20 min after the completion of a mentally fatiguing task (Jacquet et al., 2021b). However, despite a pioneer study conducted by Davis (1946), which evidenced only a partial recovery from mental fatigue after a calculation task of 30 min, few studies have evaluated the time course and persistence of the effect of mental fatigue. A previous study evidenced that a 12 min break following 90 min of a cognitively demanding task was not enough to observe a rebound in behavioral performances (a temporal discrimination task) despite a positive effect of this 12 min break on the subjective feeling of mental fatigue (Matuz et al., 2019). Our study also appears to indicate a dissociation of recovery effects between behavioral performances and the subjective feeling of mental fatigue. Although a decrease in the subjective feeling of mental fatigue seemed to indicate a recovery effect following a break, behavioral performances (i.e., motor task) were increasingly impacted by mental fatigue. This dissociation between subjective markers of mental fatigue and its growing effects on motor control has already been reported (Jacquet et al., 2021b). Furthermore, Loch et al. (2020) also evidenced a decrease in subjective markers of mental fatigue during the 20-min following a mentally fatiguing task, but without positive effects on cognitive performances. These observations show the importance of using different markers in order to improve the characterization of mental fatigue. While the VAS has recently been suggested as the most practical method to attest to mental fatigue (Smith et al., 2019), our results suggest that it is necessary to combine objective and subjective markers to highlight mental fatigue.

While the effects of mental fatigue have been described widely in the literature, the explanatory mechanisms remain unclear. Several models have been developed to understand this phenomenon and explain its deleterious effects on performance: the model of ego depletion (Baumeister et al., 1998), the motivational control theory (Hockey, 1997, 2011), the model of costs and benefits (Boksem and Tops, 2008) and the model of the dual regulation of mental fatigue (Ishii et al., 2014). Despite some differences, these models suggested that a decrease in performance when there is mental fatigue is the result of a decrease in resources allocated to perform the required task. Among the brain areas involved in the allocation of resources is the anterior cingulate cortex that is implicated in the evaluation of the rewards (Parkinson et al., 2000). The activity of this brain area seems particularly impacted by mental fatigue (Tanaka et al., 2014). To account for this reduced anterior cingulate cortex activity, a theory in favor of a failure of the dopaminergic networks has been proposed (Chaudhuri and Behan, 2000). Prolonged neural activity can lead to an increase in adenosine concentration due to the degradation of adenosine triphosphate (Lovatt et al., 2012). As the receptors of adenosine and dopamine (A_2A and the D2, respectively) are colocalized, adenosine would stop the dopaminergic signal (Schiffmann et al., 2007). The increase in the concentration of adenosine has already been proposed as a mechanism to explain the effects of mental fatigue (Pageaux et al., 2014).

As previously found by Jacquet et al. (2021b), the pilot experiment evidenced that arm-pointing movement performance was impaired with mental fatigue and that the performance was impaired even more during the 20-min period following mental fatigue induction despite a progressive decrease in the subjective feeling of mental fatigue. The main experiment showed that the negative effects of mental fatigue on the arm-pointing task could be counteracted by 15 min of listening to music or moderate physical activity. Indeed, there was no longer any significant difference between the performance on the arm-pointing task before and after the mentally fatiguing task when it was following by either 15 min of cycling at a moderate intensity or 15 min of listening to some pleasant music, selected by the participants. However, it should be pointed that the subjective feeling of mental fatigue indicated a similar recovery for all groups (i.e., control, physical activity, and listening to music groups). Although the subjective feeling of mental fatigue decreased, it remained higher than at the beginning of the experiment. Concerning electrophysiological markers (i.e., brain oscillations at rest), the results did not seem to indicate a recovery effect. Indeed, an increase in alpha oscillations occurred after both physical activity and listening to music, even if the increase in alpha power is more pronounced after the practice of the physical activity. Alpha power has been linked to mental fatigue (Tran et al., 2020) and this result might suggest that participants were more mentally fatigued after the completion of both compensation activities. However, an increase in alpha power is not only related to mental fatigue but could also be related to the performed compensation activity itself. To clarify that point, it has been shown that a physical exercise consisting of 15-min cycling exercise induced an increase in alpha power (Fumoto et al., 2010). This increase in alpha power was attributed to the increase in serotonin secretion induced by physical activity (Chaouloff et al., 1986). Listening to music can also induce an increase in alpha power (Verrusio et al., 2015), especially for preferred music (Gentry et al., 2013), as was the case in our study. In this context, alpha power was likely not to be relevant to assessing the presence of mental fatigue after physical exercise or listening to music.

Both 15 min of moderate physical activity and listening to music thus appear efficient in counteracting the effects of mental fatigue. Previous studies have already demonstrated the beneficial effect of certain strategies to counter mental fatigue, such as caffeine (Azevedo et al., 2016; Franco-Alvarenga et al., 2019), or creatine intake (Van Cutsem et al., 2020). The positive effects on mental fatigue of both caffeine (Huang et al., 2005; Hsu et al., 2010) and creatine (Matthews et al., 1999; Klivenyi et al., 2003) have been attributed to dopamine secretion. An increase in dopamine could compensate for the decreased activity of the dopaminergic system induced by mental fatigue, preserve the activity of some brain areas despite mental fatigue, and consequently maintain performance. In the present experiment, the beneficial effect of listening to music and physical activity could therefore be attributed to their effects on dopamine production. It has already been demonstrated that both practicing acute physical exercise (Hattori et al., 1994) and listening to music (Salimpoor et al., 2011) could increase dopamine secretion, and as for caffeine or creatine, the resulting higher levels of dopamine could help to alleviate the effects of mental fatigue.

Furthermore, previous studies evidenced that both acute physical activity (Byun et al., 2014) and listening to music (Chabris, 1999) could lead to increased arousal levels and enhance performance. Although increased arousal levels do not seem to impact movement time (Ando et al., 2008), they may improve attentional processes (Heuer and Reisberg, 1990). This could account for the compensation effect of mental fatigue from both acute physical activity and listening to music observed on the arm-pointing task.

To conclude, the present study demonstrated that both physical activity at a moderate intensity and listening to pleasant music could be efficient strategies to counteract the negative effects of mental fatigue on motor performance. It would be interesting to verify the positive effects of these compensation strategies on other cognitive processing (e.g., attention, planning, and inhibition) or subsequent physical tasks (e.g., endurance exercise and technical skills for specific sports). Physical activity and listening to music are already well known for their numerous positive effects, notably on arousal, attributed to brain neurotransmitter release, especially dopamine. Neuroimaging techniques such as PET (Positron Emission Tomography) could be interesting to further examine the mechanisms involved in the beneficial effects of physical activity and listening to music to counteract mental fatigue and further evaluate the potential role of brain neurotransmitters.

DECLARATION OF COMPETING INTEREST

The authors have no conflict of interest to disclose in respect to this manuscript.

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APPENDIX A. SUPPLEMENTARY DATA

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