Cerebral Mechanisms Underlying the Effects of Music during a Fatiguing Isometric Ankle-Dorsiflexion Task

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Abstract

The brain mechanisms by which music-related interventions ameliorate fatigue-related symptoms during the execution of fatiguing motor tasks are hitherto under-researched. The objective of the present study was to investigate the effects of music on brain electrical activity and psychophysiological measures during the execution of an isometric fatiguing ankle-dorsiflexion task performed until the point of volitional exhaustion. Nineteen healthy participants performed two fatigue tests at 40% of maximal voluntary contraction while listening to music or in silence. Electrical activity in the brain was assessed by use of a 64-channel EEG. The results indicated that music down-regulated theta waves in the frontal, central, and parietal regions of the brain during exercise. Music also induced a partial attentional switching from associative thoughts to task-unrelated factors (dissociative thoughts) during exercise, which led to improvements in task performance. Moreover, participants experienced a more positive affective state while performing the isometric task under the influence of music.

Keywords: attention, brain, music, muscle fatigue, psychophysiology

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Introduction

Performing movements that are integral to activities of daily life (ADL) such as walking do not impose great physical or cognitive demands on the human body. During low-intensity exercise, humans are readily able to allocate attention to environmental stimuli such as auditory and visual cues (Lavie, Hirst, de Fockert, & Viding, 2004). Beautiful scenery, the sweet sound of bird song, or a gentle breeze are good examples of stimuli that have the potential to elicit feelings of relaxation and general wellbeing (Gladwell, Brown, Wood, Sandercock, & Barton, 2013). Nonetheless, the brain has limited capacity to process sensory signals (Treisman, 1964; Watanabe & Funahashi, 2014). During high-intensity activity, the brain selects the most salient signals in an automated manner, and duly allocates the most attentional capacity toward them (Rejeski, 1985). Environmental stimuli (e.g., auditory and visual cues), however, have the potential to distract exercisers from the physical effects of exertion, improving performance and endurance (Hutchinson, Karageorghis, & Jones, 2015). The cerebral mechanisms that underlie selective attention during physical activity are hitherto under-researched. This is due to the fact that currently available neuroimaging techniques are highly sensitive to movement artifacts and thus require participants to remain still.

Attentional Focus

An increase in exercise intensity creates an attentional shift from an external focus on the surrounding environment to an internal focus on bodily sensations such as muscular contraction and respiration (Hutchinson et al., 2015). This phenomenon occurs gradually with the increasing intensity of exercise. When a given exercise load is sustained for a long duration, the levels of perceived exertion associated with that exercise load increase over time. This shift of attentional focus is referred to as attentional switching (AS) and represents the moment in the exercise when attention shifts from internal to external sensations or vice versa (Hutchinson & Karageorghis, 2013). AS typically occurs at exercise intensities approximating the *ventilatory threshold*: This phenomenon is demarcated by a disproportionate increase in pulmonary ventilation compared to oxygen uptake, caused by an increase in CO_2 production, which in turn results from the buffering of lactate build-up in the working muscles.

In addition to physical exercise, attentional focus depends on a person's cognitive strategy. Some people may generally focus more on bodily sensations than on the external environment. Attentional focus is also influenced by the attentional style of humans (Baghurst, Thierry, & Holder, 2004) and this, in turn, influences the cognitive strategy employed during everyday tasks such as exercise. *Association* is a cognitive strategy in which the exerciser focuses on internal processes such as bodily sensations and performance-related information. Conversely, *dissociation* refers to a strategy in which the exerciser focuses on task-unrelated cues such as environmental stimuli. Some exercisers also demonstrate a constant shift of attention between associative and dissociative focus and are thus referred to as *switchers* (Hutchinson & Karageorghis, 2013). Such individuals exhibit a malleable attentional style that enables them to shift their attentional focus in accord with situational demands.

The attentional style of exercisers can also influence how attention is allocated across the full spectrum of exercise intensities. Associators benefit from the use of internal bodily sensations to improve concentration and manipulate arousal responses before explosive and short-term physical activities such as the 100-m dash (Ille, Selin, Do, & Thon, 2013). Interestingly, the same cognitive strategy can compromise the execution of long-term modes of exercise such as marathons, because associative strategies may increase fatigue-related symptoms with the attendant impairment of performance-related variables (Lohse, Sherwood, & Healy, 2010). In such instances, a dissociative attentional style alleviates perceptions of exertion and postpones AS from external to internal cues, thus boosting performance (Hutchinson et al., 2015). Despite its importance, the effects of a malleable attentional style on psychophysiological responses and performance are difficult to examine, as switching attentional focus between internal cues is difficult to manipulate and quantify (cf. Guinote, 2007).

Sensory Modulation

Sensory strategies such as auditory stimuli have been extensively used as a means by which to ameliorate the effects of fatigue-related symptoms during exercise (Karageorghis & Priest, 2012b).

Through the purposeful use of sensory stimuli, individuals experience more pleasant sensations and lower perceived exertion than under normal circumstances. In such applications, sensory stimuli force one's attentional focus to external sensory cues, causing significant psychophysiological effects (see Karageorghis & Priest, 2012a, 2012b for a review). A recent study indicates that even at high exercise intensities, affective responses are more positive under conditions of auditory and audiovisual stimulation (Jones, Karageorghis, & Ekkekakis, 2014).

Razon et al. (2009) identified a strong effect of external stimulation on AS. Participants were asked to perform a handgrip-squeezing task at 30% of their maximal handgrip capacity until volitional exhaustion. The authors also used sensory deprivation as a means by which to increase fatigue-related symptoms, preponing AS over time. Sensory deprivation is expected to increase associative strategies during exercise. In such applications, exercisers are hypothesized to allocate attentional focus to internal bodily sensations, with consequent detrimental effect on endurance performance. Results indicated that AS occurred approximately 1 min later under the influence of music and normal vision, with subsequent impact upon time to exhaustion. A similar effect was previously reported by Boutcher and Trenske (1990) who demonstrated that sensory deprivation has a negative influence on affective valence and perception of effort at different exercise intensities. Based on the aforementioned studies, sensory modulation appears to be a worthwhile pathway for researchers to use in order to examine the mechanisms that underlie AS during exercise.

Cerebral Mechanisms Underlying Attentional Switching

Attention switches several times throughout a physical task depending on the physiological load, attentional style, and one's desired focus of attention (Bigliassi, 2015). Attentional focus is the apparent trigger responsible for modulating the sense of effort (Hutchinson & Karageorghis, 2013). Accordingly, selective attention could not only integrate but also underpin the mechanisms of fatigue and task disengagement (Marcora, 2008; Noakes, 2011). The psychobiological model proposed by Marcora, Staiano, and Manning (2009) indicates that motivation is the trigger responsible for influencing perception of effort and neural activation. As suggested by Pageaux (2014):

> The psychobiological model is an effort-based decision making model based on motivational intensity theory, and postulates that the conscious regulation of pace is determined primarily

> by five different cognitive/motivational factors: Perception of effort; potential motivation; knowledge of the distance/time to cover; knowledge of the distance/time remaining; previous experience/memory of perception of effort during exercise of varying intensity and duration. (p. 1319)

It is also hypothesized that other psychological phenomena such as attentional focus should be integrated into the psychobiological model, because exertional responses are conscious and active processes (Bigliassi, 2015; Rejeski, 1985). However, exercise-specific tasks cannot easily be reproduced by use of common brain functional imaging methods (e.g., *f*MRI), owing to the artefacts associated with muscular contractions and movement patterns (Fontes et al., 2013).

High temporal resolution is necessary to identify action potentials that are usually associated with rapid psychological phenomena such as shifts of attention. Therefore, electroencephalography (EEG) represents an appropriate technique to identify the mechanisms that underlie attentional processes during exercise (Luck, Woodman, & Vogel, 2000). The identification of the brain mechanisms associated with AS can lead to future studies on the use of pharmacological or electrical procedures to manipulate attentional focus in high-risk populations (e.g., obese), or even to strengthen the use of associative strategies during highly demanding cognitive-motor tasks (e.g., shooting and golf performance).

Brain Waves during Exercise

A very limited number of studies have addressed the effects of exercise on the electrical activity in the brain. Recently, Aspinall, Mavros, Coyne, and Roe (2015) explored the use of a wireless EEG device as a method to further understanding of the emotional experiences of walkers in different urban environments. The results indicated that green spaces (e.g., parks and rural areas) induced feelings of relaxation. This study illustrates how mobile EEG devices can be used to acquire physiological indices of emotional experiences during ADL. Furthermore, changes in the brain's electrical frequency are directly connected to affective/perceptual changes caused by external and interoceptive cues during exercise.

Bailey, Hall, Folger, and Miller (2008) investigated changes in EEG activity during graded exercise on a recumbent cycle ergometer. They identified a substantial increase in low-frequency brain waves (theta and alpha) in the frontal, central, and parietal regions of the cortex during the execution of incremental exercise performed to the point of volitional exhaustion. Immediately after completing the exercise bout, the power of low-frequency waves decreased substantially. This study indicated that frequency modulations in the brain during exercise are associated with the exercise intensity and feasibly interconnected with affective (e.g., a reduction in affective valence) and perceptual (e.g., an increase in perceived exertion) responses. The increase in low-frequency components during incremental modes of exercise is theoretically linked to an increase in low-frequency output that serves to contract the working muscles (Arendt-Nielsen & Mills, 1988). In other words, fatigue-related symptoms downregulate high-frequency output to generate greater muscular contraction. Therefore, fatigue-related symptoms cause a substantial increase in low-frequency brain waves such as theta and alpha.

Aims of the Present Study

EEG was used in the present study with a view to shedding new light on the mechanisms that underlie AS during a physically demanding motor task. Through frequency analyses, this approach also served to ascertain key cortical areas/networks that activate in response to an auditory stimulus (musical excerpt). The stimulus was used to manipulate AS and thus further understanding of the attentional processes that underlie a fatiguing isometric ankle-dorsiflexion task.

Hypotheses

Affective and perceptual responses. Sensory stimulation was hypothesized to slightly enhance exercise performance (ankle flexion fatigue tests) and induce moderate changes in psychological responses (e.g., affective valence and fatigue-related symptoms). This hypothesis is predicated on the fact that local exertion produces a limited amount of corollary discharge (De Morree, Klein, & Marcora, 2012), with partial effects on affective valence (hedonic tone of feelings), situational motivation, and felt arousal (for details, see the psychobiological model; Pageaux, 2014). Based on this assumption, the use of auditory stimulation is hypothesized to have a salient impact upon psychological responses during the execution of a fatiguing test.

Electrical activity in the muscle. Internal association to physiological sensory cues is expected to elicit *co-contraction* (simultaneous contraction of agonist and antagonist muscles; Lohse

& Sherwood, 2012) and prompt a degradation in physical performance. Based on this assumption, AS is expected to modulate muscle activity and coordination between agonist and antagonist muscles during isometric modes of exercise. An auditory stimulus was adopted to guide attentional focus toward external sensory cues, and it was therefore hypothesized that this approach would ameliorate the effects of fatigue and enhance the neural activation of the working muscles during a fatiguing motor task.

Cerebral mechanisms. The central regions of the cortex (central motor command: precentral and paracentral gyri) are hypothesized to reduce action potentials to the working muscles in cases of peripheral fatigue, and this could be reflected in the EEG as an increase in low-frequency waves such as delta, theta, and low-alpha waves in the frontal and central areas (cf. Craig, Tran, Wijesuriya, & Nguyen, 2012). This hypothesis is predicated on the modulation of output frequency (increase in low-frequency components) to sustain muscular contractions over long periods of time (Cifrek, Medved, Tonković, & Ostojić, 2009). The present authors hypothesized that the precentral and paracentral gyri could potentially reduce neural output to the working muscles in case of fatigue-related sensations (e.g., limb discomfort) caused by interoceptive sensory cues (i.e., group III and IV muscle afferents). The premotor cortex is responsible for controlling the muscles, which suggests that a reduction in action potentials originates in this region. Other somatosensory regions of the brain (e.g., postcentral gyrus) are hypothesized to process fatigue-related symptoms and accordingly up-/down-modulate the activity of the central motor command (i.e., an indirect response; de Morree, Klein, & Marcora, 2012). Auditory Stimuli should divert attention away from internal sensory cues and increase exercise performance. It is hypothesized that the beneficial effects of listening to music during exercise should correspond with frequency modulations in the frontal and central regions of the cortex (Bigliassi et al., 2016).

Methods

Participants

Ethical clearance was secured from the first author's institutional ethics committee and written informed consent was obtained from all participants. Undergraduate students were invited to participate via institutional email. Participants who demonstrated an interest in taking part were initially surveyed by the first author to collate demographic data such as age, gender, ethnicity, and sociocultural background. Furthermore, participants were administered the Attentional Focusing Questionnaire (AFQ; Brewer et al., 1996) in order to assess their dominant attentional style during exercise. The inclusion criteria were that participants needed to be: right-handed, music listeners, non-musicians, and apparently healthy. Sample size was calculated using G*Power (3.1) for a one-way ANOVA (within-subject factors; three experimental conditions). Alpha level was set at 0.5 and 1-beta at 0.8 (Cohen, 1994). Based on a large effect size of sensory modulation on attentional focus ($f = 1$; Hutchinson et al., 2015), 15 participants were required. An additional four participants were included in order to account for the likelihood of experimental attrition. In total, 19 participants (10 men and 9 women; $M_{age} = 26.4$, $SD = 3.6$ years; $M_{height} = 170.3$, $SD = 9.4$ cm; $M_{weight} = 67.0$, $SD = 11.5$ kg; $M_{physical\ activity} = 203.1$, $SD = 5$ min/week) completed each experimental phase of the study.

Experimental Design

Participants were invited to the laboratory in order to be familiarized with the apparatus and procedures. Researchers also explained the psychometric measures and addressed any queries that participants had. Subsequently, each participant had her/his legs and face cleaned with preparation pads saturated with 70% isopropyl alcohol. Five EMG surface electrodes (Goldy Karaya Gel electrodes, 28 mm diameter, silver/silver chloride, Arbo, Henley Medical, Stevenage, UK) were placed on the participant's right leg, and 64 EEG electrodes (Quik Cap; Compumedics Neuromedical Supplies) were placed on their scalp.

Participants were instructed that exercise should be sustained until the point of volitional exhaustion or when the participant could no longer tolerate the proposed exercise intensity for more than 3 s. The period of time that participants sustained the contraction was recorded by use of a handheld stopwatch (Casio, model HS-80TW-1EF) and variations in produced force ≤ 10% were permitted. The same piece of music used in the sensory stimulation condition (see Music Selection section) was administered again 5 min after the final experimental condition, as a means by which to identify the sole effects of music that are not evident during exercise. The music-only effects (MO) were subsequently compared with the control condition (CO; no intervention) and music-during-movement condition (MM) in order to explore the brain activity that is exclusively representative of the interaction between music and motor task.

*****Figure 1*****

Music Selection

Eye Of The Tiger by Survivor (109 bpm) was used in the present study as a means by which to ameliorate the effects of fatigue-related symptoms that occur during the execution of exhaustive motor tasks. The rationale underlying this choice was predicated on participants' likely extramusical associations and level of familiarity with this particular track (North, Hargreaves, & Hargreaves, 2004). The track was expected to awaken long-term memories (Watanabe, Yagishita, & Kikyo, 2008) of the *Rocky* movie series and evoke positive emotions (Juslin, 2013) during exercise-related situations (Karageorghis & Priest, 2012a). Participants were asked about their level of familiarity with the stimulus after completing all the experimental phases; all were familiar with the auditory stimulus and related the piece of music to the *Rocky* movie series.

Procedure

Participants were randomly permuted into one block of two experimental conditions (MM and CO) using a deterministic algorithm designed to generate random values. A force transducer (Model 615, S-Type Load Cell, Tedea-Huntleigh Electronics, UK, max 100 kg) was used to measure the foot pressure generated by each participant, who was able to observe the strength line (Spike 2 v4.11; Cambridge Electronic Design) in order to adjust the required rate of contraction. The force signal was amplified 1000 times, low-pass filtered at 2 KHz, and digitized at 1 KHz using a data acquisition unit (micro 1401). In all experimental conditions, the participant was requested to perform an isometric ankle-dorsiflexion contraction until the point of volitional exhaustion at 40% of maximum voluntary contraction (MVC). The maximum voluntary contraction (MVC) was assessed three times in order to identify the peak value before commencement of the exercise bout. The participant was asked to perform the strongest ankle-dorsiflexion contraction for 5 s and a 2-min rest interval punctuated each attempt in order to minimize the effects of muscular fatigue.

A 6-8 min interval was used to induce appropriate recovery between experimental conditions. It was intended that the participant started their next experimental condition when psychophysiological indices returned to baseline levels. Thus, the category ratio (CR10) was administered to assess the limb discomfort and the participant was required to perform a new MVC test. The menstrual cycle of women was not monitored in the present study, because there is strong evidence to suggest that this variable does not influence isometric strength (Nicolay, Kenney, & Lucki, 2007) regardless of the use of contraceptive medication (Elliott, Cable, & Reilly, 2005).

Electromyography

Electrical activity in the muscles was measured by use of electromyography (EMG), which identifies the electrical potential generated by muscle cells. Surface electrodes were placed on the tibialis anterior and lateral gastrocnemius in accord with the recommendations of the SENIAM project (Surface Electromyography for the Non-Invasive Assessment of Muscles) and the ground electrode was placed on the lateral malleolus. The EMG signal was amplified 1000 times, low-pass filtered at 20 Hz, and digitized at 1 KHz using a data acquisition unit (micro 1401).

Electroencephalography

Electrical activity in the brain was assessed by means of a 64-channel Quik-cap. The 64 Ag/AgCl electrodes were attached to the scalp based on the international 10-20 system and filled with Quik gel (Compumedics Neuromedical Supplies). The mastoids were used to digitally reference the brain electrical signal. Two pairs of electrodes captured the horizontal (HEO) and vertical eye movements (VEO). Impedance was kept below 5 kΩ. The brain electrical signal was amplified at a gain of 1000. Online bandpass filters 0.1 – 100 Hz were used to reduce electrical interference and muscle artifacts. The signal was acquired through the use of the software Scan 4.4 acquisition and digitized at 1000 Hz.

In-task Measures

Selective attention was assessed every 30 s by use of the Tammen's (1996) single-item state attention scale (SIAS). The SIAS measures the allocation of attentional focus to internal and external sensory information during the execution of physical tasks. Limb discomfort (CR10; Borg, 1982), situational motivation (MOT, Tenenbaum, Kamata, & Hayashi, 2007), affective valence (Feeling Scale [FS]; Hardy & Rejeski, 1989) and felt arousal (Felt Arousal Scale [FAS], Svebak & Murgatroyd, 1985) were assessed prior to and immediately after the exercise bout. An order of administration was established and applied consistently throughout the experiment (1st SIAS, 2nd CR10, 3rd MOT, 4th FS, and 5th FAS). The CR10 was used to measure the level of limb discomfort associated with the active limb during the execution of a fatiguing task using the response set “How much discomfort are you feeling in your leg?” Situational motivation was used to measure how motivated participants were feeling at that moment using the response set “How motivated are you feeling?” The FS was applied to assess participants’ affective state using the response set “How are you feeling right now?” The FAS was used to measure the level of perceived activation/arousal that one experiences using the response set “How aroused are you feeling right now?”

Data Analysis

Electromyography. Spike2 (v4.11; Cambridge Electronic Design) was used to obtain time and frequency indices from the muscle electrical signal, which was initially filtered, rectified, and smoothed. Time and frequency domains were used to identify the motor unit recruitment and fatigue-related symptoms, respectively. The root mean square value obtained from the raw EMG data is representative of the motor units necessary to produce a certain level of contractile strength. The mean frequency obtained from the frequency spectrum was used as an index of fatigue (Arendt-Nielsen & Mills, 1988). Fatigue-related symptoms usually increase over time as a response to increasing exercise intensity. Accordingly, the mean frequency is expected to decrease, because the firing rate of electrical signals emitted by the brain also decreases over time as a response of increasing RPE (Cifrek, Medved, Tonković, & Ostojić, 2009). Fast Fourier Transform was used to decompose the EEG signals into different wave frequencies. The mean frequency of the power spectrum (MF) was calculated as a means to compare experimental conditions and identify the trend by which fatigue occurs over time (De Luca, Sabbahi, & Roy, 1986). The root mean square (RMS) was used to identify the motor unit recruitment. The recruitment of motor units is expected to increase over time as a means by which to compensate the increasing exercise intensity (Chester & Durfee, 1997). The agonist-antagonist ratio was calculated by dividing the average of the anterior tibialis RMS value by the average of the gastrocnemius RMS value.

Electroencephalography. A default EEG cap (Neuroscan Quik-cap 64) was used to create topographical results. The brain electrical signal was visually checked in an attempt to identify bad electrodes; these were subsequently removed for further analyses. Bad electrodes were only identified in two instances and discarded. Large artifacts were identified observing the raw file and discarded before subsequent transformations. Blink events were created and consequently corrected (blink artifact rejection) using independent component analysis by tracking down the activity of vertical eye movements. The EEG data were imported to the database by splitting the original file into 1-s windows (asynchronous samples), DC-offset correcting, and re-sampling the original file at 1000 Hz (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011). The EMG signal was used to indicate the period of time between the participant starting and finishing the test. The initial and final 5 s of contraction were also removed as a means to prevent the influence of rapid neurological adaptations to the onset and offset of movement execution. Therefore, the EEG signal processed in the present experiment overlapped muscular contractions due to the fact that the fatiguing test was conducted isometrically for approximately 2–3 min. Subsequently, the 1 s samples were submitted to bandpass filters 0.5–30 Hz, 24 dB/octave. The number of samples varied according to participants and experimental conditions, because the exercise was performed until volitional exhaustion.

Three folders were created to separate the experimental conditions (19 files each; CO, MM, and MO). The results are presented for group data ensemble-averaged waveforms. Fast Fourier Transform (FFT) was used to decompose each 1 s asynchronous samples into different frequencies. Three wave frequencies (theta [3–8 Hz], alpha [8–12.5 Hz], and beta [12.5–35 Hz] bands) were selected to investigate the interconnection between music and the motor task involved (Schneider, Askew, Abel, Mierau, & Strüder, 2010). The average power of FFT values was saved across files (average the spectra) and topographical results were presented for each experimental condition. The power spectrum was exported to excel files for each electrode (62 electrode sites) and band frequency. The mean values were compared between experimental conditions as a means by which to identify the effects of music, exercise, and music-and-exercise on the brain electrical activity. All the EEG procedures applied in the present research were performed with Brainstorm (Tadel et al., 2011), which is documented and freely available for download online under the GNU general public license (http://neuroimage.usc.edu/brainstorm).

Statistical Analysis

The Shapiro-Wilk test was used to verify the suitability of data for parametric analysis. Outlier cases were subsequently excluded as a means to avoid the interference of extreme values on normal distribution. Multiple imputation was used to replace missing values by comparing five different methods of linear regression (see He, 2010). The imputations were consequently compared by use of *F* tests as a means to identify the most appropriate method (greatest *p* value). A multivariate general linear model was used to compare psychological variables, EMG indices, and task performance across two experimental conditions (2 moments: pre and post; 2 experimental conditions: MM and CO). When the assumption of spherecity was violated, a Greenhouse-Geisser correction was applied to the *F* test. Bonferroni adjustments were used to locate statistically significant differences. The EEG signal (power values) was log10 transformed due to exhibiting a platykurtic profile. Electrode sites (62) and band frequencies (theta, alpha, and beta) were compared across three experimental conditions (one-way ANOVA). Interactional analyses were not used to compare active electrode sites. Bonferroni adjustments were used to locate statistically significant differences. The statistical procedures used in the present experiment were conducted on SPSS 17.0.

Results

Checks for univariate outliers indicated that 17 cells had abnormal Gaussian distribution; box plot checks were used to identify these cases which were subsequently removed. Multiple imputation was used to replace the missing values by applying methods of linear interpolation (He, 2010). Four variables (FS, FAS, CR10, and SIAS) did not present normal distribution and had their values corrected through the use of logarithmic transformations (Bland & Altman, 1996). All variables were successfully corrected prior to running the main analyses.

Psychological Responses and Task Performance

ANOVA and *t* test results are presented in Table 1. Participants' attentional style had no influence on the dependent variables of the present study ($p > .05$). The fatigue test used in the present study elicited detrimental effects in participants' affective states; however, values for this variable did not change when participants executed the motor task under the influence of music (CO: FSpre M = 2.31, SD = 1.33, FSpost M = 1.63, SD = 1.30; MM: FSpre M = 2.47, SD = 1.26, FSpost M = 2.31, SD

= 1.45). There were no statistically significant differences between MM and CO for felt arousal (FAS), situational motivation (MOT), and limb discomfort (CR10) measures (see Figure 2). Changes in AS were analyzed over time by calculating the rate of change along the regression line; the attentional slope represents the magnitude by which fatigue-related symptoms force the reallocation of attentional focus to associative thoughts (attentional shift). Participants who performed the task under the influence of music demonstrated greater levels of dissociation throughout the exercise bout (CO: M = -16.36, SD = 9.19; MM: M = -12.61, SD = 6.34). Task performance was significantly different between MM and CO (CO: M =167.58, SD = 81.39 s; MM: M = 196.53, SD = 103.32 s; ~15% of difference).

*****Table 1*****

*****Figure 2*****

Electrical Activity in the Muscles

No statistical differences were identified in the mean frequency of the power spectrum when comparing CO and MM (CO: M = 74.20, SD = 16.85; MM: M = 73.65, SD = 17.13; t = .218; p = .830); correspondingly, the agonist-antagonist ratio was similar between CO and MM (CO: M = 184.07, SD = 71.19; MM: M = 181.92, SD = 65.57; t = .039; p = .969). The electrical activity in the muscles was similar on time and frequency domains, but those results need to be analyzed in tandem with indices of task performance, given that participants who executed the motor task under the influence of music had significant improvements in time to exhaustion, meaning that the auditory stimulus partially *controlled* fatigue and the recruitment of motor units (see Figure 3).

*****Figure 3*****

Electrical Activity in the Brain

The brain electrical activity was analyzed on frequency domain at each electrode site. Results indicated statistically significant differences between CO, MM, and MO (see Table 2). A difference was identified at low-frequency components of the power spectrum. When participants executed the motor task in the absence of music, an increase in low-frequency waves (mostly theta rhythm) was evident in the frontal, central, and parietal regions of the cortex. Conversely, listening to music elicited a decrease in theta waves through the entire surface of the brain compared to CO (see Figure 4 and Figure 5). The same pattern of response was identified when participants exercised in the presence of music; low-frequency waves in the frontal, central and parietal areas were partially suppressed in MM, but the magnitude of the differences was moderated by exercise-related signals. AF3 was the only electrode site that MM differed statistically from both CO and MO (***; $p < .05$). In other words, the results of the present study indicated that theta waves in MM were partially suppressed/inhibited by music and partially stimulated by exertion-related cues (parallel processing of internal and external sensory information).

*****Table 2*****

*****Figure 4*****

*****Figure 5*****

Discussion

The main objective of the present investigation was to further understanding of the attentional processes that occur during a fatiguing isometric ankle-dorsiflexion task by applying music as a potential external distractor. The presence of music was expected to partially reallocate the participants' attentional focus to task-unrelated factors and subsequently ameliorate the effects of peripheral fatigue (Rejeski, 1985; Treisman, 1964; Van Duinen, Renken, Maurits, & Zijdewind, 2007). Due to the multifaceted effects of music on brain activation (Levitin, 2008), the authors also expected a more positive affective state coupled with improvements in task performance.

Affective and Perceptual Responses

The authors of the present study predicted that music would promote a dissociative attentional style, with consequent effects on psychophysiological responses, affect, and task performance. This hypothesis was supported by the results. The findings indicate that music primarily forces attention to auditory areas and therefore evokes positive affective responses. This response is subsequently overcome by the detrimental effects of peripheral discomfort that naturally lead to volitional exhaustion. However, participants sustained the task for a longer period of time under the influence of music, meaning that the reallocation of attentional focus to task-unrelated information led to improvements in task performance when the symptoms of fatigue were fairly light or moderate. Limb discomfort, felt arousal, and situational motivation were similar when compared between MM and

CO. These results are also surprising given that participants who executed the motor task under the influence of music were able to sustain the contraction for a longer duration, which, in accord with the dual-mode theory of affective responses (see Ekkekakis, 2003), should lead to more negative affective responses. The dual-mode theory suggests that affective valence is influenced by cognitive processes and interoceptive cues. Therefore, the increasing exercise intensity is hypothesized to up-regulate afferent feedback from peripheral organs and down-regulate protective cognitive processes such as self-efficacy. This combination of peripheral and central processes is hypothesized to generate negative affective responses during exercises performed at high intensities. The results support the notion that task disengagement relies on the *worthiness* of the action (i.e., one's desire to persist), which is assessed continuously via conscious pathways (Pageaux, 2014). Music-related interventions reduce focal awareness and render reflexive control of movement execution (Kiefer, 2012). The upshot of this is a partial reduction in the interpretation of fatigue-related sensations and consequent increase in time-to-exhaustion.

It is apparent that music-related interventions bear direct and measurable influence on the brain during the execution of exhaustive motor tasks. Moreover, under the influence of auditory stimuli, affective responses to such exhaustive tasks are altered. Jones et al. (2014) demonstrated that even high-intensity bouts of physical activity can feel more pleasant under the influence of music. The authors suggest that subcortical regions of the brain might be responsible for controlling the execution of motor tasks and the processing of music; in this case, little processing would need to take place for music to have its beneficial effects on affective responses. Furthermore, it has been indicated that music could not only activate one sensory region, but also reduce the activity in other sensory regions (Hernández-Peón, Brust-Carmona, Peñaloza-Rojas, & Bach-Y-Rita, 1961) and these combined responses could be responsible for the positive effects of music on fatigue-related symptoms and affective responses (Karageorghis & Priest, 2012a). The present results are noticeably similar to those found by Jones et al. (2014) and Hutchinson et al. (2015), and support the notion that music-related interventions are facilitative strategies that modulate affective valence, attentional focus, and task performance during the execution of exhaustive or fatiguing motor tasks.

Electrical Activity in the Muscles

The authors who developed the present experiment hypothesized that internal association to interoceptive sensory cues was expected to decrease the agonist-antagonist ratio and thus degrade physical performance. Based on this assumption, shifts of attentional focus were expected to modulate the electrical activity in the musculature and the coordination between agonist and antagonist muscles during isometric motor tasks (Lohse & Sherwood, 2012). The use of an auditory stimulus was hypothesized to guide the attentional focus to external sensory cues, ameliorate the effects of fatigue, and consequently enhance the neural activation of the working muscles during a fatiguing bout of physical activity. The results of the present experiment partially support the hypotheses previously proposed. The auditory stimulus was not sufficiently powerful to modulate the mean frequency of the power spectrum and the agonist-antagonist ratio; however, these results need to be interpreted with caution because the motor task was conducted to the point of volitional exhaustion, meaning that the end point varied across participants.

Based on the electrical signal extracted from the anterior tibialis and gastrocnemius (see Figure 3), the present authors were able to identify a physiological index of attentional distraction; participants presumably fell into a partial “trance” (e.g., resting state and meditation; Aftanas & Golocheikine, 2001) during the execution of the motor task. During various periods of time, participants were only partially aware of the fatigue-related symptoms because the auditory stimulus reallocated attentional focus toward somatosensory regions, and the execution of the movements was reflexively controlled by the central motor command. This result is supported by the notion that simple motor tasks can be performed with partial focal awareness if they do not involve extreme symptoms of fatigue or pain (e.g., Kiefer, 2012).

Rejeski (1985) suggested that perceived exertion could be an active process because of its interaction with cognitive factors prior to perception. The present results indicate that Rejeski was possibly correct in his assertions; if music enhanced endurance performance but maintained the recruitment of motor units and the mean frequency of the power spectrum, fatigue-related symptoms had to be only active creations of the brain (De Morree et al., 2012) and activated by attentional processes (Bigliassi, 2015). Interestingly, fatigue-related symptoms (e.g., corollary discharges and internal sensory cues) overcome the protective effects of external sensory information and led participants toward volitional exhaustion (Boullosa & Nakamura, 2013). This faculty was developed through human evolution as a means by which to avoid catastrophic situations and protect humans against osteoarticular injuries, strokes, and seizures (see Noakes, 2012).

Cerebral Responses

The central motor command (precentral and paracentral gyri; Voss et al., 2006) was expected to reduce action potentials to the working muscles and possibly generate an increase in low-frequency waves such as theta and alpha (initial hypotheses; e.g., Cao, Wan, Wong, da Cruz, & Hu, 2014). The effects of music were expected to partially block the processing of internal sensory cues and enhance exercise performance with possible effects on the brain electrical activity (Bigliassi et al., 2016). The results indicated that music not only reallocated the participants' attentional focus toward sensory regions but also rearranged the brain activity throughout the exercise bout. Music suppressed the sharp increase of low-frequency waves in the frontal, central, and parietal regions (see Figure 5). For a short period of time, fatigue-related symptoms were somewhat inhibited by the *defensive* effects of music. The *barrier* imposed by music to reduce exertional responses was initially triggered by attentional processes, because participants were only partially aware of internal sensory cues at light-to-moderate levels of exertion (attentional shift; see Figure 2).

The fatiguing test used in the present experiment was considerably challenging to execute and participants had to control numerous internal (e.g., sensations of fatigue) and external factors (e.g., level of strength produced). The increasing symptoms of fatigue compromised task performance and participants had to maintain force at the target level (40% of MVC), which means that the difficulty should increase over time due to a presumed increase in lactic acidosis and other biochemical metabolic markers. An increase in low-frequency waves in the frontal, central, and parietal regions is possibly associated with the effects of fatigue-related symptoms on executive control during the execution of fatiguing motor tasks. The considerable complexity of the physical task and necessary control to sustain the contraction at the target level naturally reallocated attentional focus toward associative thoughts such as internal sensory cues and task-related information (Hutchinson & Karageorghis, 2013).

The execution of a fatiguing motor task increased low-frequency waves through the entire surface of the cortex. This result has been previously identified by Craig et al. (2012) who demonstrated that fatigue-related symptoms have a strong effect on low-frequency waves in the frontal and central areas. The authors of this study hypothesize that exertional responses modulated theta waves as a means by which to reduce the neural output to activate the working muscles. In order to counteract the effects of fatigue, high-frequency waves are generally manifest in the central regions of the cortex as a means by which to increase neural output and overcome the influence of interoceptive sensory cues (e.g., Bigliassi et al., 2016; Craig et al., 2012). Previous studies have indicated an increase in low-frequency waves (Bailey et al., 2008) and a reduction of high-frequency output as a neural mechanism that controls the working muscles (Hunter, St Clair Gibson, Lambert, Nobbs, & Noakes, 2003; Thongpanja, Phinyomark, Phukpattaranont, & Limsakul, 2012) as a direct response to the increasing exercise intensities. The present results confirmed the psychophysiological mechanisms postulated by Rejeski (1985) that fatigue-related symptoms are strong signals and usually more relevant than external sensory cues (e.g., music). In such instances, it is only a *matter of time* until exertion-related signals *control* decision-making processes. The cerebral mechanisms that underpin such responses are possibly associated with a significant modulation of theta waves in the frontal, central, and parietal regions of the cortex. The left frontal regions of the brain are possibly associated with processes of selective attention during the execution of highly demanding cognitive-motor tasks (cf. Chong, Williams, Cunnington, & Mattingley, 2008).

Limitations of the Present Study

The piece of music used in the present experiment was chosen by the researchers and might not elicit precisely the same cluster of psychophysiological responses across participants, given that music preference is highly personal (North et al., 2004). However, different pieces of music could pose a threat to the internal validity of the experiment due to differences in the psychoacoustic properties of the stimulus (Karageorghis & Priest, 2012b). Based on this assumption, the research team decided to partially compromise the ecological validity of the experiment given its laboratory-based approach. Secondly, the motor task used in the present study can only induce peripheral fatigue (limb discomfort) and might not be sufficiently effective to discharge a large number of corollary signals to sensory regions. Whole-body modes of physical activity can possibly cause substantial discharges of corollary signals from the central motor command and increase the input of afferent feedback; in such instances, the brain regions that activate in response to the sensory stimulus would be possibly different from those identified in the present experiment. However, this study represents the first scientific attempt to illuminate the complex effects of music and exercise on cerebral activity. It is noteworthy that the carryover effects of fatigue might have influenced task performance across conditions, despite the physiological (cardiac stress), neural (MVC), and perceptual (limb discomfort) parameters that were monitored to ensure that participants had regained homeostasis. Moreover, a randomized, counterbalanced design was employed to address the potential confound of fatigue carryover on EEG activity, task performance, and psychophysiological responses.

Conclusions

The present experiment was undertaken as a means by which to further understanding of the effects of music on electrical activity in the brain and psychophysiological responses during the execution of a fatiguing isometric ankle-dorsiflexion task. The findings indicate that music induces a partial attentional switching from associative thoughts to task-unrelated factors during exercise, which leads to improvements in task performance. Participants also experienced a more positive affective state under the influence of music. These psychological responses are possibly associated with a mechanism pertaining to suppression of fatigue-related symptoms that are triggered by attentional processes (corollary discharges/afferent feedback; Bigliassi, 2015). The stimulative piece of music used in the present study down-regulated theta waves in the frontal, central, and parietal regions of the brain when participants executed a fatiguing motor tasks. The effects of music on electrical activity in the brain are possibly associated with a mechanism of attention reallocation, wherein exercise-related afferent cues remain outside of focal awareness over a broader range of intensity.

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