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Effects of auditory stimuli on electrical activity in the brain during cycle ergometry☆

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ABSTRACT

The present study sought to further understanding of the brain mechanisms that underlie the effects of music on perceptual, affective, and visceral responses during whole-body modes of exercise. Eighteen participants were administered light-to-moderate intensity bouts of cycle ergometer exercise. Each exercise bout was of 12-min duration (warm-up [3 min], exercise [6 min], and warm-down [3 min]). Portable techniques were used to monitor the electrical activity in the brain, heart, and muscle during the administration of three conditions: music, audiobook, and control. Conditions were randomized and counterbalanced to prevent any influence of systematic order on the dependent variables. Oscillatory potentials at the Cz electrode site were used to further understanding of time–frequency changes influenced by voluntary control of movements. Spectral coherence analysis between Cz and frontal, frontal-central, central, central-parietal, and parietal electrode sites was also calculated. Perceptual and affective measures were taken at five timepoints during the exercise bout. Results indicated that music reallocated participants' attentional focus toward auditory pathways and reduced perceived exertion. The music also inhibited alpha resynchronization at the Cz electrode site and reduced the spectral coherence values at Cz–C4 and Cz–Fz. The reduced focal awareness induced by music led to a more autonomous control of cycle movements performed at light-to-moderate-intensities. Processing of interoceptive sensory cues appears to upmodulate fatigue-related sensations, increase the connectivity in the frontal and central regions of the brain, and is associated with neural resynchronization to sustain the imposed exercise intensity.

1. Introduction

Auditory stimuli have been used in sport and exercise settings to assuage the effects of fatigue-related sensations and render a given activity more pleasant than under normal circumstances [13,36]. Music-related interventions have been widely used in a range of contexts and exercise modalities such as running [89] and swimming [41]. In exercise-related applications, auditory distractions have been proven to have a substantial effect on attentional focus, rendering execution of the exercise more automatic/unconscious (i.e., increase of dissociative thoughts; [45]). The effects of auditory stimuli on information processing during exercise appears to be the trigger responsible for initiating "domino reactions" that lead to psychophysiological benefits (see [5]). However, the cerebral mechanisms that underpin the effects of environmental distractions on psychophysiological parameters during exercise remain unclear.

1.1. Music: from the brain to the heart

The effects of music-related interventions on brain activity have been extensively studied in non-exercise-related settings (e.g., [50,78]). Researchers have demonstrated that music is processed by a sequence of neuronal processes starting at the level of cochlear cells, which leads to a multifaceted response that connects perceptual and emotional areas (see [97]). The brain appears to process music through a hierarchical sequence of neural events [66]. Relevant neuronal processing of an auditory input begins in the brainstem and temporal lobe (components processing; e.g., pitch and tempo), and can subsequently evoke emotional responses in the frontal lobe (e.g., orbitofrontal cortex), cingulate gyrus, and subcortical regions of the brain such as amygdala [4,51]. The emotions elicited by music are characterized by an idiosyncratic pattern of response [38]. In other words, an individual's response to a piece of music is partly governed by personal

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factors such as sociocultural background and pre-existing mood.

1.2. Exercise and brain activity

The effects of physical exercise on brain activity have been investigated extensively (e.g., [69,82,92]). Early studies demonstrated that physical exercise increases the release of calcium in the blood with consequent effects on the synthesis of dopamine in the brain (e.g., [81]). Interestingly, the examination of the brain function during physical tasks has been conducted relatively recently [28], because limb movements and muscular contractions usually elicit artefacts in the biological data that severely compromise its quality [49,91]. With the benefits afforded by technological advances, researchers are now able to investigate the brain during exercise (e.g., [25]). The modulation of brain frequencies has been examined extensively and linked to diverse cognitive processes (e.g., [53]), sensory stimuli (e.g., [75]), and physical tasks (e.g., [77]).

Using a stationary isometric exertion task in combination with a traditional EEG system, Bigliassi et al. [8] demonstrated that environmental sensory cues serve to downregulate low-frequency waves (i.e., theta) in the frontal regions (F8 electrode site) and upregulate high-frequency waves (i.e., beta) in the central regions (C3 and C4 electrode sites) in counteracting the effects of fatigue-related sensations during the execution of a highly fatiguing motoric task (i.e., handgrip-squeezing task). However, whole-body exercise modes are hypothesized to generate a larger number of afferent signals from working muscle than peripheral fatiguing tasks (i.e., local exercise modes). In such instances, music-related interventions serve to reallocate attentional focus toward external influences and make the execution of movements reflexively controlled by the central motor command (i.e., precentral and paracentral gyri; [98]), a mechanism that has been coined *partial trance* [6].

1.3. Whole-body exercise modes

Whole-body exercise modes (e.g., running) represent types of physical effort that require a substantial proportion of the musculature to contract simultaneously in order to generate precise movements. Part-body exercise modes (e.g., handgrip) only induce peripheral fatigue, sometimes referred to as limb discomfort [29], and are commonly perceived by the organism as muscle pain. Conversely, whole-body exercise modes induce strong exertional responses that force exercisers to disengage from the task [59,62]. Whole-body exercises require a substantial number of action potentials from the central motor command (precentral and paracentral gyri) to enable movements such as walking [59,62]. The greater signal output emitted by the brain is also hypothesized to produce larger corollary discharges (efference copies) to areas of the brain associated with perceptions of effort [64]. This physiological response appears to be consequent to the large proportion of working muscles that characterize whole-body modes of exercise [56].

Afferent feedback from working muscles increases fatigue-related sensations during exercise [68] by reallocating one's attentional focus toward task-related information (i.e., indirect effect determined by selective attention; see [5]). Therefore, exertional responses are simply active creations of the human brain [73]; a complex faculty developed to protect the organism against tragic situations (e.g., injuries) caused by *purposeless actions*. Using this as a premise, reallocation of attentional focus toward task-unrelated information has been proven to ameliorate the effects of fatigue and enhance task performance across the gamut of intensities associated with whole-body modes of exercise [34,36]. The underlying mechanisms of attention reallocation during exercise are related to the fact that dissociative thoughts (i.e., focusing outwardly toward environmental cues) induce a more restful state (e.g., meditation), that renders the exercise more automatic and unconscious [45]; thereby reducing exertion and enhancing pleasure.

1.4. Aim of the present study

For a period spanning over a century, researchers have examined the effects of music using a diversity of exercise modalities [1,80]. Musical components have been thoroughly investigated [10,11,27] and conceptual frameworks developed (e.g., [39]). However, the neural underpinnings of music-related interventions during real-life exercise modes (e.g., cycling) are relatively unchartered waters for investigators. The present study sought to further understanding of the cerebral processes that underlie the effects of music on psychological and visceral responses during a whole-body mode of exercise (stationary cycling) performed at light-to-moderate intensities.

1.5. Research hypotheses

The execution of whole-body modes of exercise in the presence of music is hypothesized to increase the number of dissociative thoughts and induce a more positive affective state [34,80]. Music is also hypothesized to ameliorate the effects of fatigue-related symptoms during exercise performed at light-to-moderate-intensities [40]. In turn, these exertional responses (e.g., increase of limb discomfort) modulate the activity of the autonomous system during exercise [76]. Sympathetic and parasympathetic activities are primarily modulated by the physiological stress imposed by muscular contractions. Processing of external sensory cues is partially overcome by the effects of afferent feedback caused by internal sensory cues [62]. Therefore, sensory stimuli are hypothesized to have only small-to-moderate effects on the neural control of the sinoatrial node during whole-body modes of exercise performed at light-to-moderate intensities (i.e., below ventilatory threshold; [24]), because mechanoreceptors strongly redirect the outflow of blood pumped by the heart to the working muscles [21] and generate numerous electrical outputs to the brain which, in theory, force attentional focus toward fatigue-related sensations [45,73].

Low- (e.g., theta) and high-frequency (e.g., beta) components of the power spectrum are expected to change in the frontal and central regions of the cortex when participants execute the exercise task in the presence of pleasant environmental stimuli [8]. Music is expected to reduce the frequency of neural outputs that is required to control the working muscles and moderate the communication across somatosensory regions. This mechanism might serve to down-modulate exercise-related consciousness, reallocate focal awareness toward pleasant environmental cues, and optimize the neural activation of working muscles; thus inducing a more autonomous control of movement [6].

2. Method

The present experiment made use of a high-temporal resolution technique (EEG) to further understanding of the cerebral mechanisms that underpin the effects of music-related interventions on psychophysiological responses during whole-body modes of exercise. The researchers decided to investigate the effects of music on the electrical activity in the brain during a simple mode of exercise to firstly characterize such responses in a real-life (e.g., cycle exercise) well-controlled movement pattern. An additional auditory stimulus condition—an audiobook—was included to facilitate identification of the effects of auditory attentional distraction that is devoid of musical components (e.g., melody and harmony). The electronic devices that were used in the present study were non-invasive and developed for application during exercise-related tasks. Ethical approval was obtained from the Brunel University London Research Ethics Committee prior to commencement of data collection.

2.1. Participants

The sample size required for the present experiment was calculated using G*Power 3.1 [26]. Results of the study by Lim, Karageorghis, Romer, and Bishop [52] were used as group parameters to estimate the effect size. It was indicated that 18 participants would be required ($d = 0.71$; $\alpha = 0.05$; $1 - \beta = 0.80$). An institutional e-mail was circulated among students to which the participant information sheet was attached detailing the objectives and potential risks associated with the study. Those who expressed an interest in taking part were initially surveyed to ascertain their sociocultural background and acquire basic demographic data such as age, nationality, and anthropometric indices (e.g., self-reported height and weight). In order to engage in the study, potential participants were required to meet the following inclusion criteria: be right-handed, music listeners (i.e., listen to music on a daily basis), apparently healthy, and not present any hearing-related disorders. Eighteen healthy adults (8 female and 10 male; $M_{age} = 25.2$, $SD = 4.1$ years; $M_{height} = 172.1$, $SD = 9.3$ cm; $M_{mass} = 71.3$; $SD = 1.7$ kg; $M_{physical\ activity} = 213.3$, $SD = 80.5$ min/week) were recruited.

2.2. Experimental procedures

Participants were administered light-to-moderate intensity bouts of physical activity performed on a mechanically-braked cycle ergometer (Monark Ergomedic 874-E). The equipment and exercise mode were selected to elucidate the effects of music on cycle exercise. This form of physical activity is commonly accompanied by music in health and leisure centers and thus represented an ecologically valid exercise mode. Moreover, the research team were able to control temperature, humidity, and environmental sensory cues with relative ease. Portable techniques, with a minimalization of cables, were used to identify the electrical activity in the brain, heart, and muscle. The duration of experimental procedures was no longer than 110 min.

2.2.1. Pre-experimental phase

Prior to engaging in the main experimental protocol, participants were asked to provide written informed consent, and complete the Physical Activity Readiness Questionnaire (PAR-Q; [94]). The psychological measures (see Psychological Measures section) were also presented at this juncture as a familiarization procedure. This strategy was intended to avoid interpretation-related mistakes and facilitate more automatic responses from participants. Subsequently, participants were administered an incremental cycle ergometer test to familiarize them with the laboratory/experimental procedures and establish ventilatory threshold (VT). During the experimental phase, this physiological index was used to determine the relative exercise intensity during the experimental phase.

Participants pedaled at 50 W and the exercise intensity was increased by 25 W every 3 min [47] up to 75% of maximal heart rate (~145 bpm) estimated by use of the age-predicted maximal heart rate equation (i.e., 208–07 × age; [87]). VT1 was expected to occur at a heart rate of ~135 bpm in healthy young participants (see [52]). A heart rate monitor (V800 Polar; H7 Polar strap; [30]) was attached to the participant's chest to enable monitoring of the cardiac stress imposed by the increasing physiological load. R–R intervals were monitored throughout the experiment and data were subsequently imported to Kubios HRV software. Time–domain (e.g., root mean square of successive differences [RMSSD]) and non-linear domain (e.g., standard deviation 1 [SD1; short-term variability]) analyses were applied to detect VT1 through the use of deflection points of HRV (HRVvt1; see [47]).

2.2.2. Experimental phase

The exercise intensity employed in the experimental phase was expected to induce only mild symptoms of fatigue. Also, recovery periods were observed in between bouts of exercise (minimum 10 min). Subsequent experimental conditions were initiated when participants had completely recovered. Physiological and perceptual measures were taken throughout each experimental trial in order to monitor the effects of limb discomfort and whole-body fatigue on perceptual variables (e.g., perceived exertion), affective (e.g., affective state), and visceral responses (e.g., heart rate).

The same heart rate monitor previously described in the pre-experimental phase section was attached to the participant's chest and a 32-channel EEG cap (EEGO Sports ANT Neuro) was placed on her/his scalp. Conductive gel (OneStep) was applied to both devices in order to improve conductance between the biological signal and electrodes. Female participants were asked to attach the heart rate strap in a concealed changing area. Participants were asked to remain motionless for 10 min and the heart rate value observed at Minute 10 was used as the heart rate rest index (baseline). The participant's affective state (see Psychological Measures section) was also assessed to identify levels of affective valence prior to initiation of the experimental phase.

Two experimental conditions (music: MU; audiobook: AB) and a control condition (CO) were administered in order to identify the effects of auditory stimuli on electrical activity in the brain and psychophysiological responses during exercise. The use of AB was expected to reveal the electrical responses associated with the use of auditory stimuli that are devoid of musical elements. A control condition (i.e., ambient noise) was used to further understanding of cortical changes associated with cycling ergometry in the absence of auditory stimuli. Thus, through comparing MU, AB, and CO, the researchers were able to partially isolate the effects of musical components on EEG activity. Conditions were randomized and counterbalanced by use of a deterministic logarithm in order to prevent any influence of systematic order on the dependent variables. The exercise bout consisted of 12 min (warm-up [3 min], exercise [6 min], and warm-down [3 min]) performed at 45 rpm. The exercise intensity increased from the warm-up period (0–3 min: 20% below VT) to the last minute of the exercise bout (3–9 min: 10% below VT) and decreased during the warm-down period (9–12 min: 20% below VT; see Fig. 1).

2.3. Music selection

The research team selected *Don't Let Me Be Misunderstood* (119 bpm) by Bennie Benjamin, Gloria Caldwell, and Sol Marcus (Santa Esmeralda version) in order to reallocate participants' attentional focus toward auditory pathways, evoke positive emotional responses, and assuage the mild effects of fatigue-related symptoms [42,43]. This piece of music was chosen due to its moderately stimulative, cheerful, and pleasant qualities. It also lasts for 16 min, 6 s, meaning that it could be

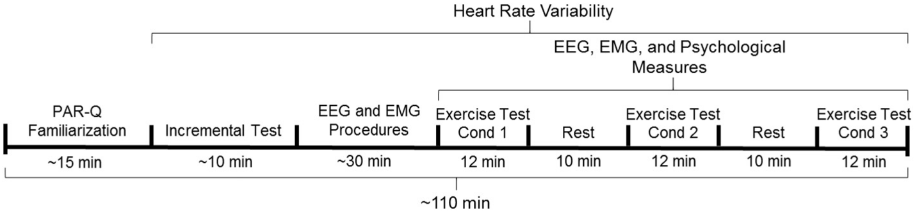

Fig. 1. Diagrammatic representation of experimental procedures for which conditions were randomized and counterbalanced.*Note.* PAR-Q = Physical Activity Readiness Questionnaire; EMG = electromyography; EEG = electroencephalography; Cond = condition (control, audiobook, or music).

played for the entire duration of the exercise bout. Music was delivered via headphones (Sony MDRZX100 ZX Series Stereo) and the sound intensity was kept at ~75 dBA, measured directly at the ear level by use of a decibel meter (BAFX). To identify participants' aesthetic appreciation of the music, a single-item liking scale ranging from 1 (*I do not like it at all*) to 10 (*I like it very much*), was used at the very end of the experiment [46].

2.4. Audiobook selection

Alice's Adventures in Wonderland [14] written by Reverend Charles Lutwidge Dodgson (Pseudo. Lewis Carroll) and read by Sir John Gielgud was used to reallocate participants' attentional focus from interoceptive sensory cues to external cues. The AB was played throughout the exercise bout via the same headphones and at the same intensity as the music. Similarly, a single-item liking scale, ranging from 1 (*I do not like it at all*) to 10 (*I like it very much*), was employed at the very end of the experiment to identify the degree to which participants liked the AB.

2.5. Perceptual and affective measures

During the exercise bouts, four psychological measures were taken at five timepoints (Minutes 0.5, 2.5, 5.5, 8.5, and 11.5) during the exercise bouts. Selective attention was assessed by use of Tammen's [86] single-item attention scale (AS). This provided an indication as to where participants were allocating their attentional focus (external or internal information; e.g., music or muscle discomfort) during exercise. Affective valence was assessed by use of the Feeling Scale (FS; [32]). This is a psychological instrument that examines the hedonic tone of emotional responses, and has been used extensively in exercise science (e.g., [20,44]). Perceived activation was assessed using the Felt Arousal Scale (FAS; [83]) and tapped core affect intensity according to Russell's [74] circumplex model of affect. Perceived exertion was assessed using Borg's [12] RPE scale, which was developed to assess exertional responses during exercise. For each trial, the psychological instruments were administered in the same order (1st AS, 2nd RPE, 3rd FS, and 4th FAS).

2.6. Heart rate variability

HRV indices were compared across conditions in order to examine the effects of different auditory stimuli on the autonomic balance during warm-up, exercise, and warm-down periods [7]. The signal was initially transferred to Polar Flow and subsequently imported into Kubios HRV for analysis [88]. A 3-min window was used to break the signal down into four time samples. Two time-domain indices were extracted from the cardiac electrical signal [9]: Standard deviation of normal-to-normal intervals (SDNN) and root mean square of the successive differences (RMSSD). SDNN was used as an index of global activity of the sympathetic-parasympathetic system, while RMSSD was used as an index of parasympathetic activity [70].

2.7. Electroencephalography and electromyography

A portable EEG system was used to monitor electrical activity in the brain throughout each exercise bout. This equipment facilitated the continuous collection of electrical activity with a 24-bit resolution, and is designed for application during everyday activities. Active shielding technology protected the core components of EEG cables against artefacts generated by body and cable movements (see [16]). The compact EEG amplifier was placed in a compatible backpack where the signal was digitized at 500 Hz. Thirty-two Ag/AgCl electrodes were attached to the participant's scalp in accord with the 10–20 International System guidelines. These were filled with conductive gel to improve electrical conductance and reduce impedance. The impedance level was kept below 10 kΩ and the signal was amplified at a gain of 1000 times. An online bandpass filter (0.5–100 Hz) was applied to reduce the influence of electrical artefacts on the acquired data. The mastoid electrodes (M1 and M2) were used to digitally reference the electrical signal from the cortex.

The EEG signal (.cnt files) was imported into the Brainstorm software [85]. An initial screening procedure entailed identification of bad electrodes and periods of electrical interference (bad segments) were the first procedure to discard irrelevant pieces of information by use of visual inspection (option: *EEG 2-D layout*). Local events were created to identify vertical eye movements (blinks) by use of independent component analysis, which were subsequently removed through the application of signal space projection. A pair of bipolar electromyography (EMG) electrodes were placed on the participant's right vastus lateralis [35] in accord with the SENIAM project recommendations (Surface Electromyography for the Non-Invasive Assessment of Muscles; [79]). Detection of analog triggers was used to accurately locate the onset of muscle contractions. Muscle bursts produced by the vastus lateralis lasted for approximately 550 ms during cycle exercise performed at 10% below VT (45 rpm). The EEG data were epoched based on the EMG bursts (− 300 [readiness potential] to 1000 ms [pedal cycle]), DC-offset corrected and time-series averaged. The root mean square (RMS) of the EMG signals was also calculated to facilitate understanding of the muscle electrical activity required to produce the power output in each condition (see Fig. 2).

Each condition lasted for 720 s but only the central part of the test (i.e., from 210 s to 510 s) was considered for subsequent EEG analysis. This was done to remove the influence of different exercise intensities (i.e., from 20% to 10% below VT) and periods of verbal communication (e.g., responding to scales) on movement patterns (e.g., revolutions per minute) and the brain's electrical activity (i.e., evoked potentials). This exercise portion consisted of ~220 trials (synchronous samples). The time-locked EEG epochs were bandpass filtered offline (0.5–30 Hz) and Fast Fourier Transform was used to decompose the EEG samples into theta (5–7 Hz), alpha (8–12 Hz), sensorimotor rhythm (SMR; 13–15), low-beta (16–19 Hz), beta central portion (BCP; 20–24 Hz), and high-beta (25–29 Hz) frequencies in order to investigate the effects of music on the electrical activity in the brain during cycle ergometer exercise performed at a light-to-moderate intensity [2,25,35]. The power spectra of five brain areas (Frontal: FpZ, Fp1, Fp2, F3, F4, F7, and F8; Frontal-Central: FC1, FC2, FC5, and FC6; Central: Cz, C3, and C4; Central-Parietal: CP1, CP2, CP5, and CP6; Parietal: P3, P4, P7, and P8) were time-averaged and the mean values were compared across conditions (cf. [6,8]).

Oscillatory potentials at the Cz electrode site [25,35] were used to further understanding of time–frequency changes influenced by voluntary control of movements [54]. This electrode site was selected given that it is over the central region of the premotor cortex, where efferent signals are generated to control the lower limbs [60]. Time–frequency maps were decomposed by use of Morlet Complex Wavelets (central frequency = 1 Hz; time resolution = 3 ms; [85]) and 1/f corrected (i.e., spectral flattening) as EEG power decreases with frequency (e.g., this transform multiplies by 8 the power at 8 Hz). Event-related spectral perturbation (ERSP; [55,85]) was calculated to investigate temporal changes in spectral power associated with the pedaling. The advantage of this measure for the present study is that unlike conventional ERP, it includes EEG spectral changes that are not phase-locked to the EMG trigger. ERSP nevertheless tracks spectral changes over time, in this case, over a consistent 1300 ms segment of the pedaling cycle.

We used the average power for each frequency band as a form of baseline index to normalize the data. We decided to use the average power for each band frequency as a baseline index with which to normalize the data given that cycle ergometry phases were constant and evoked potentials were oscillatory in nature (i.e., continuous control of lower limbs and stabilizing muscles). Alpha frequencies were selected to extract the synchronization–desynchronization–resynchro-

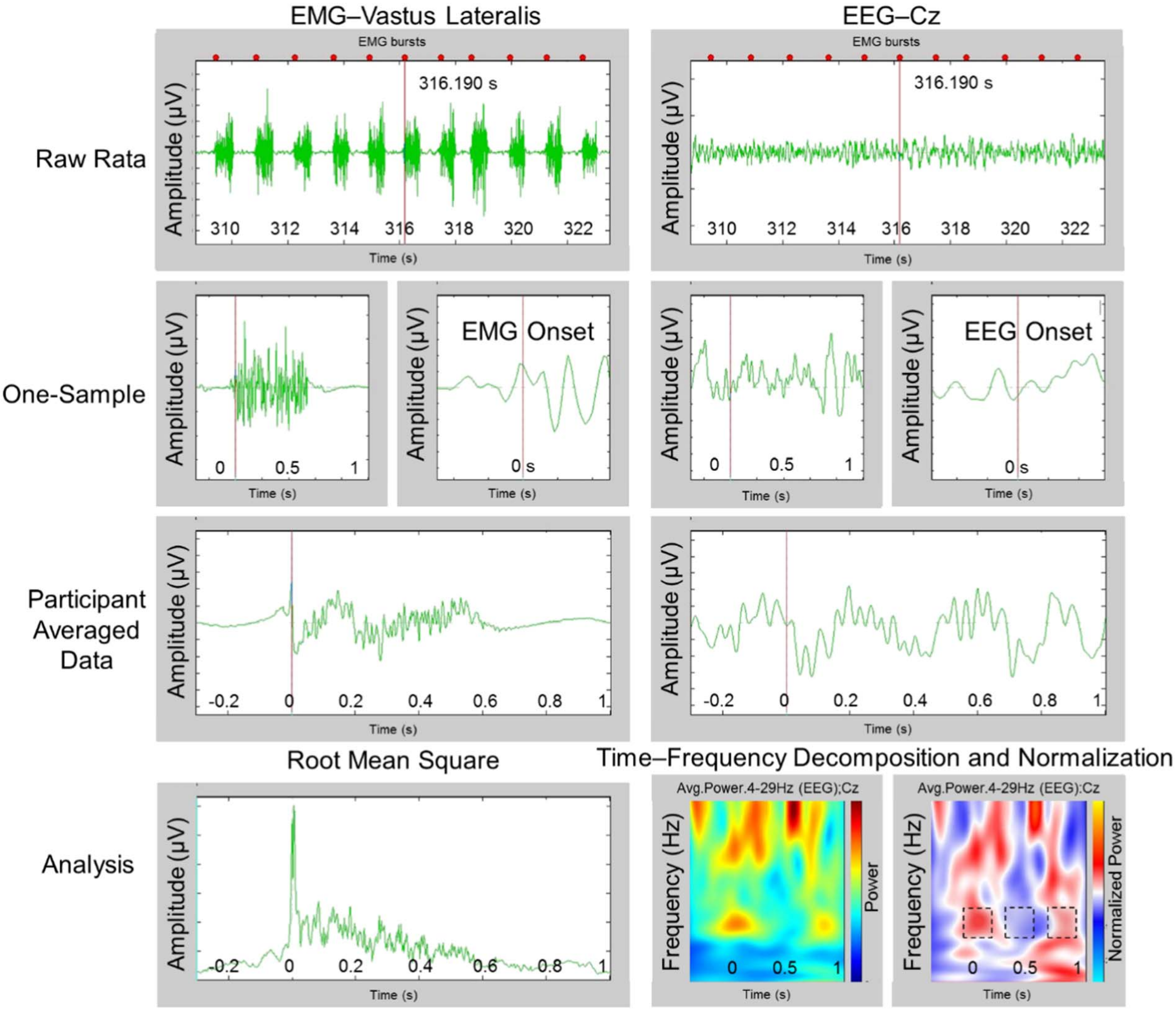

Fig. 2. Offline procedures conducted to process the biological signal. This figure is divided into two columns: The left column indicates the procedures undertaken to process the EMG data; the right column indicates the procedures undertaken to process the EEG data. The first row illustrates the raw data where EMG bursts (top red dots) were reliably identified by use of the *triggers detection* option. The second row illustrates the epoched data followed by the amplified EMG/EEG onset. The time-series waveforms were subsequently averaged for each participant (third row). The root mean square of the EMG signals was then calculated as an indirect measure of motor unit recruitment, while the EEG waveform was decomposed by use of time–frequency techniques and normalized using event-related perturbation (i.e., synchronization–desynchronization analysis). Values within the windows represent the synchronization–desynchronization–resynchronization cycle; these were averaged for each participant and compared across conditions.*Note.* EMG = electromyography; EEG = electroencephalography. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

nization cycle (see Fig. 2). Brain connectivity analysis between Cz and frontal (FpZ, Fp1, Fp2, F3, F4, F7, and F8) frontal–central (FC1, FC2, FC5, and FC6), central (C3, and C4), central–parietal (CP1, CP2, CP5, and CP6), and parietal (P3, P4, P7, and P8) electrode sites was also calculated to explore the communication across wider sensorimotor locations [65,95]. Alpha magnitude-squared coherence values were analyzed throughout the epoch [37].

2.8. Data analysis

For all statistical analyses, univariate outliers were identified through use of the standardized scores (*z*-scores) method on SPSS 17.0. Accordingly, datapoints lying beyond three standard deviations (i.e., $z > \pm 3.29$; [84]) for the same dependent variable and condition were considered to be outliers. Data normality was initially checked to identify patterns of data distribution that did not fit the Gaussian curve. Log10 transformations were conducted to correct abnormal data as a precursor to parametric analyses [71]. A repeated-measures (RM) general linear model was used to compare the perceptual (attentional focus and perceived exertion; 3 Conditions × 5 Timepoints), affective (affective valence and felt arousal; 3 Conditions × 5 Timepoints), and cardiac (SDNN and RMSSD; 3 Conditions × 4 Timepoints) variables over time followed by Bonferroni-adjusted pairwise comparisons. Post hoc results were included in the figures in cases where significant Condition × Time interactions were identified.

The sphericity assumption was checked by use of Mauchly's *W* test and Greenhouse–Geisser corrections were applied where the assumption was violated. The RMS values were compared across conditions as a counterproof method to further understanding of the neurophysiological mechanisms that underlie the effects of auditory stimuli on the activity of the central motor command. Group data time-averaged band frequencies, RMS amplitudes, time–frequency oscillatory components, and coherence values were compared across conditions using oneway RM ANOVA accompanied by Bonferroni-adjusted post hoc tests. A paired-samples *t*-test was used to compare liking scores for the audiobook and music selection.

3. Results

Analysis of *z*-scores indicated that there were no univariate outliers. The piece of music selected for the present experiment was considered

Table 1
Twoway repeated-measures (RM) ANOVA results for perceptual, affective, and physiological variables.

	Sphericity			RM ANOVA			
	W	*p*	ε	*F*	*df*	*p*	η_p^2
Attentional focus							
Time	0.008	0.001	0.355	5.95	1.42, 24.15	0.014	0.26
Condition	0.751	0.101	0.801	7.53	2, 34	0.002	0.30
Time × Condition	0.003	0.001	0.425	2.69	3.4, 57.80	0.048	0.13
Perceived exertion							
Time	0.009	0.001	0.333	34.55	1.3, 22.63	0.001	0.67
Condition	0.890	0.392	0.901	6.26	2, 34	0.005	0.27
Time × condition	0.022	0.029	0.544	1.94	4.35, 73.99	0.107	0.10
Affective valence							
Time	0.029	0.001	0.384	6.06	1.53, 26.08	0.011	0.26
Condition	0.351	0.001	0.606	8.57	1.21, 20.61	0.006	0.33
Time × condition	0.058	0.275	0.632	1.93	8, 136	0.060	0.10
Felt arousal							
Time	0.159	0.001	0.528	3.81	2.11, 35.90	0.029	0.18
Condition	0.632	0.025	0.731	3.17	1.46, 24.84	0.073	0.15
Time × condition	0.032	0.078	0.684	1.00	8, 136	0.434	0.05
SDNN							
Time	0.134	0.001	0.494	57.21	1.48, 25.20	0.001	0.77
Condition	0.965	0.752	0.966	1.39	2, 34	0.262	0.07
Time × condition	0.126	0.065	0.544	1.79	6, 102	0.107	0.09
RMSSD							
Time	0.169	0.001	0.486	23.72	1.46, 24.79	0.001	0.58
Condition	0.947	0.646	0.950	1.90	2, 34	0.165	0.10
Time × condition	0.004	0.001	0.430	0.98	2.58, 43.90	0.399	0.05

to be moderately pleasant while the audiobook was considered to be moderately unpleasant ($M_{MU} = 6.72$, $SE = 0.28$; $M_{AB} = 4.50$, $SE = 0.50$; $t_{17} = 3.79$; $p < 0.001$).

3.1. Perceptual responses

Attentional focus was mostly externally allocated at 20% below VT. An increase in associative thoughts was manifest when participants exercised at 10% below VT (see Table 1). The audiobook was not sufficiently engaging to guide participants' attentional focus toward auditory sensory cues. Within-subjects interaction analyses indicated that attentional focus was significantly influenced by both condition and time factors. Multiple comparison tests indicated that the piece of music used in the present study increased the use of dissociative thoughts throughout the execution of cycle exercise performed at light-to-moderate-intensities (see Fig. 3A). For all conditions, exertional responses increased over time, from the warm-up period (20% below VT) to exercise (10% below VT), and slightly reduced during the warm-down period across all conditions. MU ameliorated fatigue related-sensations during the execution of the cycle task with a large effect of condition evident ($\eta_p^2 = 0.27$), while the audiobook had no significant effect. Rate of perceived exertion was not influenced by condition or time factors.

3.2. Affective responses

Execution of the cycle task led to reductions in participants' affective states (see Table 1). When compared with CO and AB the music condition upregulated participants' affective states to a greater degree ($\eta_p^2 = 0.33$). However, no significant Condition × Time interaction was evident. Similarly, no significant interactions were identified for felt arousal. Despite temporal changes associated with the effects of exercise, auditory stimuli were not sufficiently effective in up/down-regulating participants' perceived activation.

3.3. Autonomic control

HRV time-domain indices were compared across conditions to further understanding of the effects of different auditory stimuli on sympathovagal balance during light-to-moderate-intensity exercises performed on a cycle ergometer. SDNN was significantly reduced over time and was associated with a large effect (see Table 1 and Fig. 5A; $\eta_p^2 = 0.77$); nonetheless, no differences were evident across conditions. No Condition × Time interaction effects were identified. A similar temporal response to SDNN was evident for a parasympathetic index (RMSSD; $\eta_p^2 = 0.58$) of the autonomic control (see Fig. 5B), and no differences were identified across conditions. No Condition × Time interactions were evident for RMSSD.

3.4. EEG frequency components

The average power of each band frequency was compared across conditions to ascertain the effects of different auditory stimuli on the brain's electrical activity during the execution of light-intensity whole-body exercise performed on a cycle ergometer. Results indicated that alpha waves were upregulated in the central, central–parietal, and parietal regions of the brain when participants exercised with the audiobook (see Table 2 and Fig. 6). SMR frequency bands were also upregulated in the frontal regions in MU and AB when compared to CO. Averaging of the power spectra partially equalized time-related changes caused by auditory cues (see Time–Frequency Oscillatory Potentials section below).

3.5. Time–frequency oscillatory potentials

Time–frequency maps at the Cz electrode site, decomposed through the use of Morlet Complex Wavelets, were compared across conditions to further understanding of the effects of auditory stimuli on the central motor command during exercise. Time–frequency signals vary from theta to high-beta frequencies (5–29 Hz; *y*-axis) and are time-locked to the onset of muscle bursts (− 0.3–1 s; *x*-axis). The warm colors represent higher-than-average EEG spectral power, while cool colors represent lower-than-average EEG spectral power. The same convention applies for 2-D topographical results. Time-series waveforms and topographical results illustrate alpha oscillatory potentials; however,

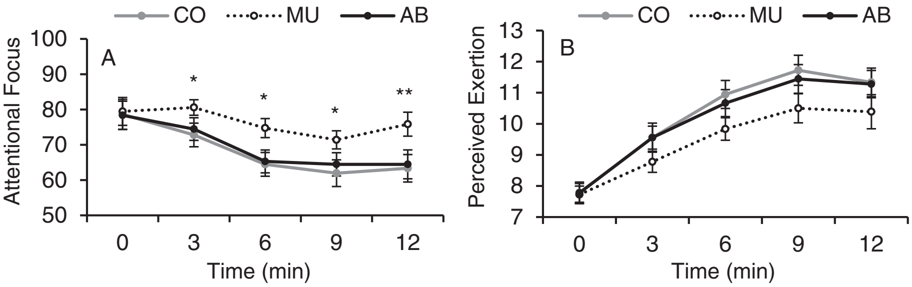

Fig. 3. Psychophysical responses compared across CO, MU, and AB. A = attentional focus compared across CO, MU, and AB; B = rating of perceived exertion compared across CO, MU, and AB. Means and standard errors are presented.*Note.* CO = control condition; MU = music condition; AB = audiobook condition; * = MU was statistically different ($p < 0.05$) to CO. ** = MU was statistically different to both CO ($p = 0.001$) and AB ($p = 0.034$).

Table 2
Oneway repeated-measures (RM) ANOVA results for time-averaged band frequencies, time–frequency oscillatory components, root mean square amplitude, and magnitude-squared coherence.

		Sphericity			RM ANOVA			
		W	*p*	ε	*F*	*df*	*p*	η_p^2
Theta	Frontal	0.483	0.003	0.659	2.01	1.31, 22.41	0.167	0.106
	Frontal–central	0.616	0.021	0.722	1.23	1.44, 24.56	0.304	0.068
	Central	0.973	0.805	0.974	1.43	2, 34	0.252	0.078
	Central–parietal	0.718	0.071	0.780	0.57	2, 34	0.567	0.033
	Parietal	0.822	0.208	0.849	0.74	2, 34	0.484	0.042
Alpha	Frontal	0.591	0.015	0.710	3.60	1.41, 24.12	0.056	0.175
	Frontal–central	0.442	0.001	0.642	2.65	1.28, 21.82	0.111	0.135
	Central	0.733	0.083	0.789	3.83	2, 34	0.032	0.184
	Central–parietal	0.940	0.608	0.943	4.59	2, 34	0.017	0.213
	Parietal	0.974	0.810	0.975	3.96	2, 34	0.028	0.189
SMR	Frontal	0.994	0.955	0.994	4.56	2, 34	0.018	0.212
	Frontal–central	0.972	0.794	0.972	2.66	2, 34	0.084	0.135
	Central	0.818	0.200	0.846	1.71	2, 34	0.196	0.091
	Central–parietal	0.724	0.075	0.784	1.26	2, 34	0.296	0.069
	Parietal	0.889	0.390	0.900	1.37	2, 34	0.266	0.075
Low-beta	Frontal	0.944	0.633	0.947	3.03	2, 34	0.650	0.151
	Frontal–central	0.944	0.629	0.947	1.47	2, 34	0.242	0.080
	Central	0.646	0.030	0.739	0.85	1.47, 25.11	0.435	0.048
	Central–parietal	0.650	0.032	0.741	0.810	1.48, 25.18	0.422	0.045
	Parietal	0.819	0.203	0.847	1.44	2, 34	0.250	0.078
BCP	Frontal	0.743	0.093	0.796	2.47	2, 34	0.103	0.125
	Frontal–central	0.754	0.105	0.803	1.70	2, 34	0.198	0.091
	Central	0.544	0.008	0.687	0.53	1.37, 23.35	0.526	0.031
	Central–parietal	0.742	0.092	0.795	0.53	2, 34	0.590	0.031
	Parietal	0.818	0.200	0.846	0.91	2, 34	0.411	0.051
High-beta	Frontal	0.291	0.001	0.585	2.07	1.71, 19.89	0.141	0.109
	Frontal–central	0.295	0.001	0.586	1.86	1.12, 19.93	0.187	0.099
	Central	0.183	0.001	0.550	0.84	1.10, 18.71	0.380	0.047
	Central–parietal	0.303	0.001	0.589	0.91	1.17, 20.03	0.366	0.051
	Parietal	0.605	0.018	0.717	1.00	1.43, 24.36	0.379	0.056
TFC	Synchronization	1.00	0.924	1.00	4.48	2, 34	0.020	0.230
	Desynchronization	0.795	0.159	0.830	0.375	2, 34	0.690	0.022
	Resynchronization	0.991	0.927	0.991	7.06	2, 34	0.003	0.294
RMS	Vastus lateralis	0.934	0.685	0.938	3.88	2, 34	0.035	0.244
MSC	Cz–FP1	0.897	0.421	0.907	1.87	2, 34	0.170	0.099
	Cz–Fpz	0.888	0.386	0.899	0.85	2, 34	0.919	0.005
	Cz–FP2	0.818	0.201	0.846	1.35	2, 34	0.273	0.074
	Cz–F7	0.884	0.374	0.896	0.459	2, 34	0.636	0.026
	Cz–F3	0.860	0.298	0.877	0.219	2, 34	0.805	0.013
	Cz–Fz	0.717	0.070	0.779	3.34	2, 34	0.047	0.165
	Cz–F4	0.897	0.418	0.906	1.52	2, 34	0.232	0.082
	Cz–F8	0.771	0.125	0.814	1.43	2, 34	0.252	0.078
	Cz–FC5	0.852	0.277	0.871	0.139	2, 34	0.870	0.008
	Cz–FC1	0.830	0.225	0.854	1.48	2, 34	0.240	0.081
	Cz–FC2	0.952	0.675	0.954	2.84	2, 34	0.072	0.143
	Cz–FC6	0.961	0.727	0.962	1.74	2, 34	0.190	0.093
	Cz–C3	0.890	0.385	0.901	0.654	2, 34	0.526	0.037
	Cz–C4	0.950	0.666	0.953	8.12	2, 34	0.001	0.323
	Cz–CP5	0.684	0.048	0.760	1.53	1.51, 25.83	0.234	0.083
	Cz–CP1	0.722	0.074	0.782	0.188	2, 34	0.830	0.011
	Cz–CP2	0.932	0.571	0.937	0.095	2, 34	0.909	0.006
	Cz–CP6	0.873	0.339	0.888	0.270	2, 34	0.765	0.016
	Cz–P7	0.666	0.039	0.750	2.03	1.5, 25.49	0.160	0.107
	Cz–P3	0.737	0.087	0.792	2.30	2, 34	0.116	0.119
	Cz–Pz	0.801	0.189	0.834	0.844	2, 34	0.439	0.050
	Cz–P4	0.919	0.509	0.925	0.774	2, 34	0.469	0.044
	Cz–P8	0.622	0.022	0.725	1.64	1.45, 24.66	0.208	0.088
	Cz–POz	0.730	0.080	0.787	2.33	2, 34	0.113	0.121

Note. SMR = sensorimotor rhythm; BCP = beta central portion; TF = time-frequency components; RMS = root mean square of the electromyographic signal; MSC = magnitude-squared coherence.

changes in EEG activity were not limited to alpha, but similarly manifest from alpha through to BCP frequency bands (see Fig. 7).

An oscillatory potential was identified during cycle exercise at 10% below VT. Synchronization of low- and high-frequency components started at approximately 0.15 s prior to commencement of the muscle burst. In the CO condition, first synchronization was followed by EEG desynchronization and subsequent resynchronization as previously observed by Jain et al. [35] during cycle exercise. The same synchronization–desynchronization–resynchronization pattern was identified when participants exercised in the presence of an audiobook stimulus (see Fig. 7; AB condition). ANOVA indicates that synchronization of the neural population underneath Cz differed significantly across conditions (see Table 2). Post hoc comparisons further indicated that MU upregulated the amplitude of alpha frequencies at the beginning of the contraction to a greater degree than CO and AB. Conversely, the amplitude of the desynchronization phase was not affected by the presence of auditory stimuli (AB and MU). The piece of music completely inhibited EEG resynchronization throughout the time–frequency map in comparison with CO and AB.

3.6. Spectral coherence

Alpha coherence values were compared across conditions to establish whether the presence/absence of auditory stimuli could influence the somatosensory connectivity during the execution of cycle exercises performed at light-to-moderate-intensities. Reduced Cz–C4 (CO: $M = 0.51$, $SE = 0.05$; AB: $M = 0.53$, $SE = 0.06$; MU: $M = 0.37$, $SE = 0.07$) coherence values were identified when participants exercised in the presence of MU when compared to CO and AB (see Table 2 and Fig. 8; $\eta_p^2 = 0.32$). MU also reduced the coherence values at Cz–Fz to a greater degree when compared to AB and MU (CO: $M = 0.39$, $SE = 0.07$; AB: $M = 0.41$, $SE = 0.08$; MU: $M = 0.26$, $SE = 0.08$; $\eta_p^2 = 0.16$).

3.7. Recruitment of motor units

The RMS values of the EMG data collected from the vastus lateralis were compared across conditions to further understanding of how motor units were recruited. The results indicated that higher RMS values were identified when participants exercised in the presence of MU when compared to CO and AB (CO: $M_{RMS} = 3.62$, $SE = 0.30\ \mu V$; MU: $M_{RMS} = 4.77$, $SE = 0.43\ \mu V$; AB: $M_{RMS} = 3.82$, $SE = 0.22\ \mu V$; $\eta_p^2 = 0.24$; see Table 2 and Fig. 9).

4. Discussion

The aim of the present study was to explore the psychophysiological mechanisms that underlie music use during whole-body exercise modes performed at light-to-moderate-intensities. Perceptual, affective, psychophysiological, and cerebral measures were obtained throughout each exercise bout. The results indicate that music reallocated attentional focus toward external stimuli and prompted the greatest use of dissociative thoughts (see Fig. 3A). This dissociation mechanism served to reduce perceived exertion and induce a more positive affective state [5,36]. An audiobook was used to examine the effects of auditory stimuli that are devoid of musical components (e.g., melody and harmony). The audiobook was not a sufficiently potent stimulus to guide participants' attentional focus toward external cues and elicit psychophysiological responses during exercise. Nonetheless, upregulation of alpha waves was evident in the central, central–parietal, and parietal regions of the brain when participants exercised in the AB condition. Interestingly, upregulation of alpha waves induced by AB was not associated with any perceptual, affective, or psychophysiological changes (see Figs. 3, 4, and 5). We hypothesize that such differences in alpha waves might have been primarily induced by semantic and perceptual processes (e.g., mental imagery that is conjured by the story; cf. [3]), with no subsequent effect on perceptual, affective, or psychophysiological responses.

The piece of music used in the present experiment significantly altered the neural power at low- (alpha and SMR) and high-frequency (BCP) bands. We hypothesize that music changed the EEG synchronization episodes, and that this is a signature of the neural processes leading to more efficient control of movements. Light-intensity exercises can be executed autonomously, to a degree, because interoceptive sensory cues (e.g., group III and IV muscle afferents) are not sufficiently potent to force attentional focus toward fatigue-related symptoms [48,73]. The physiological mechanisms that underlie the frequency band and timing of neural synchronization episodes might be associated with the effects of associative thoughts (e.g., focusing inwardly toward interoceptive sensory cues) as resynchronization of neurons occurred at approximately 700 ms after the onset of muscle bursts. As music reallocates attention to external influences, internal sensory cues might have been only partially processed, and thus fatigue-related sensations were dampened. In such instances, the central motor command is hypothesized to resynchronize only at higher frequencies as a means by which to counteract the effects of fatigue and sustain the imposed exercise intensity [8].

It could also be hypothesized that MU only changed the movement pattern as RMS values were considerably greater when compared to CO and AB. A second EMG peak has been identified within the same period of contraction (see Fig. 9) that might characterize a difference in the recruitment of the vastus lateralis when participants exercised in the presence of music. A more efficient cycling pattern in biomechanical terms has the potential to mitigate fatigue-related symptoms [90] and lead, indirectly, to more positive affective responses. As RMS values were upregulated in the vastus lateralis, EMG amplitudes could have been downregulated in other working muscles to sustain the same exercise intensity. Accordingly, medium-tempo popular music appears to down-modulate fatigue-related symptoms, induce more positive affective responses, reduce the connectivity in the frontal and central regions of the brain, moderate neural resynchronization at the Cz electrode site, and facilitate the neural activation of working muscles.

4.1. Perceptual, affective, and psychophysiological responses

The music prompted an increase in the use of dissociative thoughts (i.e., task-unrelated factors; see Fig. 3). Conversely, AB was not sufficiently potent to direct attentional focus toward auditory sensory information. The differences between experimental conditions might be associated with the level of pleasantness that participants reported when they were administered the two auditory conditions. AB did not appear to modulate participants' attention, given that they reported similar perceptual and affective outcomes when compared with CO. However, the present results do not serve to explain whether central and peripheral changes were caused solely by musical components given that participants perceived the two auditory stimuli to be different in terms of pleasantness ($M_{MU} = 6.72$, $SE = 0.28$; $M_{AB} = 4.50$, $SE = 0.50$; see Results section).

The pattern of change observed in participants' rating of perceived exertion followed a similar pattern to that of attentional focus (see

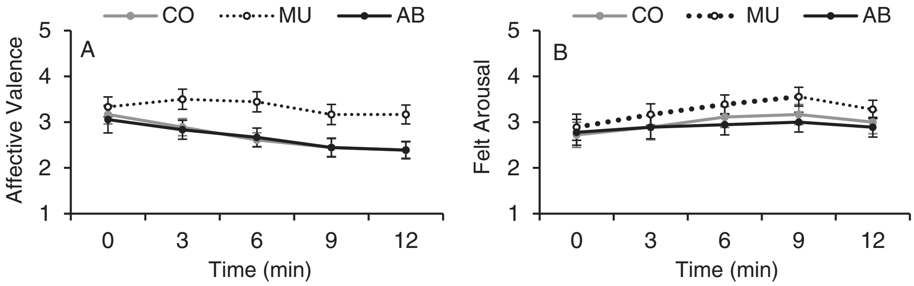

Fig. 4. Affective responses compared across CO, MU, and AB. A = affective valence compared across CO, MU, and AB; B = felt arousal compared across CO, MU, and AB. Means and standard errors are presented.*Note.* CO = control condition; MU = music condition; AB = audiobook condition.

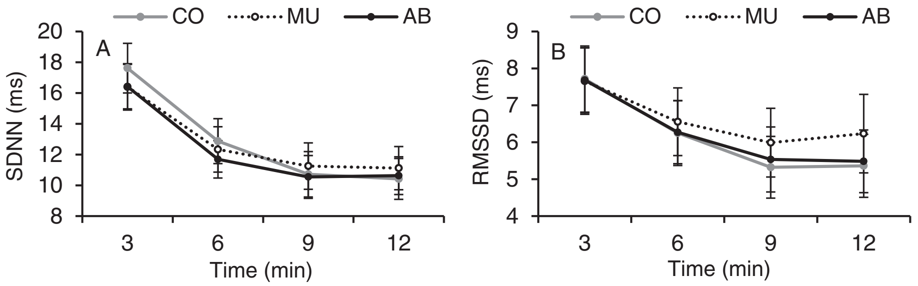

Fig. 5. Sympathovagal indices compared across CO, MU, and AB. A = SDNN compared across CO, MU, and AB; B = RMSSD compared across CO, MU, and AB. Means and standard error are presented.*Note.* CO = control condition; MU = music condition; AB = audiobook condition; SDNN = standard deviation of normal-to-normal intervals; RMSSD = root mean square of the successive differences.

Fig. 3). It has been suggested that music-related interventions have the potential to assuage the effects of fatigue [13,33]. The mechanisms that underlie the effects of music on one's perception of effort are possibly associated with the distractive and stimulative characteristics of music [40]. Bigliassi et al. [6] demonstrated that a motivational music selection downregulated low-frequency components of the power spectrum (theta waves) in the frontal and central electrode sites during the execution of a highly fatiguing isometric ankle-dorsiflexion task performed to volitional exhaustion. In theory, the amplitude of low-frequencies increase to induce a resting state (see [18]). Thus, the brain attempts to slow the body down by upregulating theta waves and reducing the frequency of neural output that controls the working muscles. This is a conscious response (see [62]) based on the execution of what the brain considers as purposeless movements (see [57]). In order to counteract the effects of fatigue and reassume the control of a given task, the brain has to upregulate high-frequency waves in the central motor command [8].

The execution of cycling exercises performed at 10% below VT had a detrimental effect on participants' affective state (see Fig. 4A). The presence of music reduced the negative effects of exercise on affective valence (condition effect). Continuous exercise regimens can be perceived as worthless actions by the human brain [57,72]. Cycling continuously in order to expend calories "that could be used in the future" might, therefore, be deemed to be a purposeless action (see [57]). Interestingly, pleasant environmental stimuli have the potential to guide selective attention toward task-unrelated factors and reduce focal awareness. In such instances, high-order cognitive skills (e.g., self-analysis) can be partially suppressed by the presence of music. During the execution of physical exercise, music-related interventions may assume a prophylactic effect by postponing interpretation of internal sensory cues [45], which subsequently cause participants to report more positive affective responses.

Participants' perceived activation was not significantly affected by music (see Fig. 4B). The piece of music used in the present study was selected by the research team to only force attentional focus toward external dissociation. It has been hypothesized that one's felt arousal could be significantly influenced by motivational stimuli during the execution of high-intensity exercise (see [42,43] for review). The selected track was task-unrelated and its psychoacoustic properties were not directed toward the upregulation of felt arousal. Participants' physiological arousal can be identified through heart rate variability analysis. Both time-domain indices reduced over time as a result of exercise-induced responses (e.g., higher oxygen consumption) and stabilized after ~9 min of exercise (see Fig. 5A and B). The selected exercise intensity was more influential on participants' cardiac stress than the presence of auditory stimuli. The relationship between one's perceived activation and peripheral autonomic responses was predominantly controlled by exercise-related signals. The results of the present study confirm the non-linear relationship between peripheral responses (e.g., heart rate) and one's perceived exertion [58], as peripheral responses are strongly influenced by situational demands (e.g., exercise intensity), while psychophysical and performance-related indices are modulated by psychological factors (e.g., attention and motivation; [6]).

4.2. Neurophysiological responses

An increase in EEG spectral power (low-to-high-frequency bands) has been consistently reported over the course of incremental exercise [2,25]. In such instances, an increase in low-frequency components of the power spectrum such as theta and alpha waves might not be directly associated with a state of relaxation, as commonly indicated by behavioral experiments in which participants are tested at rest (e.g., [31]). Craig et al. [18] suggested that upregulations in low-frequency

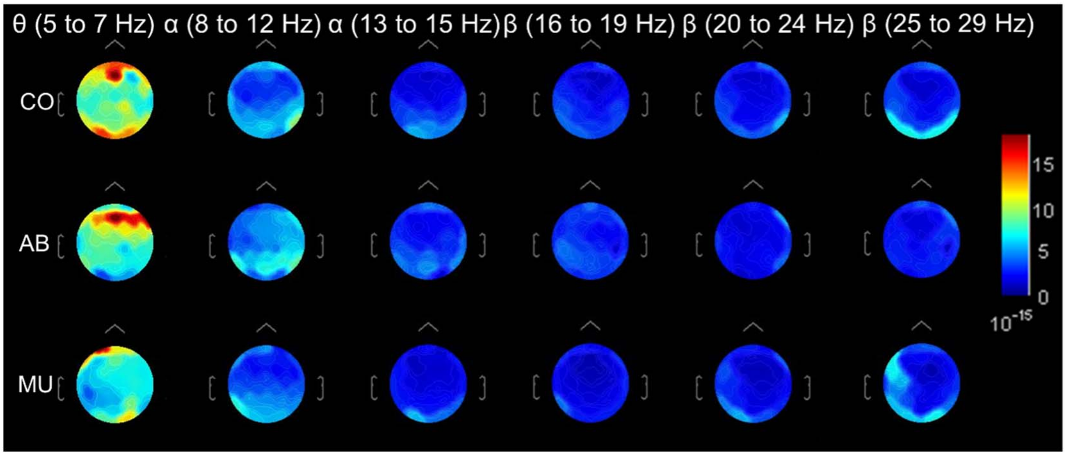

Fig. 6. Group data time-averaged band frequencies for CO, AB, and MU.*Note.* The colored scale indicates the power of the band frequencies (power [signal unitsˆ2/Hz*10ˆ{ − 15}]); CO = control condition; AB = audiobook condition; MU = music condition.

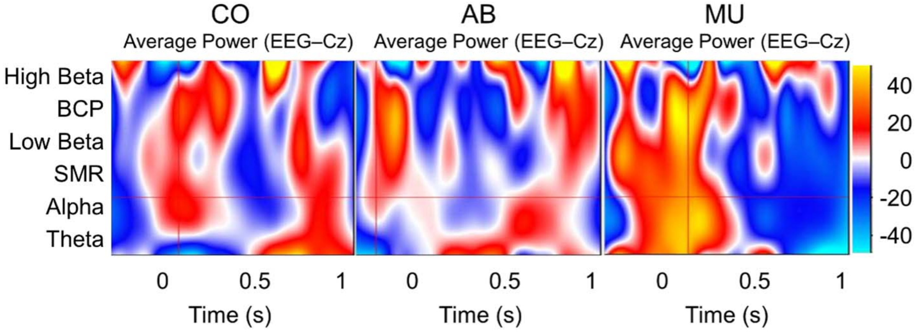

Fig. 7. Group data averaged time–frequency maps (theta, alpha, sensorimotor rhythm, low-beta, beta central portion, and high-beta frequency components) in CO (control condition), AB (audiobook condition), and MU (music condition). MU upregulated alpha synchronization to a greater extent when compared to CO and AB. Resynchronization of low- and high-frequencies was fully inhibited when participants exercised in the presence of music.

waves could be directly associated with fatigue. Therefore, the brain is hypothesized to increase the power of low-frequency waves as a means by which to slow the body down and induce a resting state. This mechanism has been repeatedly supported through the decomposition of EMG signals [17,67], as the median/mean frequency of the power spectrum tends to decrease as participants fatigue.

Time–frequency analysis was employed in the present study to further understanding of frequency modulations that occur in the central motor command over periods of muscle contraction. An oscillatory potential was clearly manifest when participants exercised in the absence of music (CO and AB; see Fig. 7). This valley waveform (i.e., characteristic synchronization–desynchronization–resynchronization pattern) had been previously identified by other studies (e.g., [35]), and suggested to be associated with a synchronization–resynchronization pattern of response. Interestingly, neural resynchronization was mostly inhibited when participants exercised with musical accompaniment. Inhibition of EEG resynchronization occurred not only at low-frequency components (e.g., alpha) of the time–frequency map, but also at high-frequencies (e.g., BCP). In all three conditions, an alpha burst is present at ~0 s, implying that cortical processing is reduced at this time. Interestingly, event-related synchronization occurred not only at alpha frequencies but also at high-frequency components of the power spectrum. It is important to highlight that the synchronization–desynchronization–resynchronization cycle does not represent positive or negative polarity but higher or lower than average spectral power (i.e., time–frequency analysis). Using this assumption as a premise, we hypothesized that synchronization–desynchronization patterns could be associated with the neural control of working muscles (Cz electrode site; [35]).

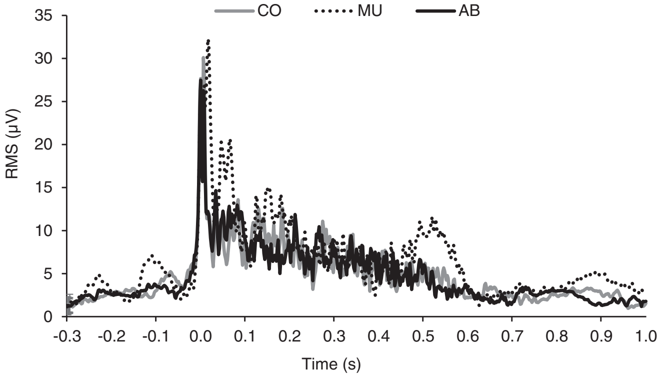

Fig. 9. Group data-averaged RMS amplitude of the EMG signal collected from the vastus lateralis presented for CO, AB, and MU.*Note.* RMS = root mean square; CO = control condition; AB = audiobook condition; MU = music condition.

In this case, music appeared to reduce the frequency at which the

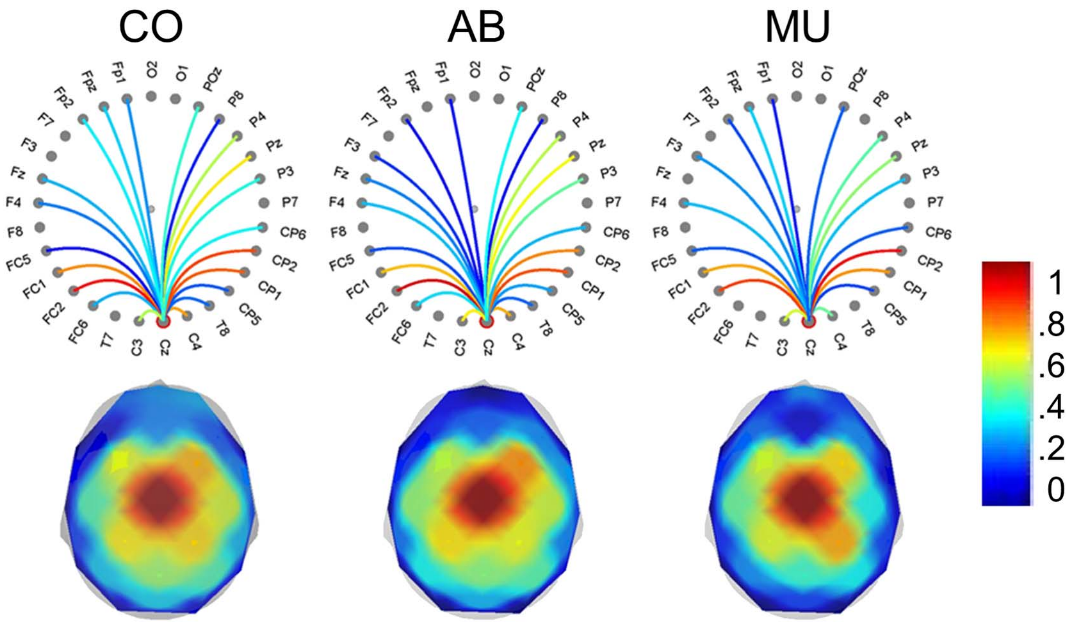

Fig. 8. Group data alpha coherence values in CO (control condition), AB (audiobook condition), and MU (music condition). Reduced spectral coherence is manifest across central and frontal electrodes sites in MU when compared to CO and AB.

brain activates the working muscle; a neurophysiological mechanism that facilitates the movement pattern (i.e., a more effective control) and reduces the communication across somatosensory regions (see Fig. 8). It is important to consider that the phase-locked EEG signals could have been influenced by the temporal characteristics of music, which would implicate an underlying mechanism of sensorimotor synchronization (i.e., coordination of rhythmic movement with an external oscillating stimulus; [19]). Similar neurophysiological responses have been identified when the median nerve was stimulated during the execution of finger movements (i.e., a gating mechanism; see [15]). Notably, the music selection was made with a view to actively discourage participants from synchronizing their pedal rotations (45 rpm) with the tempo of the music (119 bpm). Auditory-motor synchronization is a potential confound in studies such as the present one, wherein there is an explicit focus on the effects of asynchronous music. The tempo of 119 bpm is not divisible by 45 and so auditory-motor synchronization was inhibited through the choice of music.

4.3. Psychobiological mechanisms

An increase in efferent signals caused by associative thoughts could potentially discharge a larger number of corollary signals to somatosensory regions of the cortex (e.g., postcentral gyrus). These efferent copies are theorized to increase one's perceived effort [22,23]. Accordingly, the recruitment of motor units is hypothesized to be reduced slightly when participants exercise in the absence of music as neural outputs are discharged at higher frequencies. In order to investigate whether the present authors' postulate held veracity, the EMG activity of the vastus lateralis was calculated for each condition. The results indicate that higher RMS values were identified when participants exercised in the presence of music when compared to CO and AB. Therefore, allocation of attentional focus toward internal sensory cues might potentially lead to interpretation of fatigue-related sensations (e.g., limb discomfort). In order to sustain the required power output, the central motor command may have had to increase the frequency of firing of neural outputs that control the working muscles. Music-related interventions caused a distractive effect and reduced the EEG amplitude at ~700 ms. A compensatory mechanism may have accounted for the production of the same power output (i.e., an increase in the recruitment of motor units; see Fig. 9).

Output of higher frequencies to control the working muscles (internal association) might have been coupled with efferent copies discharged from the central motor command to somatosensory regions of the cortex [63]. Spectral coherence analysis indicated that the presence of music reduced the communication across frontal and central electrodes sites (see Fig. 8). We hypothesize that reduced brain connectivity in the frontal and central regions of the brain could be associated with reduced exercise consciousness (see Fig. 3; [16,93]) that is commonly induced by the presence of dissociative strategies such as pleasant music [6]. Reallocation of attention toward environmental sensory cues rendered an autonomous and almost reflexive control of movements (i.e., reduced exercise consciousness; see Fig. 3A). This neurophysiological mechanism is proposed to downmodulate neural resynchronization and reduce connectivity across frontal and central regions of the cortex with corollary effects on participants' perceived effort and affective state.

4.4. Limitations of the present study

We attempted to select a piece of music that would elicit similar psychophysiological responses across participants; however, participants tend to react to the same piece of music differently regardless of its characteristics (i.e., they exhibit an idiosyncratic response; [38,61]). The selected piece was only considered to be moderately pleasant, meaning that, in theory at least, personally selected tracks might have elicited more positive affective responses (e.g., [80]). Secondly, a mechanically-braked cycle ergometer was used and thus the revolutions were controlled by the participant. Changes in rpm might have induced slight changes in the epoched data given that crank encoders were not used to determine the pedal rate. However, we detected the very onset of muscle burst, which is a reliable method with which to epoch the EEG data (see Fig. 2). The EMG data were visually checked to ensure that Cz oscillatory potentials were precisely time-locked to muscle contractions.

In regard to preprocessing methods used to clean the raw data, we conducted traditional signal processing procedures to remove electrical artefacts generated by ocular and muscular interferences (see Electroencephalography and Electromyography section). However, it is noteworthy that the electrical activity in the brain might have been minimally contaminated by body movements and repetitive contractions from stabilizing muscles (e.g., trapezius and deltoid; [49]).

5. Conclusions

This study examined the possible effects of music on electroencephalographic activity associated with the execution of whole-body, low-intensity exercise. The results indicate that music reallocated attentional focus toward pleasant sensory stimuli, increased the use of dissociative thoughts, and partially reduced participants' rating of perceived exertion. In other words, interoceptive sensory cues were partially suppressed, as were fatigue-related sensations. Participants also experienced more positive affective responses in the presence music. The music downregulated the EEG amplitude at ~700 ms after the onset of muscle bursts. Accordingly, the EMG activity of the vastus lateralis was calculated as a *counterproof* method by which to investigate whether EEG resynchronization at Cz was associated with efferent control of working muscles. As a result, an increase in the motor unit recruitment was manifest when participants exercised with music, indicating that dissociative thoughts appear to optimize the execution of repetitive movements performed at light-to-moderate-intensities. Reduced focal awareness rendered a more autonomous control of movements and led participants to report more positive perceptual and affective responses. Interpretation of interoceptive sensory cues appears to intensify fatigue-related sensations (e.g., limb discomfort), increase the connectivity in the frontal and central regions of the brain, and demand neural resynchronization to sustain the imposed exercise intensity. Conversely, exercising in the presence of music can lower one's perceived exertion, elicit more positive affective responses, reduce the communication across somatosensory regions, inhibit neural resynchronization in the central motor command, and optimize gross motor control.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.physbeh.2017.04.023.

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