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Cerebral effects of music during isometric exercise: An *f*MRI study☆

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ABSTRACT

A block-design experiment was conducted using *f*MRI to examine the brain regions that activate during the execution of an isometric handgrip exercise performed at light-to-moderate-intensity in the presence of music. Nineteen healthy adults (7 women and 12 men; M_{age} = 24.2, SD = 4.9 years) were exposed to an experimental condition (music [MU]) and a no-music control condition (CO) in a randomized order within a single session. Each condition lasted for 10 min and participants were required to execute 30 exercise trials (i.e., 1 trial = 10 s exercise + 10 s rest). Attention allocation, exertional responses, and affective changes were assessed immediately after each condition. The BOLD response was compared between conditions to identify the combined effects of music and exercise on neural activity. The findings indicate that music reallocated attention toward task-unrelated thoughts (d = 0.52) and upregulated affective arousal (d = 0.72) to a greater degree when compared to a no-music condition. The activity of the left inferior frontal gyrus (lIFG) also increased when participants executed the motor task in the presence of music (F = 24.65), and a significant negative correlation was identified between lIFG activity and perceived exertion for MU (limb discomfort: r = −0.54; overall exertion: r = −0.62). The authors hypothesize that the lIFG activates in response to motor tasks that are executed in the presence of environmental sensory stimuli. Activation of this region might also moderate processing of interoceptive signals – a neurophysiological mechanism responsible for reducing exercise consciousness and ameliorating fatigue-related symptoms.

1. Introduction

Environmental sensory stimuli such as music have been used extensively in exercise- and sport-related tasks (e.g., Terry et al., 2012). They are a means by which to assuage fatigue-related symptoms, elicit more positive affective responses, up/downregulate affective arousal, and enhance the neural control of working muscles (Bigliassi et al., 2017; Hutchinson et al., 2018). Music has also been considered a sensory distraction with the potential to increase adherence to physical activity and counteract the detrimental effects of sedentariness (Clark et al., 2016). Interestingly, the brain mechanisms that underlie the effects of music on exercise have only recently been investigated (e.g., Bigliassi et al., 2016; Tabei et al., 2017). Ascertaining the key networks that activate in response to music will facilitate further understanding of complex phenomena such as selective attention and the perception of fatigue.

1.1. Psychophysiological mechanisms

The combined effects of peripheral feedback associated with interoceptive cues (e.g., group III and IV muscle afferents) are hypothesized to elicit the conscious perception of fatigue (Pollak et al., 2014; St Clair Gibson et al., 2003). An increase in exercise intensity draws the exerciser's attentional focus toward bodily sensations, thereby eliciting greater awareness of fatigue-related symptoms (e.g., limb discomfort). Conversely, exposure to environmental sensory cues (e.g., music or video images) can guide attentional focus toward task-irrelevant cues during exercise (Karageorghis and Jones, 2014). Therefore, exercise-related signals are hypothesized to be in constant competition for attention with external influences (Rejeski, 1985). It should be noted that attentional focus is usually allocated to both internal and external sensory cues in tandem. Nonetheless, the degree to which attention is directed toward interoceptive or exteroceptive signals is primarily defined by the stimulus relevance (Broadbent, 1958; Tenenbaum, 2001).

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Music-related interventions have the potential to increase the frequency of dissociative thoughts, moderate the salience of fatigue-related cues, and make exercise feel more pleasant than under no-music control conditions (e.g., Hutchinson and Karageorghis, 2013; Lim et al., 2014). Ameliorated fatigue enables exercisers to experience several positive outcomes, such as enhanced affective valence and situational motivation (Hutchinson and Karageorghis, 2013). Stimulative pieces of music might also modulate cardiac, respiratory, and muscular activities via neurohumoral pathways, as advanced by Conrad et al. (2007). According to these authors, music may up/downregulate physiological arousal with consequent impact upon the activity of the autonomic system.

Psychophysiological responses elicited by music during the execution of movements are primarily moderated by interoceptive signals (Boutcher and Trenske, 1990; Karageorghis et al., 2017). As the organ responsible for processing and generating signals, the human brain facilitates the interpretation of interoceptive cues and controls bodily functions (Chiel et al., 2009). Attentional reallocation induced by auditory and motor signals is accordingly controlled by the brain (Zatorre et al., 2007). Therefore, the human brain will, presumably, hold the answer in terms of furthering understanding of the mechanisms that underlie the multifarious effects of music during exercise-related tasks.

Bigliassi et al. (2016) recently conducted an experiment employing electroencephalography (EEG) to investigate the cerebral and psychophysiological mechanisms that underlie the effects of music during an isolated limb exercise. The results indicated that music promoted the use of dissociative thoughts and enhanced task performance during the execution of a highly fatiguing isometric ankle-dorsiflexion task. The brain mechanisms associated with this response appeared to be associated with the down-modulation of low-frequency components (mainly theta waves) of the power spectrum at the frontal, central, and parietal electrode sites. The authors hypothesized that low-frequency components of the EEG waveform are upregulated by processing of interoceptive signals (Craig et al., 2012; Pires et al., 2018). As music redirects attention toward task-irrelevant cues, the detrimental effects of fatigue are partially suppressed. Thus, the central motor command (i.e., precentral and paracentral gyri; Voss et al., 2006) is able to maintain the efferent control of working muscles for a longer period of time (de Morree et al., 2014).

1.2. Effects of exercise and music on brain activity

Brain assessment techniques are frequently used in the field of cognitive psychology and behavioral medicine as a means by which to explore the neurophysiological mechanisms that underlie the effects of music on attentional and emotional responses (Bigliass et al., 2018a; Juslin, 2013). The manifold effects of music on brain activity include increased activation in the temporal lobe, insular cortex, limbic system, and frontal regions of the brain (see Koelsch, 2011; Warren, 2008). This is primarily attributed to the fact that each brain region is concerned with the processing of specific components of music (e.g., melody and harmony) and/or subsequent emotional responses that are elicited by music (Levitin, 2008).

Interestingly, the execution of movement prompts increased activation in brain regions that are also affected by music (Enders et al., 2016; Fontes et al., 2015; van Praag, 2009). For example, Schneider et al. (2010) examined brain function using EEG before and after an exhaustive running task. The results of this study indicated that an incremental treadmill test increased the activity of the left frontal regions of the brain. The researchers postulated that such an increase in brain activity was, perhaps, associated with emotional processing. This hypothesis was based on the long-held view that left-hemisphere brain regions are associated with positive emotions such as happiness and joy (Demaree et al., 2005), while the right-hemisphere regions are associated with negative affect. Along similar lines, the right dorsolateral prefrontal cortex has also been hypothesized to play an important role in the modulation of pain (Dunckley et al., 2007). Accordingly, this region could be germane to the perception of muscular fatigue during exercise (Karageorghis et al., 2017).

It should be emphasized that *f*MRI experiments have seldom been investigated during the execution of physical tasks. This is because limb movements cause artefacts that are challenging to remove using traditional cleaning procedures (Maclaren et al., 2013; Oakes et al., 2005). Furthermore, MRI scanners generate a strong magnetic field, meaning that only compatible nonmagnetic devices can be used in the scanning room to measure participants' movements (e.g., force produced; Thickbroom et al., 1998).

1.3. Aim of the present study

Very few studies have examined the effects of music and isolated limb exercises using an MRI scanner to ascertain the neurophysiological mechanisms that underlie commonly observed phenomena such as attentional dissociation and variations in core affect (cf. Bishop et al., 2014; Brown et al., 2006). Accordingly, a block-design experiment was conducted using *f*MRI in order to examine the neural networks that activate during the execution of handgrip tasks performed at light-to-moderate intensities in the presence of ambient music.

1.4. Research hypotheses

We hypothesized that the presence of music would guide attentional focus externally, thus partially preventing afferent signals from entering focal awareness. The upshot would be the amelioration of fatigue-related sensations (e.g., limb discomfort), upregulation of affective arousal, and elicitation of a more positive affective state (Karageorghis, 2017). We also hypothesized that attentional shifts induced by the presence of music would influence the neural control of working muscles (i.e., decreasing the activity of the precentral gyrus; Bigliassi et al., 2017). Bigliassi et al. (2017) identified that music-related interventions have the potential to rearrange the electrical frequency of the central motor command and reduce communication across somatosensory regions of the cortex. Moreover, they demonstrated that music suppressed the resynchronization of the neural population beneath the Cz electrode site (i.e., central area of the precentral gyrus). The authors suggested that music can reallocate attention externally and induce more autonomous control of the working muscles. Therefore, it appears reasonable to surmise that the activity of the left precentral gyrus would decrease when participants exercise in the presence of music.

It has also been hypothesized that the activity of the right dorsolateral prefrontal cortex would decrease when participants exercise in the presence of music (see Karageorghis et al., 2017). This reduction could cause a delay in the eventual decline in prefrontal oxygenation and thus prolong exercise performance. Karageorghis et al. (2017) also suggested that there could be a smaller increase in oxygenation at moderate exercise intensities; presumably due to the lower level of experienced displeasure, thus reducing the need for a participant to cognitively control the displeasure, even in the absence of any ergogenic effect. With this premise, we hypothesize that a decrease in activation of the right dorsolateral prefrontal cortex will manifest when participants exercise with music.

2. Method

2.1. Participants

The required sample size was calculated using G*Power 3.1 (Faul et al., 2007) for an F test (within-factors, repeated-measures ANOVA). The effects of stimulative music on attentional focus during isometric exercise performed to the point of volitional exhaustion were used as group parameters to estimate the effect size required to calculate the necessary sample size. The study by Bigliassi et al. (2016) was used to estimate the effect size of asynchronous music on psychological responses during exercise (effect size $d = 0.66$), given similarities with the present study in terms of exercise mode and complexity (i.e., an isolated limb task). The software indicated that 17 participants would be required to detect an effect of this magnitude ($\alpha = 0.05$; $1-\beta = 0.80$). Three additional participants were recruited to account for the possibility of experimental dropout. Immediately after each day of data collection, the biological signals were processed offline in order to check for head movements or incomplete data. One participant was asked to repeat the trials given that his movements compromised part of the data and realignment procedures were not sufficient to correct for such movements. This participant was asked to rest for at least 30 min prior to recommencing the trial in order to prevent the carry-over effects of fatigue on perceptual responses and task performance. Also, one participant was excluded due to feeling claustrophobic inside the *f*MRI scanner. Participants with a cardiac pacemaker, aneurysm clip, cochlear implants, pregnancy beyond the first half of the first trimester, bullet or shrapnel wounds, history of metal fragments in eyes, neurostimulators, body mass ≥ 113 kg, or claustrophobia were not allowed to take part in the present study, as these were universally applied scanner restrictions. Participants with previous history of psychiatric disorders, traumatic brain injuries, epilepsy, diabetes, thermoregulatory problems, and heart disease were also excluded. Nineteen healthy adults comprised the final sample (7 women and 12 men; $M_{age} = 24.2$, $SD = 4.9$ years; $M_{height} = 173.8$, $SD = 9.9$ cm; $M_{weight} = 70.9$, $SD = 14.5$ kg; $M_{physical\ activity} = 284.2$, $SD = 161.7$ min).

An institutional email was circulated among undergraduate and postgraduate students. The email contained the participant information sheet that detailed the general objectives and potential risks associated with the present study. Those who expressed an interest in taking part were surveyed in order to establish their sociocultural background and obtain basic demographic and anthropometric data. In order to participate, participants needed to meet the following inclusion criteria: Be apparently healthy (i.e., present no conditions/illnesses that might inhibit engagement in physical activity), right-handed, and not presenting visual- or hearing-related disorders. They were engaged in light-to-moderate-intensity motor tasks over short time periods (~20 min; see 2.2 Experimental procedures section) and only noninvasive techniques were used. The study was approved by the Institutional Research Ethics Committee at Brunel University London.

2.2. Experimental procedures

2.2.1. Pre-experimental phase

Participants were asked to read the participant information sheet, provide written informed consent, and complete the Physical Activity Readiness Questionnaire (PAR-Q; Shephard, 1988). Subsequently, they were asked to report how many minutes in total they participated in moderate-to-vigorous physical activity in a typical week. Participants were also asked to avoid drinking coffee and large volumes of fluid for at least 2 h prior to data collection, and refrain from vigorous exercise for at least 24 h prior to tests. The psychological measures were then presented to participants as a form of familiarization. Participants also received instructions regarding issues surrounding metallic objects and the emergency procedures. The experimental protocol was explained verbally and participants were afforded time for questions prior to commencement of the experimental phase.

Participants were instructed to lie horizontally on a stretcher outside the MRI scanner and a handgrip dynamometer (Grip-D 5401, Takei) was used to determine their maximal voluntary contraction (MVC; i.e., peak value). MVC tests were conducted three times in order to identify the most appropriate resistance to be used during the experimental phase. MVC tests were also separated by a minimum of a 1-min respite in order to enable participants to fully recover.

2.2.2. Main experimental phase

Participants were positioned in the MRI scanner, and instructions on how to proceed (e.g., period of contraction) were provided using PowerPoint (Microsoft) slides. Participants were engaged in repetitive bouts of light-to-moderate-intensity isometric exercises performed at 30% of MVC. During the trials, each participant was required to squeeze a silicone grip ring (RitFit) using her/his right hand. A bar timer was projected on a screen overhead and used to indicate the periods of contraction and recovery. This squeezing task was selected with a view to preventing head movements, which could have compromised the fidelity of the scan. The experimental procedures took no longer than 1 h from start to finish. The exercise intensity employed induced only light-to-moderate symptoms of fatigue. Rest periods were used in between conditions to facilitate recovery (a minimum of 5 min). All participants gave a verbal indication that they were fully recovered following this 5-min break. One experimental condition (music [MU]) and a no-music control condition (CO) were administered to identify the effects of auditory stimuli on the BOLD response and psychological responses. Conditions were randomized and counterbalanced to prevent any influence of systematic order on dependent variables. Each condition lasted for 10 min and participants were required to execute 30 exercise trials (i.e., 1 trial = 10 s contraction + 10 s rest). Brain activity was compared between conditions as a means by which to identify the effects of music and isometric exercise on brain activity.

2.3. Auditory stimuli

I Heard It Through The Grapevine (119 bpm; Creedence Clearwater Revival version; *Cosmo's Factory* album, 1970) written by Norman Whitfield and Barrett Strong and performed by Marvin Gaye, was selected as a means by which to guide participants' attentional focus externally and evoke positive affective responses (Baumgartner et al., 2006; Karageorghis and Jones, 2014). This piece of music lasts for 11.06 min and therefore the same track could be played throughout the exercise bout, avoiding the influence of track variation (e.g., in tempo, timbre, harmony, and rhythm) on psychological and neurophysiological responses. The music was delivered via MRI-compatible earphones and sound intensity was maintained at ~75 dBA, which is deemed entirely safe from an audiological perspective (see Lindgren and Axelsson, 1988).

2.4. Psychological measures

Five psychological measures were taken immediately after each exercise bout. At the end of each condition, the scales were presented on the MRI scanner's rear projection screen and participants were asked to provide verbal responses. Attention allocation to task-related and task-unrelated factors was assessed by use of a single-item attention scale (AS) developed by Tammen (1996). This scale ranges from 0 (*internal association*) to 100 (*external dissociation*). Examples of task-related (e.g., "thinking about how fatigued you felt during the session") and task-unrelated (e.g., "daydreaming during the task") thoughts were provided as parenthetical details at the bottom of the scale. AS has been used extensively in the field of sport and exercises sciences as a means by which to investigate an individual's predominant focus of attention during the execution of motor tasks (e.g., Hutchinson and Karageorghis, 2013; Hutchinson et al., 2015).

Limb discomfort (LD) and overall exertion (OE) were assessed by use of Borg's (1982) single-item scale, which ranges from 0 (*nothing at all*) to 10 (*very hard*). The scale has been used extensively in the exercise context to investigate exertional responses (e.g., Barreto-Silva et al., 2018; Lima-Silva et al., 2012), and has proven to be a valid and reliable instrument for this purpose (see e.g., Chen et al., 2002).

On the basis that we conceptualize affect as a dimensional domain, affective valence was assessed by use of the Feeling Scale (FS; Hardy and Rejeski, 1989), and affective arousal by use of the Felt Arousal

Scale (FAS; Svebak and Murgatroyd, 1985). The FS is a single-item affective valence scale ranging from −5 (*very bad*) to +5 (*very good*). The FS has been developed to assess the hedonic tone of emotional responses during exercise. The FAS is a single-item arousal scale ranging from 1 (*low arousal*) to 6 (*high arousal*). The FAS has been used to investigate perceived activation (i.e., how worked-up one feels) during exercise. The FS and FAS are valid and reliable instruments (see e.g., Van Landuyt et al., 2000) that have been used extensively in field of exercise science to assess core affect (e.g., Bigliassi et al., 2018b; Karageorghis et al., 2010). The psychological measures were administered in the same order for each exercise bout (1st AS, 2nd LD, 3rd OE, 4th FS, and 5th FAS).

2.4.1. Manipulation check

A single-item liking scale was used at the end of the experiment to assess the degree to which participants liked the music selection (Karageorghis et al., 2008). Also, two questions were asked at the very end of the experiment to gauge the efficacy of the auditory interventions ("Did the music have any effects on how you were feeling during the exercise?" and "If yes, please briefly describe the changes that you noticed when you exercised with music"; Karageorghis and Jones, 2014).

2.5. Data acquisition and analysis

The brain was scanned continuously by use of a 3 T MRI scanner (Siemens Magnetom Trio). An eight-channel array headcoil was used to reproduce brain images. For each functional run, an ultra-fast echo planar gradient-echo imaging sequence sensitive to blood-oxygen-level dependent (BOLD) contrast was used to acquire 41 transverse slices (3 mm thickness) per TR (3000 ms, echo time = 31 ms, flip angle = 90°). For each version of the experiment, 360 volumes were acquired in a 192 × 192 mm field of view with a matrix size of 64 × 64 mm, giving an in-plane spatial resolution of 3 mm, which subsequently generates 3 mm^3 voxels. A three-dimensional, high-resolution (1 mm) anatomical scan (MP-RAGE, Siemens) was also acquired during the experimental protocol. The same plane and orientation were used for the anatomical data, resulting in 176 slices of 1 mm each (pulse repetition time = 1830 ms, echo time = 4.43 ms, field of view = 256 mm, and a GRAPPA acceleration factor of two). Slices were collected sequentially and the slice timing was not corrected, given that the pulse repetition time used in the present study was relatively short. In such instances, correction is not mandatory because the hemodynamic response is extremely slow (cf. Sladky et al., 2011). The BOLD response was subsequently identified using the software SPM12 (Friston et al., 2007). Head motion was assessed for each participant separately and realigned based on the functional volume of the first image. Subsequently, the functional files were co-registered in order to align images from different modalities (i.e., anatomical and functional). The standard of stereotactic space proposed by the Montreal Neurological Institute (MNI) was used to normalize the anatomical and functional properties of the brain images. Finally, functional scans were smoothed with a 6-mm isotropic Gaussian filter to increase the signal-to-noise ratio.

First-level analyses were conducted for each participant to explore the effects of exercise (exercise > rest), music (music > no music), and music and exercise (music and exercise > exercise > music) on brain activity. It should be highlighted that the no-music condition mentioned herein is the same as the rest period mentioned for the *t* contrast of the first comparison (i.e., exercise > rest). We simply decided to call it "no music" to avoid any possible misinterpretation. Second-level analyses were subsequently undertaken using the group data (i.e., contrast files of 19 participants). In order to identify the statistical differences associated with each experimental condition, *t* and *F* test contrasts were conducted using an alpha level of $p < .0001$, uncorrected for the whole brain mass and a voxel extent threshold of 30 (cf. Dai et al., 2001). The Pickatlas toolbox (Maldjian et al., 2003) was used to label the active brain regions and extract statistical values from significant voxels. Pearson's product moment correlation analysis was also implemented to verify the relationship between the BOLD response, represented by beta values, in the left precentral gyrus and right dorsolateral prefrontal cortex area and psychometric measures (see Poldrack, 2007). Post hoc correlation analyses were also conducted between the beta weights of all other active brain regions and the psychological measures. In such instances, the MarsBar toolbox (Brett et al., 2002) was used to create spherical regions of interest (ROIs) and calculate the beta weights in these regions to be correlated with the self-reported measures. Finally, Mango software (Lancaster et al., 2010) was used to recreate three-dimensional images of the brain.

2.6. Statistical analysis

All statistical procedures were conducted by use of SPSS 22.0. Univariate outliers were identified through the use of standardized scores (≥3.29 or ≤−3.29) and discarded from subsequent analyses. Data normality was checked through application of the Shapiro-Wilk test to identify patterns of data distribution that did not fit the Gaussian curve. Data transformations (e.g., square root corrections) were computed in the case of non-normal profiles. Paired-samples *t*-tests were used to compare the scores from psychological variables between conditions, with the alpha level set at $p < .05$.

3. Results

Two univariate outliers (i.e., cell cases) were identified for affective valence in the music condition during the initial screening procedure and removed from subsequent analyses. The associated cases were only excluded from the statistical analyses that involved this variable. A leptokurtic Gaussian curve with positive skewness was identified for attentional focus in the music condition, which warranted square root transformations (see Tabachnick and; Fidell, 2014, p. 87). After data correction, attentional focus presented a normal profile for both control ($p = .105$) and music ($p = .178$) conditions.

Participants considered the piece of music to be pleasant ($M_{liking\ score} = 7.10$, $SD = 1.88$ *Median* = 8, Q1 = 7 [$n = 5$], Q3 = 8 [$n = 6$]; *Min* = 3 [$n = 2$], *Max* = 9 [$n = 4$] arbitrary units), and indicated that they felt generally distracted when exercising in the presence of music (e.g., "It was much quicker with music, right?", Participant 4; Participant 9; "It was so boring without music", Participant 14; "I got so distracted with music that it felt like the whole exercise took only one minute", Participant 15; "It was definitively much easier with music", Participant 19).

3.1. Perceptual and affective responses

No significant differences were identified between control and music for limb discomfort (CO: $M = 4.89$, $SE = 0.35$; MU: $M = 4.39$, $SE = 0.40$; $t_{18} = 1.264$; $p = .222$; $d = 0.29$), overall exertion (CO: $M = 3.15$, $SE = 0.31$; MU: $M = 2.89$, $SE = 0.28$; $t_{18} = 0.815$; $p = .426$; $d = 0.18$), and affective valence (CO: $M = 1.41$, $SE = 0.49$; MU: $M = 2.17$, $SE = 0.40$; $t_{16} = 1.879$; $p = .079$; $d = 0.43$). However, MU reallocated attention toward task-unrelated thoughts (CO: $M = 44.73$, $SE = 3.68$; MU: $M = 59.73$, $SE = 4.11$; $t_{18} = 2.286$; $p = .035$; $d = 0.52$; see Fig. 1A) and upregulated affective arousal (CO: $M = 2.39$, $SE = 0.18$; MU: $M = 2.94$, $SE = 0.15$; $t_{18} = 3.162$; $p = .005$; $d = 0.72$; see Fig. 1B) when compared to CO.

3.2. BOLD response

The execution of movements (i.e., exercise > rest) entailed increased activation of the left precentral gyrus (Brodmann area 4, MNI coordinates: $x = -34$, $y = -22$, $z = 52$; $t = 5.79$; $d = 1.32$) and

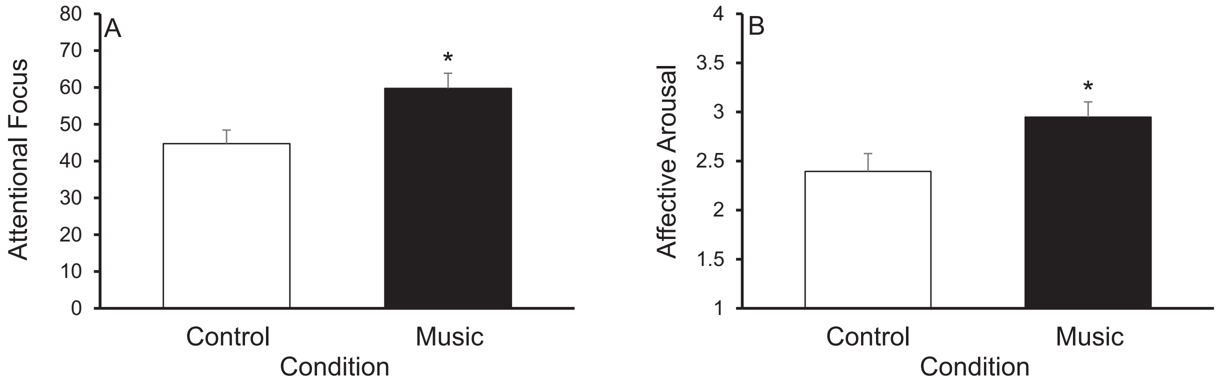

Fig. 1. Comparison of psychological responses between CO and MU. Note. Means and standard errors are presented; A = attentional focus; B = affective arousal; * = $p < .05$.

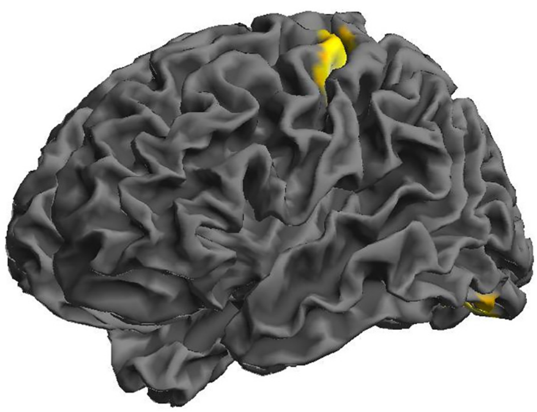

Fig. 2. Significant group-level, random-effects activation of left precentral gyrus and lingual gyrus during the execution of movements (contrast: exercise > rest). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

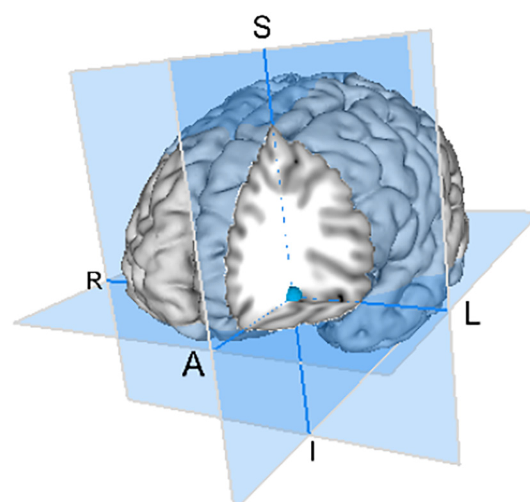

Fig. 4. Significant group-level, random-effects activation of left inferior frontal gyrus during exercise and music (contrast: exercise and music > exercise > music). Note. The blue blob represents the activity of the left inferior frontal gyrus; S = Superior; I = Inferior; R = Right; L = Left; A = Anterior. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lingual gyrus (Brodmann area 18, MNI coordinates: $x = -8$, $y = -86$, $z = -20$; $t = 5.67$; $d = 1.30$; see Fig. 2), while music listening (i.e., music > no music) increased activity of the superior temporal gyrus (Brodmann area 41, MNI coordinates: $x = -34$, $y = -28$, $z = 12$; $t = 7.01$; $d = 1.60$), transverse temporal gyrus (Brodmann area 42, MNI coordinates: $x = 56$, $y = -22$, $z = 14$; $t = 6.44$; $d = 1.47$), and insula (Brodmann area 13, MNI coordinates: $x = -42$, $y = -16$, $z = 0$; $t = 6.14$; $d = 1.40$; see Fig. 3). Moreover, the combined effects of exercise and music (e.g., exercise and music > exercise > music) elicited significant activation of the left inferior frontal gyrus (Brodmann area 47, lIFG; MNI coordinates: $x = -18$, $y = 28$, $z = -8$; $F = 24.65$; $d = 2.28$; see Fig. 4).

3.3. Correlational analysis

We did not anticipate that the execution of isometric exercises performed in the presence of music would elicit increased activation of

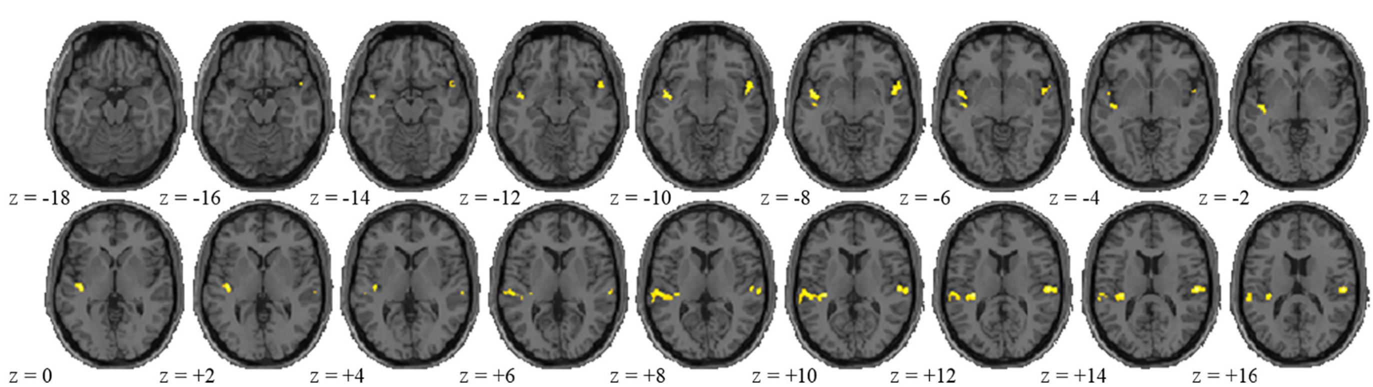

Fig. 3. Significant group-level, random-effects activation of superior temporal gyrus, transverse temporal gyrus, and insula during music listening (contrast: music > no music). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

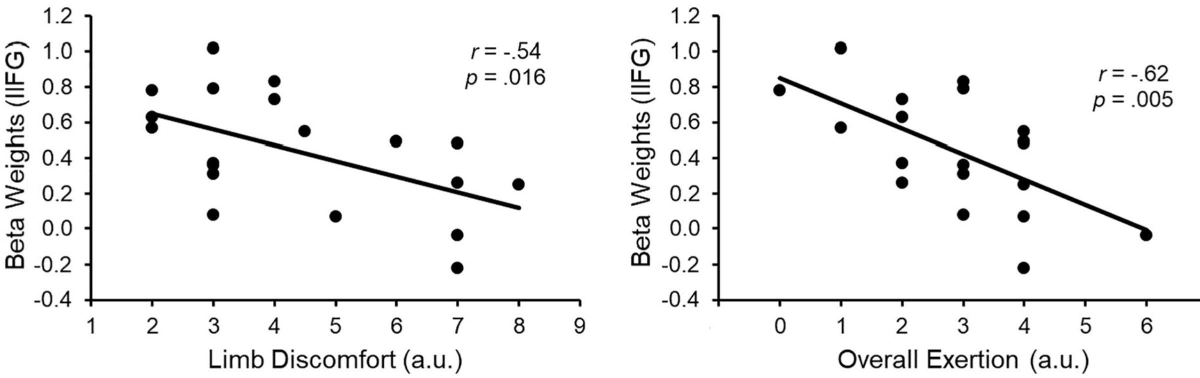

Fig. 5. Significant correlation between the beta weights of the left inferior frontal gyrus and limb discomfort for the music condition (n = 19). Note. lIFG = left inferior frontal gyrus; a.u. = arbitrary units.

the lIFG. In order to clarify the potential significance of the lIFG in this context, post hoc correlation analyses were conducted between the beta weights of this region (ROI: 5 mm sphere centered on $x = -18$, $y = 28$, $z = -8$) and the psychological measures. Significant negative correlations were identified between lIFG activity and exertional responses for MU (limb discomfort: $r = -0.54$, $p = .016$; overall exertion: $r = -0.62$, $p = .005$; see Fig. 5) but not for CO (limb discomfort: $r = -0.25$, $p = .303$; see Fig. 5; overall exertion: $r = -0.25$, $p = .289$). No significant correlations were identified with attentional focus (CO: $r = 0.09$, $p = .696$; MU: $r = -0.05$, $p = .827$), affective valence (CO: $r = 0.42$, $p = .073$; MU: $r = -0.271$, $p = .262$), and affective arousal (CO: $r = 0.10$, $p = .672$; MU: $r = -0.05$, $p = .845$).

To avoid circular inference (i.e., double dipping; for details, see Kriegeskorte et al., 2009), correlational analyses were conducted between psychological measures and activations in somatosensory regions of the brain (see 1.4 Research hypotheses section). No significant correlations were identified between the activity of the left precentral gyrus (ROI: 5 mm sphere centered on $x = -34$, $y = -22$, $z = 52$) and any of the psychometric measures for both CO (attentional focus: $r = -0.35$, $p = .141$; limb discomfort: $r = -0.06$, $p = .806$; overall exertion: $r = -0.13$, $p = .578$, affective valence: $r = 0.28$, $p = .233$; affective arousal: $r = 0.34$, $p = .149$) and MU (attentional focus: $r = 0.10$, $p = .673$; limb discomfort: $r = 0.42$, $p = .864$; overall exertion: $r = -0.13$, $p = .572$, affective valence: $r = 0.45$, $p = .053$; affective arousal: $r = 0.12$, $p = .616$).

The present authors also decided to investigate whether the presence of music could influence the activity of the right dorsolateral prefrontal cortex as previously hypothesized by Karageorghis et al. (2017). In this case, a third 5 mm sphere was centered on $x = 46$, $y = 38$, $z = 12$ to extract the beta weights in the right dorsolateral prefrontal cortex. Similarly, no significant correlations were identified between psychometric measures and the activity of the right dorsolateral prefrontal cortex for both control (attentional focus: $r = 0.25$, $p = .301$; limb discomfort: $r = -0.24$, $p = .316$; overall exertion: $r = -0.07$, $p = .773$, affective valence: $r = 0.25$, $p = .290$; affective arousal: $r = 0.14$, $p = .562$) and music (attentional focus: $r = 0.03$, $p = .894$; limb discomfort: $r = -0.28$, $p = .234$; overall exertion: $r = -0.38$, $p = .103$, affective valence: $r = -0.09$, $p = .692$; affective arousal: $r = -0.06$, $p = .812$) conditions.

4. Discussion

The aim of the present study was to explore the brain regions that activate in response to isometric handgrip exercise accompanied by music, with the ultimate goal of furthering our understanding of complex psychophysical phenomena such as attention and fatigue. The results of this study only partially support the research hypotheses. Indeed, the present authors did not anticipate that the lIFG would activate in response to isometric exercise and music (see Fig. 4) and correlate negatively with exertional responses (limb discomfort: $r = -0.54$; overall exertion: $r = -0.62$; see Fig. 5). In such instances, activity of the lIFG appears to reduce when individuals experience fatigue-related sensations such as limb discomfort. This could represent a neurophysiological mechanism that underlies the protective effects of music on the negative bodily sensations commonly reported during exercise (Karageorghis et al., 2017).

The piece of music used in the present study was sufficiently potent to direct attentional focus toward task-unrelated thoughts ($d = 0.52$) and up-regulate affective arousal ($d = 0.72$) to a greater degree when compared to CO (see Fig. 1). The effects of music on perceptual and affective responses have been widely reported in the literature (see e.g., Karageorghis, 2017) and are mostly in line with the present findings. Interestingly, affective valence and perceived exertion (limb discomfort and overall exertion) did not differ across conditions. This could be due to the fact that the exercise intensity employed in the present study was relatively light (cf. Bigliassi et al., 2018b). Furthermore, the scanner environment could have somehow moderated the commonly observed effects of music on exercise and physical activity (e.g., Clark et al., 2016).

4.1. Brain activity

The execution of movements yielded greater activation in the precentral gyrus and lingual gyrus (see Fig. 2). This result was highly expected given that the left side of the premotor cortex has been consistently associated with movements of the right hand (e.g., Sclocco et al., 2014; Thickbroom et al., 1998). The lingual gyrus has also been found to play an important role during visual motion tasks (Cheong et al., 2012) and could have been influenced by the visual stimulus used during the task (i.e., a bar timer). It is important to emphasize that the bar timer was also presented during the rest period, in order that participants were aware of the recovery period. However, this area may have activated in response to visual–motion predictions (i.e., in preparing the prime movers to contract) and such activation was not manifest during the recovery phase.

Group-level random-effects analyses showed that music listening (i.e., music > no music) increased the activity of the temporal regions and insular cortex (see Fig. 3). The results generally fall in line with the extant literature given that the physical features of the auditory stimulus are primarily processed in the temporal lobes (Liégeois-Chauvel et al., 1998). Moreover, the insular cortex is strongly associated with emotional reactions to environmental sensory stimuli such as music (Juslin, 2013; Koelsch, 2014). The most interesting finding to emerge is related to the significant activation in the lIFG that was elicited by the interactive effects of exercise and music (see Fig. 4). Moreover, music has the potential to shift attention externally, upregulate affective arousal, and increase activation of the lIFG during execution of an isometric muscle contraction. We have also identified that the activity of this region was moderately correlated with limb discomfort and overall exertion. Ostensibly, the presence of pleasant music has the potential to redirect attentional focus and reduce processing of interoceptive cues (Bigliassi et al., 2017). It is conceivable that the lIFG represents a hub of sensory integration where internal and external sensory signals are processed in tandem during exercise-related situations (cf. the parallel processing model; Rejeski, 1985).

Activity of the lIFG has been associated with a number of different cognitive processes such as syntactic processing (Tyler et al., 2011), language function (Hartwigsen et al., 2013), sentence comprehension (Friederici et al., 2003), decision-making (Reckless et al., 2014), and emotion recognition (Monte et al., 2013). It is also noteworthy that this region has been implicated in mechanisms that underlie selective attention (Rushworth et al., 2005) and intention to move (van Duinen et al., 2007). More importantly, in the present context, the lIFG appears to play a key role in mediating interoceptive awareness (Pollatos et al., 2007) and fatigue perception (Shigihara et al., 2013); a mechanism that might account for the increased activation of this region when participants engage in isometric-type exercise with music (see Fig. 4) and the negative relationship with exertional responses (see Fig. 5).

It is important to highlight that the combined effects of exercise and music did not elicit increased activation of the left precentral gyrus and right dorsolateral prefrontal cortex. These two regions have been previously hypothesized by the research team to activate when participants exercise in the presence of music. This was due to the fact that Bigliassi et al. (2017) identified that music has the potential to influence the activity of the premotor cortex and inhibit the resynchronization of the neural population in this region. Along similar lines, Karageorghis et al. (2017) hypothesized that music-related interventions could reduce the activity of the right dorsolateral prefrontal cortex during exercise as a means by which to lower the level of experienced displeasure that is commonly reported during physical tasks performed at moderate-to-severe intensities. Interestingly, no significant voxels were identified in the left precentral gyrus and right dorsolateral prefrontal cortex area. The main reason for this could be due to the fact that the exercise intensity employed in the present experiment was relatively light and, therefore, negative affective responses and extreme exertional responses were not elicited. Moreover, a smaller proportion of the musculature was engaged in the handgrip task when compared to cycle ergometry (Bigliassi et al., 2017). Accordingly, it would be reasonable to deduce that a number of moderators, such as exercise mode and intensity, are salient in regard to how music influences brain activity.

4.2. Limitations

The piece of music used in this study might not elicit the same cluster of perceptual and affective responses across participants. This is due to the fact that that music preference is highly idiosyncratic (Karageorghis, 2017; North et al., 2004). However, participants considered the piece of music to be moderately pleasant (see 3 Results section). It is also important to emphasize that different auditory stimuli (e.g., self-selected music) could have imposed a threat to internal validity (Karageorghis and Priest, 2012). We decided to standardize the auditory stimulus, given that the BOLD response could have been affected by different physical features of the music such as timbre and tempo (Levitin, 2008) and, by extension, served to compromise data analysis and interpretation.

Secondly, the exercise intensity imposed by the handgrip-squeezing task was not maintained perfectly at 30% of MVC. This is because the silicone grip rings were not connected to force cells that allowed participants to monitor the level of pressure produced throughout the trials. However, participants were provided with clear instructions on how to squeeze the silicone grip rings prior to commencement of data collection and maintain the same amount of pressure during periods of muscle contraction. Moreover, monitoring of force produced (i.e., signal amplitude) and contraction period (i.e., follow the bar timer) could have posed a cognitive demand and directed participants' attention toward task-related thoughts. In such instances, the presence of music can elicit a negative effect, meaning that participants would need to ignore the auditory cues (i.e., a suppression mechanism) to ensure successful task execution (cf. Bigliass et al., 2018a).

Thirdly, it is important to highlight that participants were not asked whether they normally listened to music while engaging in physical activity. Accordingly, their previous experiences with music could have had a bearing on the results. There are other related confounds that could have influenced the present results. For example, participants' familiarity with the music used, their attentional style (see e.g., Tammen, 1996), and music preferences (Karageorghis, 2017, p. 36–39). To partially assuage the influence of such confounds, we did ask participants how they felt at the end of trials. This enabled us to ascertain whether the experience was more positive or negative when they completed the exercise-related task in the presence of music. We also employed a crossover experimental design that served to partially counteract the threats to internal validity of such confounds. Moreover, we administered a single-item, music-liking scale at the end of the experiment to assess the degree to which participants liked the music selection. Responses to the scale indicated that participants considered the piece of music to be moderately pleasant ($M_{liking\ score} = 7.10$, $SD = 1.88$ arbitrary units; coefficient of variation: ~26%).

Finally, it is necessary to highlight that the inter-individual variability of physical activity ($M_{physical\ activity} = 284.2$, $SD = 161.7$ min) could also have posed a threat to internal validity. Accordingly, physical activity level has the potential to moderate the effects of music on cerebral and psychological responses during exercise (see Karageorghis, 2017). To counter this potential confound, future studies should aim to recruit participants with similar levels of physical fitness. Despite the limitations presented herein, it is noteworthy that this study represents the first scientific attempt to further understanding of the combined effects of isometric exercise and music on brain activity by use of *f*MRI.

4.3. Conclusions

The present study explored the effects of music on brain activity and psychological responses during the execution of part-body exercises performed at light-to-moderate intensities. The findings indicate that music guided attentional focus toward task-unrelated information and upregulated affective arousal to a greater degree than a no-music control condition. Execution of movements in the presence of music also yielded greater activation of the lIFG. A significant inverse relationship between the BOLD response of the lIFG and fatigue-related sensations (limb discomfort and overall exertion) was also identified. We hypothesize that the presence of ambient music has the potential to reduce processing of interoceptive cues (e.g., muscle afferent feedback) by increasing activation in the lIFG. This region of the frontal cortex could represent a hub for sensory integration where internal and external sensory cues are processed during the execution of movements. In such instances, an increase in external influences (e.g., auditory stimuli) can prevent interoceptive signals from entering focal awareness and thus assuage negative bodily sensations such as limb discomfort. It would seem that as well as being the "food of love", as suggested in Shakespeare's *Twelfth Night*, music has the potential to fuel superior motor performance.

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