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Brain Mechanisms that Underlie the Effects of Motivational Audiovisual Stimuli on Psychophysiological Responses during Exercise

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Highlights

- We investigated the mechanisms that underlie environmental motivational stimuli.
- A highly fatiguing handgrip-squeezing task was employed.
- Motivational stimuli enhanced task performance and situational motivation.
- The stimuli modulated brain activity in the frontal and central brain areas.
- Effects of fatigue on efferent control were ameliorated by the motivational stimuli.

Abstract

Motivational audiovisual stimuli such as music and video have been widely used in the realm of exercise and sport as a means by which to increase situational motivation and enhance performance. The present study addressed the mechanisms that underlie the effects of motivational stimuli on psychophysiological responses and exercise performance. Twenty-two participants completed fatiguing isometric handgrip-squeezing tasks under two experimental conditions (motivational audiovisual condition and neutral audiovisual condition) and a control condition. Electrical activity in the brain and working muscles was analyzed by use of electroencephalography and electromyography, respectively. Participants were asked to squeeze the dynamometer maximally for 30 s. A single-item motivation scale was administered after each squeeze. Results indicated that task performance and situational motivational were superior under the influence of motivational stimuli when compared to the other two conditions (~20% and ~25%, respectively). The motivational stimulus downregulated the predominance of low-frequency waves (theta) in the right frontal regions of the cortex (F8), and upregulated high-frequency waves (beta) in the central areas (C3 and C4). It is suggested that motivational sensory cues serve to readjust electrical activity in the brain; a mechanism by which the detrimental effects of fatigue on the efferent control of working muscles is ameliorated.

Keywords: motivation, exercise, sensory aids, muscle fatigue, brain waves.

1. Introduction

Sensory stimulation such as music listening and video watching has been commonly used as a means by which to increase situational motivation during exercise (Hutchinson, Karageorghis, & Jones, 2015; Karageorghis et al., 2013). Auditory and visual stimuli also serve to reallocate an individual's attentional focus to external influences and thus make exercise feel more enjoyable, even at relatively high intensities (Jones, Karageorghis, & Ekkekakis, 2014). Despite the fact that motivational stimuli have been used extensively in the realms of exercise and sports (Karageorghis & Priest, 2012a, 2012b; McCormick, Meijen, & Marcora, 2015), the mechanisms that underlie the effects of music and video during physically demanding tasks are hitherto under-researched.

A possible explanation underlying the beneficial effects of sensory stimuli during exercise involves the integration of multiple physiological systems (e.g., central and peripheral; see Noakes, 2000). In such instances, the attentional and emotional effects of sensory stimuli can permeate throughout the body, modulating the pulmonary, cardiac, hormonal, and muscular systems (e.g., Conrad et al., 2007; Tan, Ozdemir, Temiz, & Celik, 2015; Zhang et al., 2012). Although sensory stimuli influence cerebral and psychophysiological responses, engaging in exercise increases an individual's rating of perceived exertion, with corollary narrowing of attentional focus toward fatigue-related sensations; such internal cues have a detrimental effect on situational motivation (e.g., Hutchinson & Karageorghis, 2013; Karageorghis et al., 2013). It is logical, therefore, that cerebral and psychophysiological measures be taken in tandem during exercise in order to explore the mechanisms that underlie interventions that entail external sensory stimulation.

1.1 Exercise Intensity and Psychological Responses

Simple patterns of movement such as walking are relatively easy for the human brain to direct. During low-intensity exercise, individuals are readily able to allocate attention to task-irrelevant cues such as auditory and visual stimuli. The reallocation of attentional focus toward environmental (*outward*) distractions tends to evoke positive affective responses (Bertollo et al., 2015; Brick, Macintyre, & Campbell, 2014; Hutchinson et al., 2015). However, as the exercise intensity increases, an individual's attentional focus is forced toward task-relevant cues such as the higher respiration rate and acidosis in the muscles (internal association/*inward monitoring*; Razon, Basevitch, Land, Thompson, & Tenenbaum, 2009; Rejeski, 1985). Thus, exercise performed at a high-intensity (i.e., beyond ventilatory threshold) normally elicits a decrease in affective valence owing to the effects of fatigue on the affective regions of the brain (see Kilpatrick, Kraemer, Bartholomew, Acevedo, & Jarreau, 2007).

High-intensity exercise increases the emission of corollary discharges (parallel messages) to the brain regions associated with exertion (Bigliassi, 2015a; de Morree, Klein, & Marcora, 2012). Fatigue-related symptoms cause a detrimental effect on situational motivation, voluntary control of movements, and neural activation of the working muscles (Marcora, 2008). Interestingly, Jones et al. (2014) identified that sensory stimuli can make exercise more pleasurable even at high-intensities, meaning that audiovisual stimuli may partially overcome the negative sensations elicited by increasing exercise intensity.

The use of auditory stimuli during exercise has attracted considerable interest over the last two decades (Karageorghis & Terry, 1997; Tuominen, Husu, Raitanen, & Luoto, 2015), and a psychologically-grounded conceptual framework has also been proposed as a means to further understanding of the antecedents, moderators, and consequences of music use during exercise (Karageorghis, 2015). Thus, researchers and exercise professionals can take a more targeted and scientifically-grounded approach when using auditory stimuli in the exercise context. Nonetheless, it is evident that the most potent effects manifest from a combination of auditory and visual stimuli (e.g., Loizou & Karageorghis, 2015). Unfortunately, the use of videos during exercise has only seldom been the subject of scientific investigation (Barwood, Weston, Thelwell, & Page, 2009; Hutchinson et al., 2015; Jones et al., 2014).

1.2 Brain Activity during Exercise

The human brain has rarely been analyzed during exercise and this is due to the fact that technology that facilitates such analysis has only been developed in recent years (Park, Fairweather, & Donaldson, 2015). Movement patterns and muscular contractions cause artefacts that often compromise the quality of electrical signals. However, artefacts can be identified and excluded by use of computational procedures (see Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011; Thompson, Steffert, Ros, Leach, & Gruzelier, 2008). Through analyzing brain activity during exercise, researchers are able to identify the brain regions associated with a certain movement pattern (e.g., cycling; Jain, Gourab, Schindler-Ivens, & Schmit, 2013), as well as the influence of music on electrical responses (e.g., Sammler, Grigutsch, Fritz, & Koelsch, 2007).

The scientific community has encountered considerable difficulties in explaining the means by which motivational audiovisual stimuli ameliorate the effects of fatigue and enhance exercise performance (Jones et al., 2014; McCormick et al., 2015). There is compelling evidence that mental fatigue upregulates low-frequency waves in the frontal and central regions of the cortex (Craig, Tran, Wijesuriya, & Nguyen, 2012). This mechanism is intended to slow down bodily activities, downregulate physiological arousal, and engender long-term recovery. The increase of low-frequency waves in the body can also be identified in the muscles when a given exercise is performed to the point of volitional exhaustion (Thongpanja, Phinyomark, Phukpattaranont, & Limsakul, 2012). Therefore, it is plausible that, motivational stimuli partially downregulate low-frequency waves (4–13 Hz; Craig et al., 2012) in the central motor command and frontal cortex with consequent effects on the spectral components of the working muscles.

1.3 Aim of the Present Study

The present piece of research aims to elucidate the mechanisms that underlie the effects of audiovisual stimuli on psychophysiological responses during exercise. A fatiguing test was employed that entailed use of a handgrip dynamometer. Auditory and visual stimuli were used as a means to increase situational motivation and prevent fatigue-related symptoms from entering focal awareness (Hutchinson et al., 2015; Razon et al., 2009). The brain and muscle electrical activities were recorded by use of EEG and electromyography (EMG), respectively.

1.4 Research Hypotheses

1.4.1 Situational motivation. The use of a motivational audiovisual clip was expected to increase exercise engagement (Tuominen et al., 2015), perceived activation, and situational motivation (Karageorghis et al., 2013). Neutral stimulation was also used as a means by which to isolate any effects that were not associated with the combined influence of visual and auditory sensory cues. The neutral stimulus was expected to cause minor effects on attentional focus but not alleviate the effects of fatigue-related symptoms, because of the high levels of perceived exertion associated with the proposed task. In this case, only sensory strategies considered to be highly stimulative were hypothesized to influence high-intensity exercises (Hutchinson et al., 2011).

1.4.2 Muscular activity. Motivational audiovisual clips were expected to reallocate an individual's attentional focus to external sensory cues. Therefore, fatigue-related signals were not expected to act upon voluntary control and neural activation (De Morree, Klein, & Marcora, 2014). Accordingly, stimulative sensory cues were expected to increase power output, maintain the firing rate of electrical signals to the working muscles, and decrease the recruitment of motor units over time. Neutral stimulation (irrelevant stimulus), on the other hand, was expected to decrease neural output and firing rate, and increase motor unit recruitment over time in order to compensate for the increasing symptoms of peripheral fatigue (Chester & Durfee, 1997).

1.4.3 Brain activity. The use of a motivational audiovisual stimulus was hypothesized to increase the predominance of high-frequency waves (14–30 Hz) in the premotor and motor areas of the brain as a means by which to compensate the detrimental effects of interoceptive sensory cues and corollary discharges on the efferent control of working muscles (Nielsen, Hyldig, Bidstrup, González-Alonso, & Christoffersen, 2001). We also hypothesized that a motivational audiovisual stimulus would ameliorate the effects of fatigue-related symptoms by downregulating low-frequency waves (4.0–13.9 Hz; theta and alpha frequencies) in the frontal and central regions of the cortex (Craig et al., 2012).

2. Method

2.1 Selection of Environmental Stimuli

During the first stage of the present study, 10 participants (5 women and 5 men; $M_{\text{age}} = 20.7$ years, $SD = 0.8$ years; $M_{\text{height}} = 171.6$ cm, $SD = 8.5$ cm; and $M_{\text{mass}} = 68.9$ kg, $SD = 12.5$ kg) were invited to assess the affective qualities of the visual and auditory stimuli by use of the Self-Assessment Manikin (SAM; Bradley & Lang, 1994). Similar approaches have been taken to assess the affective qualities of auditory and visual stimuli in past research (e.g., Hutchinson et al., 2015; León-Carrión et al., 2006). Participants who were engaged in this preparatory phase were not also involved in the experimental phase, but shared a similar demographic profile to experimental participants. The presentation order of the two pieces of video footage was counterbalanced.

The motivational video clip used in the present study (see https://www.youtube.com/watch?v=9d1QYV0er5o) portrayed a well-known arm-wrestling bout drawn from the movie *Over The Top* (Globus & Golan, 1987). This particular clip was selected due to the congruence between the physical effort evident in the scene and the isometric nature of the physical task adopted for the present study. Furthermore, the soundtrack, which was characterized by a cheering crowd, was deemed to be potentially rousing. This auditory stimulus served to enable participants to visualize themselves within the story that was being depicted. During the arm-wrestling bout, the protagonist Lincoln Hawk played by Sylvester Stallone wrestles for 25 s and wins the contest during the last 5 s.

The neutral audiovisual stimulus depicted pedestrians in the center of New York City (see https://www.youtube.com/watch?v=-tJZYYT4qKs). The neutral stimulus was not expected to alter participants' affective responses given the everyday, bland images that were portrayed. The video soundtrack included the sound produced by cars and by people talking, albeit that the chatter was indiscernible; accordingly the soundtrack was also not expected to change participants' affective state by a major degree. Participants were asked about their degree of familiarity with the video clips. We expected greater familiarity ratings for the stimulative clip, due to the fact that *Over The Top* was a successful Hollywood film during the 1990s, an epoch that coincided with the formative years of most of the participants. Contrastingly, the neutral stimulus did not depict any iconic New York City landmarks (e.g., Statue of Liberty, Empire State Building, and Central Park) that might have elicited memories or strong cultural associations.

2.2 Participants

The present study received full approval from the ethics committee of Londrina State University, Brazil. A power analysis was conducted using G*Power 3.1 to determine an appropriate sample size. Based on a large predicted effect size derived from Razon et al. (2009; $f = 1$), an alpha level of 0.05, and power at 0.8, the analysis indicated that 16 participants would be required. Six additional participants were recruited in order to minimize the impact of participant attrition, therefore a total of 22 participants took part (10 women and 12 men; M_{age} = 23.6 years, *SD* = 2.61 years; M_{height} = 171.0 cm, *SD* = 8.52 cm; and M_{mass} = 72.63 kg, *SD* = 13.38 kg).

Participants who indicated an interest in taking part were initially surveyed in order to glean some relevant demographic details. Due to the potential confound of hand dominance on brain electrical activity (see Legon, Dionne, Meehan, & Staines, 2010), only right-handed participants were recruited. Furthermore, participants were questioned regarding their auditory and visual faculties. Only participants with full audition and corrected-to-normal vision were permitted to engage in the study. Participants did not report any relevant disturbances in their mental state, which may have an adverse effect on the results of the present study.

2.3 Procedure

2.3.1 Identification of baseline values. Participants were required to respond to the Brunel Mood Scale (BRUMS; Terry, Lane, & Fogarty, 2003) as an index of mood state prior to commencing the physical tests (Anger: *M* = 0.40, *SD* = 0.79; Confusion: *M* = 0.86, *SD* = 1.45; Depression: *M* = 0.63, *SD* = 0.95; Fatigue: *M* = 2.54, *SD* = 2.20; Tension: *M* = 2.36, *SD* = 1.67; Vigor: *M* = 8.95, *SD* = 2.60). This psychometric test was administered in order to mitigate the influence of mood variability on psychophysiological variables and exercise performance (Parry, Chinnasamy, Papadopoulou, Noakes, & Micklewright, 2011). Subsequently, a heart rate monitor (Polar RS800CX) was attached to the participant’s chest to establish the cardiac electrical signal at rest (HRrest). The participant was requested to sit comfortably on a chair for 10 min and the 10th minute was considered to be the HRrest (M_{HRrest} = 74 bpm, *SD* = 11 bpm). Participants were then asked to perform three maximal handgrip-squeezing trials for 5 s using a handgrip dynamometer (Jamar) separated by a 3-min rest period. These maximal trials were used to assess their maximal strength and normalize indices pertaining to task performance (see Figure 4). This physical test was conducted to identify the participant's maximal capacity (*M_{MVC}* = 36.09 kg, *SD* = 9.71 kg) and prevent the influence of extremely different strength-related parameters on physiological responses to exercise. Finally, 20 Ag/AgCl electrodes (NeuroVirtual) were attached to the participant's scalp according to the International 10-20 system, and two EMG electrodes (Noraxon) were placed on the flexor carpi radialis (Duque, Masset, & Malchaire, 1995). Given the noninvasive nature of the physiological techniques, the participant's attention was not expected to shift from external to internal sensory cues that were unrelated to the muscular contraction (see Hutchinson & Tenenbaum, 2007; Lohse & Sherwood, 2011, 2012).

2.3.2 Experimental set-up. Participants were asked to sit on a comfortable chair, which was positioned 1.5 m away from a white screen (LG; Figure 1). The visual stimuli were delivered using a projector (ViewSonic PJD5255 XGA DLP Projector, 3200 Lumens) positioned 30 cm above the participant's head. Two speakers (Logitech Z120 Stereo Speakers) were positioned 45 cm from the participant's ears and the sound intensity was set at 75 dBA, which was standardized by use of a decibel meter (Mercury Digital Sound Level Meter, Model 33-099). The equipment cables were arranged in such a way that the participant would not be inhibited by the electronic devices. The handgrip dynamometer was held by the participant with their elbow flexed at 90^{o}, and a digital camera (iPhone 6, Apple) was positioned in front of the dynamometer scale in order to capture the force that was generated.

Figure 1

2.3.4 Experimental trials. During the main experimental phase, participants were asked to maximally squeeze the dynamometer for 30 s on one occasion under each condition. Two experimental conditions (Motivational Stimulus, MS; Neutral Stimulus, NS) and a control condition (CO) were administered. The three conditions were randomly administered by use of a deterministic logarithm (see http://randomization.com/). The interval between conditions was determined by the recovery profile of physiological and perceptual parameters, with a minimum rest period of 6 min. Subsequent conditions were only initiated after complete cardiac recovery (HRrest values). Additionally, it was necessary for self-reported measures of limb discomfort (forearm fatigue) to return to baseline values to further avoid any influence of fatigue-related symptoms associated with the preceding condition (Category Ratio 10; Borg, 1982). A single-item motivation scale (Tenenbaum, Kamata, & Hayashi, 2007) was used after each exercise bout to assess *situational motivation*. Responses are provided on a scale that has a range of 0 (*not motivated at all*) to 10 (*extremely motivated*). The force produced by each participant was normalized based on the MVC values and compared across conditions.

2.4 Data Acquisition and Processing

2.4.1 Electromyography. The raw EMG data were collected using the muscular electrical activity produced by the flexor carpi radialis during isometric contraction (Duque et al., 1995; Reaz, Hussain, & Mohd-Yasin, 2006). The two-channel EMG device (TeleMyo 2400 TG2, Noraxon) was connected to bipolar surface electrodes. The sampling rate was established at 2000 Hz with a common-mode rejection ratio of 95 dB. The procedures to acquire EMG data followed the Takala and Toivonen (2013) guidelines. The EMG signal was processed in time and frequency domains. The time domain (root mean square; RMS) was used to investigate the effects of sensory modulation on the motor unit recruitment, and frequency domain analysis was used to elucidate the effects of sensory modulation on fatigue-based components of the power spectrum. The raw EMG data were filtered (band-pass filter 20–500 Hz), rectified (turning negative to positive values; i.e., integration), and smoothed (three-point moving average). The Fourier Transform method was used with a rectangular processing window algorithm. The median frequency of the power spectrum (MF) was calculated every 5 s to identify the degree to which neuromuscular output decreased in response to the increasing symptoms of fatigue (Buckthorpe, Pain, & Folland, 2014; Gandevia, 2001). EMG and EEG systems were synchronized by use of Bayonet Neill–Concelman (BNC) connectors attached to a bespoke device that functioned as a synchronizer. EMG and EEG data were continuously recorded using Acknowledge 4 software. The generation of event markers was not necessary because the onset of each muscular burst (EMG) was used to identify EEG activity that corresponded with muscle contraction. This was facilitated by use of the *detection of analog triggers* option on Brainstorm (Tadel et al., 2011). Video presentation and task performance were not synchronized with EMG and EEG given that such synchronization was not relevant to the present experiment.

2.4.2 Electroencephalography. The brain electrical activity was examined through the use of a 20-channel EEG device (NeuroVirtual BWII EEG). The 16 Ag/AgCl electrodes were attached to the scalp according to the international 10-20 system. Impedance was kept below 10 kΩ and electrical artefacts produced by eye movements were subsequently excluded using independent component analysis (ICA) by identifying the activity of vertical eye movements. A ground electrode was placed on the participant's forehead in order to ground the system and reduce electrical artefacts (Light et al., 2010). Reference electrodes were attached to the participant's earlobes and re-referenced accordingly (Gonzalez Andino et al., 1990). The brain electrical signal was acquired during the execution of the task, therefore, the EEG signal overlapped the muscular contractions. Muscle artefacts were identified through observation of the raw EEG signal and duly removed prior to subsequent procedures. The EEG signal was digitized at 250 Hz and filtered through the use of an online band pass filter of 100 Hz. The brain electrical signal was subsequently broken down into 1-s asynchronous sample windows (30 samples), DC-offset corrected (baseline correction), and filtered (0.5 to 30 Hz). The 1-s asynchronous samples (event-unrelated windows) were decomposed into different wave frequencies using the Fast Fourier Transform (FFT) method. The FFT values were saved across files (option: average the spectra). The eight channels (F3, F4, F7, F8, C3, C4, P3, and P4) and three brain frequencies (theta [4–8 Hz] alpha [8.5–12 Hz], beta [12.5–30 Hz]) were analyzed (see Bailey, Hall, Folger, & Miller, 2008). The mean FFT values were compared across conditions in order to ascertain the effects of two differing audiovisual stimuli on electrical frequencies in the brain. All the EEG procedures applied in the present experiment were performed with Brainstorm (Tadel et al., 2011), which is documented and freely available for download online under the GNU general public license (see http://neuroimage.usc.edu/brainstorm).

2.5 Data Analysis

Data normality was tested by use of skewness and kurtosis tests, followed by visual inspection, coefficient of variation calculations, and the Shapiro-Wilk test. In case of the assumption not being met, outliers were excluded (three cells). Logarithmic transformations were not required due to previous data corrections. Multiple imputation was applied in the case of five missing values. Accordingly, five contrasting linear regression methods were compared in order to input missing values (He, 2010). Paired-samples *t* tests were used to compare scores for affective valence and arousal between MS and NS. One-way ANOVA was used to compare EMG indices (time and frequency domains) across conditions. Two-way repeated measures ANOVA was used to compare situational motivation (moments: pre and post) and produced force (time points: 10 s, 20 s, and 30 s) across conditions. Bonferroni adjustments were employed for multiple comparisons. When the principles of sphericity were violated, Greenhouse-Geisser corrections were applied to the *F* test. The EEG signals were compared using the paired-samples *t* tests on Brainstorm and the *p* value thresholds were corrected dynamically for multiple comparisons by use of the Bonferroni method.

3. Results

3.1 Sensory Stimuli

The sensory stimuli were initially evaluated by 10 participants to determine the differences in affective valence and arousal between MS and NS. The results indicated that MS significantly differed from NS for both affective valence (MS: $M = 6.80$, $SD = 0.78$; NS: $M = 3.80$, $SD = 0.79$; $t = 11.61$; $p < 0.001$) and arousal indices (MS: $M = 7.1$, $SD = 1.37$; NS: $M = 3.80$, $SD = 0.77$; $t = 8.33$; $p < 0.001$; see Figure 2). The motivational audiovisual stimulus was considered highly pleasant and arousing, and participant responses plot in the upper-right quadrant of the circumplex. Conversely, NS elicited a neutral response for both affective valence and arousal dimensions (located close to the origin). All participants who took part in the present experiment were familiar with MS, but not familiar with NS.

Figure 2

3.2 Situational Motivation

Situational motivation was compared pre- and post-exercise to identify the combined effects of different sensory stimuli and time (exercise effects) on perceived motivation. A statistically significant interaction was identified between condition and time (pre-post) ($F = 6.09$; $df = 1.76$; $p = 0.013$; $\eta_p^2 = 0.40$; observed power = 0.79). The results indicated that MS elicited higher situational motivation scores following the execution of an exhaustive isometric handgrip-squeezing task; conversely, NS and CO decreased situational motivation scores. The neutral stimulus had a slightly negative effect on participants’ situational motivation, and no statistical differences were identified between MS and NS ($p > 0.05$). However, the complete absence of external sensory cues was clearly unfavorable during a high-intensity task. Multiple comparisons indicated that the main differences in situational motivation were evident between MS and CO ($p = 0.038$; see Figure 3).

Figure 3

3.3 Produced Force

The force produced by participants during the exercise bouts decreased over time across all conditions ($F = 51.78$; $df = 1.74$; $p < 0.05$; $\eta_p^2 = 0.73$ observed power = 1.00). However, the rate of change differed across conditions ($F = 2.79$; $df = 3.31$; $p = 0.042$; $\eta_p^2 =$ 12; observed power = 0.68). Albeit that results were similar during the first 20 s of contraction ($p > 0.05$), the application of the MS increased the force produced during the last 10 s (Figure 4). Multiple comparisons indicated that MS differed significantly from NS ($p < 0.001$) and CO ($p < 0.001$).

Figure 4

3.4 Muscular Activity

The median frequency of the power spectrum and the recruitment of motor units were assessed to deduce the effects of different sensory stimuli on peripheral fatigue and neural activation of the working muscles. Despite significant differences in the force produced, the rate of change (slope) of the median frequency and the RMS values was similar across conditions (frequency-domain analysis: $F = 0.17$; $p = 0.845$; time-domain analysis: $F = 0.03$; $p = 0.970$; see Figure 5).

Figure 5

3.5 Electrical Activity in the Brain

Theta, alpha, and beta waves were analyzed for all electrodes and compared across conditions (Figure 6). Statistically significant differences were identified in the right frontal region of the cortex; the motivational stimulus attenuated the amplitude of theta waves at F8 in comparison with NS and CO ($p < 0.05$). The amplitude of beta waves was also influenced by the sensory stimuli. The motivational audiovisual stimulus caused a significant up-modulation in the amplitude of beta waves in the central regions (C3 and C4) of the brain that was not observed in NS and CO.

Figure 6

4. Discussion

The present study aimed to further understanding of the psychophysiological mechanisms that underlie the effects of motivational sensory stimuli during exercise. An exhaustive isometric handgrip-squeezing task was employed to investigate the effects of motivational audiovisual stimuli on force produced and task-related responses. The administration of motivational stimuli was expected to increase affective valence, felt arousal, and situational motivation (Bigliassi, 2015a). It was also hypothesized that MS could increase the predominance of high-frequency brain waves in the central motor command (Marcora, 2009) as a means to resist the negative (prophylactic) influence of perceived exertion on neural activation of the working muscles and voluntary control of movements (Pageaux, 2014).

4.1 Psychophysiological Responses

The present results indicate that the MS increased situational motivation after the execution of an exhaustive isometric handgrip-squeezing task; conversely, NS and CO elicited small detriments in situational motivation. A decrease in positive psychological responses such as motivation and affective valence is normally expected after exhaustive bouts of exercise (Hutchinson & Karageorghis, 2013). The Dual-Mode Theory (Ekkekakis, 2003) proposes that affective responses to exercise are influenced by cognitive processes (e.g., self-efficacy) and internal sensory cues (e.g., afferent feedback). Therefore, the increasing exercise intensity upregulates afferent output from peripheral organs and downregulates protective cognitive processes. This combined effect generates negative psychological responses at high-intensity exercises. The Dual-Mode Theory may serve to explain the protective mechanisms of fatigue-related symptoms that occur during exercise that is performed at high-intensities. However, humans are able to resist the negative influence of fatigue-related symptoms through the use of self-regulation strategies (e.g., positive self-talk or mental arithmetic as a form of dissociation; (Blanchfield, Hardy, De Morree, Staiano, & Marcora, 2014; Johnson & Siegel, 1987) and external sensory cues (e.g., auditory and visual stimuli; Jones et al., 2014). Therefore, situational motivation could represent the hub responsible for permitting the detrimental effects of internal sensory cues (corollary discharges and peripheral feedback) on task performance and affective valence (Marcora, 2008; Pageaux, 2014). The results of the present experiment indicate that sensory stimuli mediate brain responses to exercise that ameliorate the effects of fatigue and increase situational motivation.

The audiovisual stimuli used in the present experiment guided participants' attentional focus toward salient environmental cues. Jones et al. (2014) demonstrated that high-intensity exercise can feel more pleasant under the influence of external sensory cues, meaning that environmental influences can be processed in tandem during the execution of highly demanding cognitive tasks (cf. Boutcher & Trenske, 1990). Neuromuscular data obtained through the use of EMG analysis indicated that both the recruitment of motor units and the median frequency of the power spectrum were conspicuously similar across conditions. Interestingly, participants who were administered the motivational stimuli produced higher levels of force during the last 10 s of contraction, which should have increased the recruitment of motor units and shifted the median frequency of the power spectrum toward the left (Thongpanja et al., 2012). The electrical activity identified in the muscle is hypothesized to represent central reactions to diverse sensory stimuli. In this case, the motivational stimulus partially blocked the effects of fatigue on the central motor command; therefore, participants were able to sustain or even increase the neural activation of the working muscles during the final moments of a fatiguing isometric motor task. The closed-loop nature of the task may have also elicited the mechanism of *teleoanticipation* (see

Wittekind, Micklewright, & Beneke, 2011); this entails participants "saving" some energy during the initial stages of the trial in order to produce greater levels of force toward the end (final sprint strategy). Interestingly, the rate of change (slope) declined over time and the motivational audiovisual stimulus was only effective in ameliorating fatigue-related symptoms (i.e., moderated the slope decline).

4.2 Cerebral Mechanisms

The motivational audiovisual stimulus used in the present study modulated the amplitude of theta waves in the frontal cortex (F8) and beta waves in the central areas (C3 and C4) of the brain. Craig, Tran, Wijesuriya, and Nguyen (2012) demonstrated that fatigue-related symptoms elicited by cognitive tasks increased the amplitude of low-frequency waves (theta and alpha 1) over the entire cortex. Conversely, an alert state usually increases the prominence of high-frequency waves such as beta in the frontal regions of the cortex. The frequency of different brain waves has been commonly associated with the level of psychophysiological arousal that one experiences (e.g., Barker & Burgwin, 1948; Craig et al., 2012). The main differences identified in the present experiment were associated with the frontal and central regions of the cortex. Based on the results (see Figure 6), we believe that the motivational content of the sensory stimulus bore influence on the activity of the central motor command by decreasing low-frequency waves (fatigue suppression) and increasing beta activity (increased arousal). This combined response elicited by the auditory and visual sensory cues appears to underlie the effects of motivational stimuli on psychophysiological responses that occur during the execution of a fatiguing motor task.

The effects of the motivational stimuli on the central regions of the cortex are possibly associated with the protective mechanisms of motivation on exercise engagement (for details, see Pageaux, Marcora, Rozand, & Lepers, 2015). Corollary discharges emitted by the central motor command theoretically decrease the amplitude of high-frequency waves in the premotor gyrus and increase low-frequency waves in the frontal regions of the cortex (de Morree et al., 2012). Nonetheless, the human brain is able to process internal and external sensory cues in tandem (see e.g., Rejeski, 1985; see Karageorghis & Jones, 2014). Accordingly, auditory and visual stimuli compete for central processing capacity and reallocate an individual's attentional focus toward external sensory cues (Hutchinson et al., 2015). Motivational sensory cues partially block the negative effects of fatigue on psychophysiological responses and exercise performance (Hutchinson et al., 2011); this "barrier" is naturally overcome by the effects of fatigue-related symptoms given the strength and relevance associated with the sensations of peripheral discomfort (Noakes, 2012).

4.3 Limitations of the Present Study

The sensory stimuli used in the present study were selected by the first author based on the likely psychological responses that such stimuli might elicit during exercise. However, visual and auditory preferences are highly personal (see e.g., North, Hargreaves, & Hargreaves, 2004; Polat & Akay, 2015) and even different pieces of music or video are theorized to induce similar physiological reactions (see Bigliassi, 2015b). In this case, cerebral analyses could have been used prior to the pre-experimental phase to identify more personalized motivational audiovisual stimuli. It is also important to emphasize that the effects of both experimental conditions might have been randomly influenced by participants' mood state (see section 2.3.1; coefficient of variation higher than 25%). Mood state represents a potential confound on sensory-based areas of research, given that participants' mood state might act as a *filter* through which sensory stimuli are processed (Chanda & Levitin, 2013).

Heart rate variability could have been monitored during the experimental trials in order to identify the sympathetic-parasympathetic balance using time and frequency indices, however, the heart rate monitor used in present experiment created electrical artefacts in the

EEG signal due to wireless data communication. Therefore, the monitor was only used during the rest periods with the purpose of ensuring that participants had fully recovered prior to commencing the next trial. Additionally, the motor task used in the present experiment might not have been sufficiently demanding to induce a large number of corollary discharges given its peripheral (limb discomfort) nature. The employment of whole-body exercise modes could have led to a much larger and more pronounced set of corollary signals. However, it is important to emphasize that the present experiment represents one of the first scientific attempts to further understanding of the cerebral mechanisms that underlie the effects of motivational stimuli during exhaustive physical tasks.

5. Conclusions

The present study attempted to further understanding of the mechanisms that underlie the effects of motivational stimuli on subjective (psychological) and objective (psychophysiological) responses during the execution of a highly-fatiguing isometric motor task through an examination of a range of self-report measures alongside physiological parameters. A neutral stimulus, in affective terms (see Figure 2), was also administered to elucidate its effects on brain electrical activity and peripheral changes. Participants who executed the motor task under the influence of motivational stimuli experienced higher levels of situational motivation immediately after the exercise bout and performance of a maximal isometric task. No differences were identified in the recruitment of motor units and median frequency of the power spectrum. This suggests that the motivational stimulus partially blocked the effects of fatigue on the central motor command, and participants were able to sustain or even increase the neural activation of the working muscles during the final moments of exercise (cf. Marcora, Staiano, & Manning, 2009). An increase in beta waves in the central regions of the cortex (C3 and C4) followed by a moderate strength decline support the notion that neural activation is partially influenced by sensory pathways. A decrease in theta waves was identified in the right frontal regions of the brain (F8) when participants exercised under the influence of motivational audiovisual stimuli. Similarly, the motivational stimulus administered during the present experiment increased the amplitude of beta waves in the central regions of the cortex. This combined response (see Figure 6) elicited by the auditory and visual sensory cues appears to underlie the effects of motivational audiovisual stimuli on psychophysiological parameters during the execution of a highly fatiguing motor task.

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Figure 1

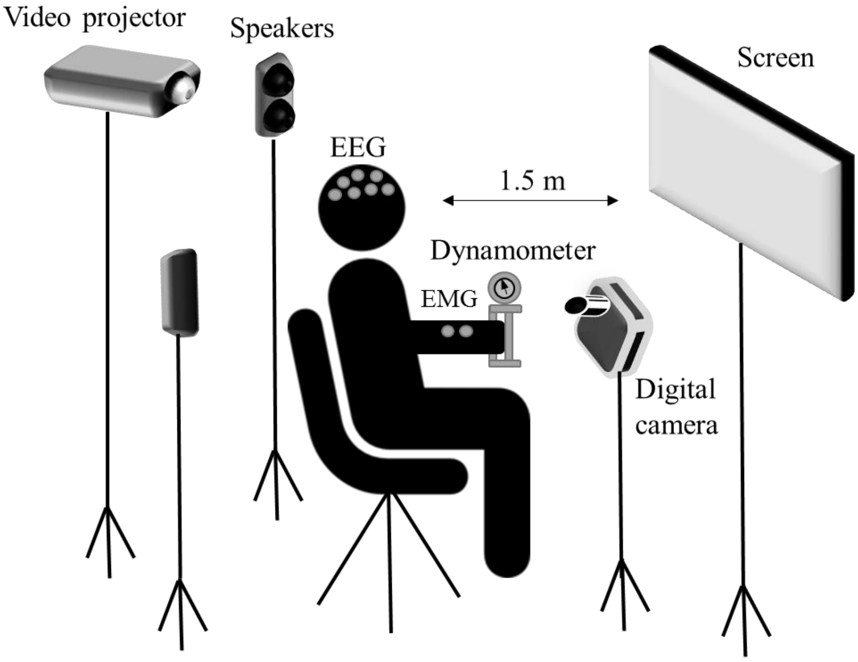

Figure 1. Experimental set-up.
Note. EEG: Electroencephalography; EMG: Electromyography.

Figure 2

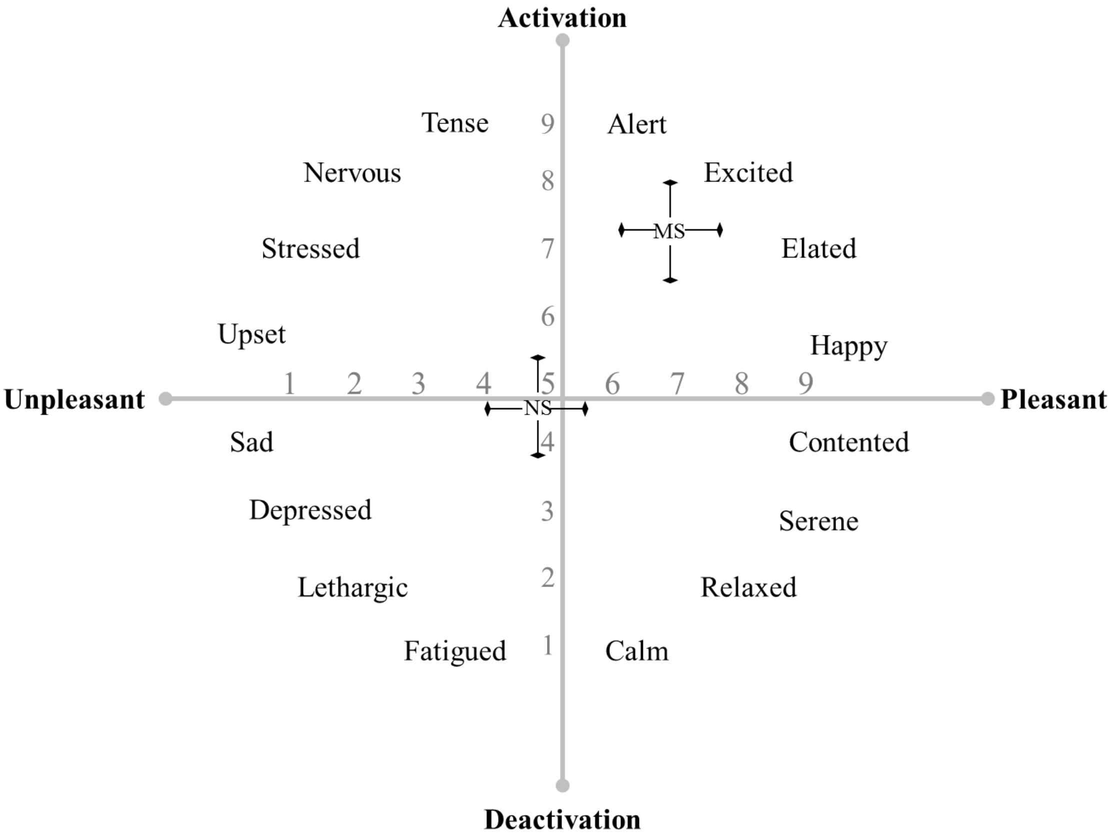

Figure 2. Two-dimensional affective space defined by Self-Assessment Manikin pleasure and arousal ratings. Error bars denote standard deviations.
Note. MS: Motivational Stimulus; NS: Neutral Stimulus.

Figure 3

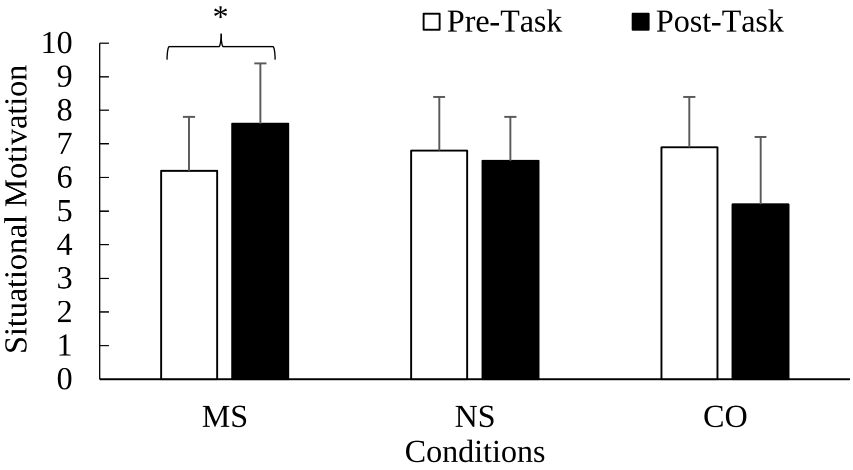

Figure 3. Condition × Time (pre-post task) interaction effect for situational motivation. Error bars denote standard deviations.
Note. MS: Motivational Stimulus; NS: Neutral Stimulus; CO: Control.
*p < 0.05.

Figure 4

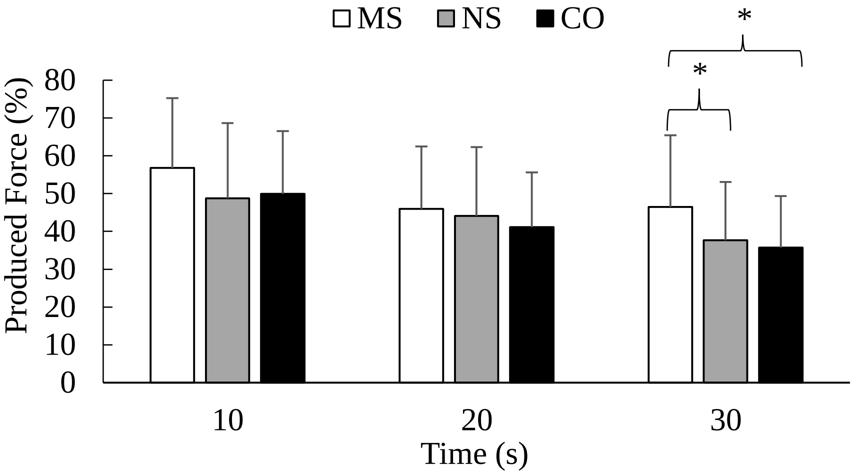

Figure 4. Experimental Condition x Time (pre-post task) interaction effect for produced force. Error bars denote standard deviations.
Note. MS: Motivational Stimulus; NS: Neutral Stimulus; CO: Control.
*$p < 0.05$.

Figure 5

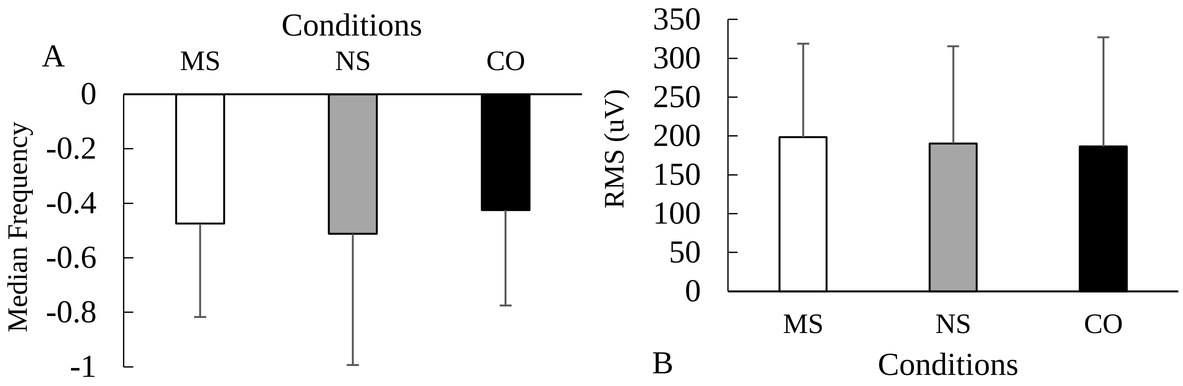

Figure 5. Condition effect for the rate of change (slope) of the median frequency (A) and recruitment of motor units (B). Error bars denote standard deviations.
Note. MS: Motivational Stimulus; NS: Neutral Stimulus; CO: Control.

Figure 6

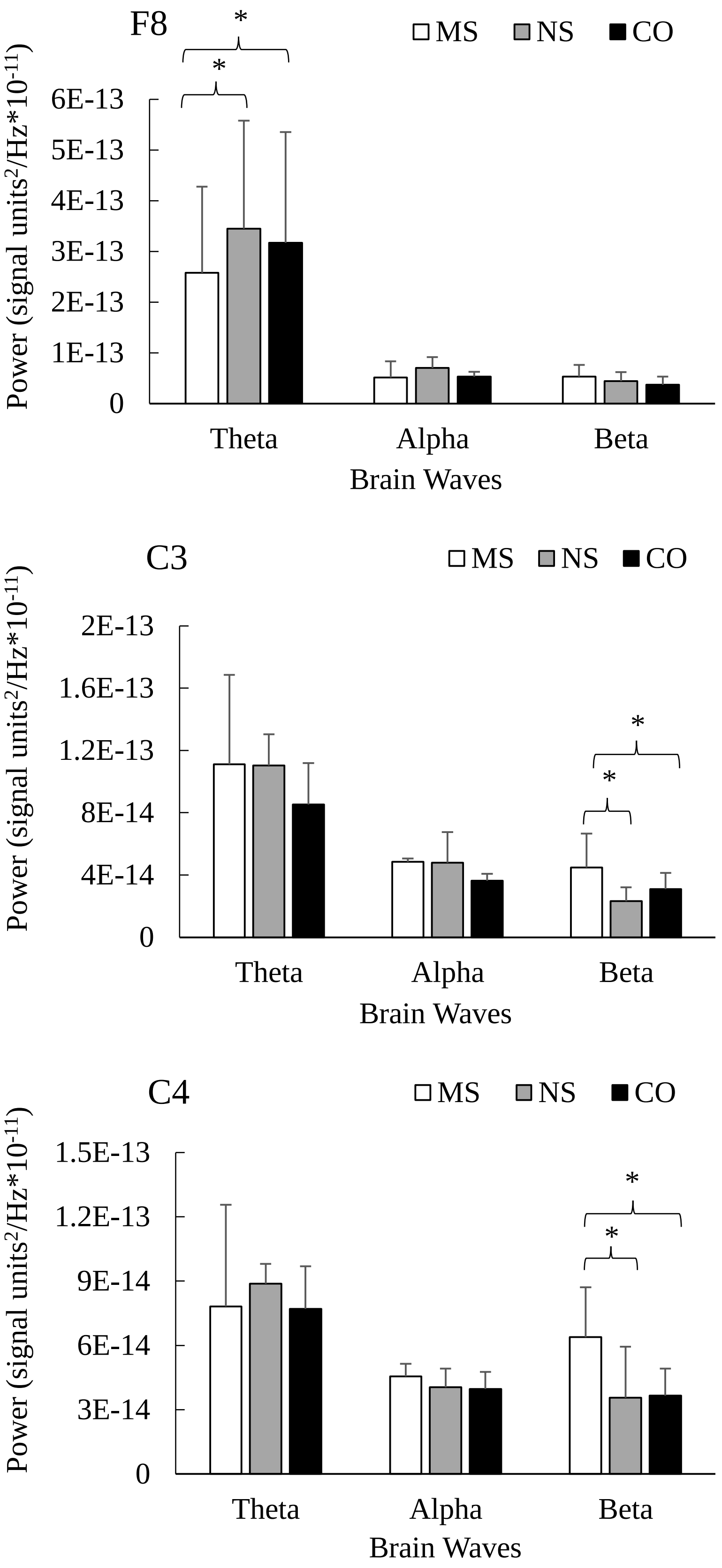

Figure 6. Condition main effect for brain waves. Error bars denote standard deviations.

Note. F8 = Right frontal electrode site (position 8); C3 = Left central electrode site (position 3); C4 = Right central electrode site (position 4).
Note. MS: Motivational Stimulus; NS: Neutral Stimulus; CO: Control.
*$p < 0.05$.