CORTICAL AND PSYCHOPHYSIOLOGICAL EFFECTS OF SENSORY MODULATION ON ATTENTIONAL SWITCHING DURING EXERCISE

A thesis submitted for the degree of Doctor of Philosophy

by

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Abstract

The present research programme sought to further understanding of the neurophysiological mechanisms that underlie the effects of music on exercise. Five original experiments were conducted using a wide range of psychophysical, psychological, physiological, and psychophysiological techniques. The results of the first study indicated that music partially reallocates attention towards task-unrelated thoughts (i.e., external dissociation), suppresses the amplitude of low-frequency waves in the brain, and enhances task performance. The findings of the second study indicated that music can have a negative effect if delivered during the execution of highly-demanding cognitive-motor tasks. In such instances, the right parietal regions of the brain activate in response to the presence of auditory distractors and prevent task performance from being compromised. The third study shed new light on the neural control of working muscles and indicated that music has the potential to reduce the frequency of electrical outputs emitted to the musculature and reduce the communication between the central motor command and adjacent regions. The fourth study of this research programme was conducted in an ecologically valid environment, wherein participants walked at self-paced speeds in the presence of different auditory stimuli. The results of the fourth study indicated that music elicits more positive affective responses and up-regulates beta waves to a greater degree than no-music conditions. Finally, the fifth study of this thesis made use of functional magnetic resonance imaging to explore the brain regions that activate in response to exercise and music. The results of this final study revealed that the left inferior frontal gyrus is highly active when individuals execute part-body exercises with music. The present research programme provides a neurophysiological basis for the use of music in exercise settings. The findings presented herein support the use of music as a valuable tool to explore more complex psychophysiological phenomena such as attention, affect, and fatigue.

Dedication

To Laís, for everything.

“A smooth sea never made a skilled sailor”
Franklin D. Roosevelt

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List of Abbreviations

3-D:	Three dimensional
AB:	Audiobook
ACC:	Anterior cingulate cortex
AD:	Auditory distraction
ADHD:	Attention deficit hyperactivity disorder
ADL:	Activities of daily life
AFQ:	Attentional Focusing Questionnaire
Ag/AgCl:	Silver chloride
ANOVA:	Analysis of variance
AS:	Attentional switching
Au:	Gold
BCP:	Beta central portion
BMRI:	Brunel Music Inventory Rating
BOLD:	Blood-oxygen-level dependent
CO_2:	Carbon dioxide
CO:	Control
Cond:	Condition
COPD:	Chronic obstructive pulmonary disease
CR10:	Category ratio
dBA:	Decibels
ECG:	Electrocardiogram
EDR:	ECG derived respiration
EEG:	Electroencephalography
EMG:	Electromyography

ERP:	Event-related potential
ERSP:	Event-related spectral perturbation
FAS:	Felt Arousal Scale
FFT:	Fast Fourier Transform
*f*MRI:	Functional magnetic resonance imaging
*f*NIRS:	Functional near-infrared spectroscopy
FS:	Feeling Scale
GRAPPA:	Generalized auto-calibrating partial parallel acquisition
H^+:	Hydrogen ions
HEO:	Horizontal eye movements
HR:	Hear rate
HRV:	Heart rate variability
lIFG:	Left inferior frontal gyrus
M:	Mean
MF:	Mean frequency
MM:	Music-during-movement
MNI:	Montreal Neurological Institute
MO:	Music-only
MOT:	Situational motivation
MRI:	Magnetic resonance imaging
MSC:	Magnitude-squared coherence.
MVC:	Maximal voluntary contraction
N1:	Negative peak that occurs at ~100–200 ms
N2:	Negative peak that occurs at ~200–350 ms
O_2:	Oxygen

OE:	Overall exertion
P1:	Positive peak that occurs at ~100–200 ms
P300:	Positive peak that occurs at ~300 ms
PACES:	Physical Activity Enjoyment Scale
PAR-Q:	Physical Activity Readiness Questionnaire
PET:	Positron emission tomography
PO:	Podcast
QRS:	Graphical deflections seen on a typical electrocardiogram
RCP:	Respiratory compensation point
RM:	Repeated measures
RMS:	Root mean square
RMSSD:	Root mean square of successive differences
ROI:	Region of interest
RPE:	Rate of perceived exertion
RPM:	Revolutions per minute
SA:	Sinoatrial node
SD:	Standard deviation
SDNN:	Standard deviation of normal-to-normal intervals
SE:	Standard error
SENIAM:	Surface Electromyography for the Non-Invasive Assessment of Muscles
SIAS:	Single-Item Attention Scale
sLORETA:	Standardised Low-Resolution Brain Electromagnetic Tomography
SMR:	Sensorimotor rhythm
Sn:	Tin
SO:	Stimulus-only

SPM: Statistical Parametric Mapping

SPSS: Statistical Package for the Social Sciences

TF: Time-frequency

TFC: Time-frequency oscillatory components

TR: Pulse repetition time

$\dot{V}CO_2$: Carbon dioxide production

VCO_2: Volume of carbon dioxide

VEO: Vertical eye movements

$\dot{V}O_2$: Oxygen consumption

VO_2: Volume of oxygen

VT: Ventilatory threshold

wMNE: Minimum Norm Method

Chapter 1: Introduction to the Research Programme

The present research programme sought to further understanding of the brain mechanisms that underlie the effects of auditory stimuli on psychophysiological responses during exercise. A review of literature was conducted to critically appraise the extant literature and explore the key psychological and neurophysiological variables that could be associated with the effects of music on exercise (see Chapter 2). Most of these variables were included in the experimental designs of five original studies in order to shine new light on the underlying mechanisms of music use during the execution of movements. It is noteworthy that music was used as a sensory stimulus that had the potential to reallocate one’s attentional focus towards environmental sensory cues and elicit a number of subsequent psychophysiological responses (Karageorghis, 2016). Accordingly, music appears to be a valuable tool to study more complex phenomena such as attentional focus and fatigue.

By exploring the mechanisms that underlie the effects of music on exercise, the author intended to provide a conceptual premise for future research in the area of psychophysiology and neuroscience. Attention and fatigue are two of the topics that have a substantial bearing on the understanding of neuronal/behavioural conditions such as attention deficit hyperactivity disorder (ADHD; Kuo & Faber Taylor, 2004), epilepsy (Arida, de Almeida, Cavalheiro, & Scorza, 2013; Maguire, 2012), and dementia (Brotons, Koger, & Pickett-Cooper, 1997; Lautenschlager, Cox, & Cyarto, 2012). Thus, attentional shifts induced by music during exercise might elucidate some of the cerebral triggers responsible for initiating cascade reactions that lead to disruptive conditions such as seizures (Jefferys, 2010) and other neuro-behavioural disorders (Hegde, 2014; Wise, Hoffman, Powell, Bombardier, & Bell, 2012).

A conceptual framework was proposed in the present thesis based on the results of five original experiments. The heuristic psychophysiological model of exercise (see sections

2.7.3 Psychophysiological Model of Exercise and 8.2 Common Themes) has several commonalities with the psychobiological model of endurance performance, and also takes the brain's electrical activity into account as the primary outcome to explicate key psychological and psychophysical responses to exercise. The model might serve as a guide for future research in the field of exercise psychophysiology. It is also intended to provide researchers and health professionals with a valuable tool to interpret the bodily reactions that are associated with the use of dissociative strategies, including the treatment of degenerative diseases such as chronic obstructive pulmonary disease (COPD; Brooks, Graydon, & Mcbride, 2003) and cystic fibrosis (Calik-Kutukcu et al., 2016).

1.1 Psychophysiological Research

Psychophysiology is considered a "scientific bridge" that links the perceptual/behavioural and biological perspectives (Cacioppo, Tassinary, & Berntson, 2007). Psychophysiologists have historically sought to investigate physiological changes that occur in response to environmental stimuli (e.g., animal fear response; Steimer, 2002) and vice-versa (e.g., emotional response to drugs; Kaelen et al., 2015). Since the late nineteenth century, psychophysiological experiments have been conducted in a systematic manner (see Darrow, 1964). The frequency of heartbeats and galvanic skin responses have been some of the most common measures of the psychophysiological sciences given the excellent temporal resolution and concomitant representation of one's affective/emotional state (Mundy-Castle & McKiever, 1953).

Exercise scientists rapidly realised the potential of the psychophysiological sciences as a means by which to explain some of the peripheral (i.e., bodily) and emotional responses to physical activity (Hatfield & Landers, 1987). In recent times, psychophysiological research has had an enormous impact upon the way researchers and exercise professionals understand the phenomenon of fatigue (Marcora, 2016; Noakes, 2011). In the present research programme, fatigue has been defined as an exercise-induced reduction in power output/produced force (Bishop, 2012). Understanding of fatigue is analogous to the “space race” of the exercise sciences. Manipulation of fatigue and fatigue-relate symptoms (e.g., breathlessness) have an important impact upon exercise performance (e.g., de Morree & Marcora, 2013) and adherence (e.g., Sadja et al., 2012). Psychophysiological research has also helped researchers to take emotional responses into consideration and expand the view from a biological and peripheral standpoint to a holistic perspective where brain activity and psychological responses act in tandem as a means by which to *create* fatigue (Noakes, 2012; Parry, Chinnasamy, Papadopoulou, Noakes, & Micklewright, 2011; St Clair Gibson et al., 2003). Despite extensive and constructive discussions between those who believe that fatigue is caused by peripheral changes (e.g., muscle metabolites) or cerebral responses (e.g., motivation) the question remains – why do we stop?

1.2 Internal and External Sensory Signals

Audiovisual stimuli have been used extensively in the realm of sport and exercise sciences as a means by which to enhance exercise performance and elicit more positive affective responses (Hutchinson, Karageorghis, & Jones, 2015; Loizou, Karageorghis, & Bishop, 2014). These environmental sensory cues are also used as valuable tools to further understanding of complex phenomena such as attention and fatigue (Bigliassi, et al., 2016a). External influences such as music can compete for attention with internal sensory cues caused by muscle contractions (i.e., afferent feedback) and reduce focal awareness (Karageorghis & Jones, 2014; Rejeski, 1985). This attentional response appears to initiate a process through which psychological, psychophysiological, and psychophysical variables are up-/down-modulated (Hutchinson & Karageorghis, 2013). Thus, external sensory cues might serve as potential strategies to investigate attentional disorders and fatigue-inducing conditions.

1.3 Operational Definition of Key Terms

Some of the key terms that were recurrently used in the present research programme are briefly described in this section as a means by which to facilitate understanding.

Attentional Switching (AS): The transition in attentional focus between external sensory cues and internal processes. This phenomenon occurs when humans shift the focus of attention to signals considered as more relevant. In the present research programme, this concept is associated with shifts of attention caused by exercise-related signals and external sensory cues such as music.

Blood-Oxygen-Level Dependent signal (BOLD): The functional imaging signal that corresponds to the concentration of haemoglobin.

Electroencephalography (EEG): A technique to analyse the electrical activity produced by neurons in the cerebral cortex. EEG is mainly characterised by its excellent temporal resolution; this characteristic makes EEG appropriate to identify the exact moment when rapid cerebral reactions occur (i.e., evoked potentials).

Electromyography (EMG): A technique to analyse the electrical activity in the muscles. By analysing EMG results, researchers can identify diverse phenomena such as neural fatigue and motor unit recruitment during the execution of movements.

Fast Fourier Transform: Fourier analysis converts a signal from its original domain to a representation in the frequency domain and vice versa.

Functional Magnetic Resonance Imaging (*f*MRI): An imaging technique developed to analyse haemodynamic responses in the brain. This technique relies on the magnetic properties of the cell to produce brain scanning images.

Harmony: The combination of different notes played simultaneously (Karageorghis, Priest, Terry, Chatzisarantis, & Lane, 2006). Karageorghis & Terry (2008) stated that

"Harmony acts to shape the mood of the music to make you feel happy, sad, soulful or romantic through hearing different notes at the same time…" (p. 14).

Heart Rate (HR): The frequency at which the left ventricle of the heart pumps blood into the aorta artery. The speed of the cardiac cycle is measured in beats per minute (bpm).

Heart Rate Variability (HRV): The pattern of variation between heartbeats, which is influenced by psychophysiological factors (Sztajzel, 2004). The analysis of HRV makes possible the identification of sympathetic and parasympathetic activity (autonomic system) on the sinoatrial node.

Loudness: The number of decibels (dBA) achieved when a sound is produced (Fletcher & Munson, 1993). Loudness is also perceived at different levels (psychological construct) based on the psychophysiological state of humans (e.g., Asutay & Västfjäll, 2012).

Melody: Melody is a series of musical notes played sequentially in order to create waves of frequency. Melody is also explained as "…the tune of a piece of music – the part you might hum or whistle along to…" (Karageorghis & Terry, 2008, p. 14).

Meter: The organization of the rhythmic structure of music. It is also conceptualised as "…a hierarchical structure, consisting of pulse sensations at different levels (time scales)" (Klapuri, Eronen, & Astola, 2006, p. 342).

Pitch: The auditory interpretation of acoustic properties based on the variations of frequency. Similar definitions consider pitch as "…the perceptual correlate of the periodicity, or repetition rate, of an acoustic waveform" (Oxenham, 2012, p. 13335); or "The frequency of the spectral component is the sound's perceived pitch" (Yost, 2009, p. 1701).

Respiratory Compensation Point (RCP): The second inflection point on the curve of carbon dioxide during conditions of exercise. This index represents the accumulation of hydrogen in the circulatory system without proper clearance.

Rhythm: The feature of music associated with the succession of sounds and silence (see Bispham, 2006). Similarly, McAuley (2010), defines rhythm as "…the serial pattern of durations marked by sounds (notes) and silences (rests)" (p. 166).

Spectral Coherence: A statistical method to examine the relationship between two signals and to estimate the power transfer of a linear system.

Tempo: "…the pace of a piece of music (i.e., how fast or slow it is) and is typically associated with the rate of periodic events (beats) that listeners perceive to occur at regular (equal) temporal intervals" (Mcauley, 2010, p. 166).

Texture: The overall quality of sound, which encompasses melody, harmony, and rhythm (Kokoras, 2007).

Timbre: The characteristic quality of sound. It also refers "…to the "colour" or quality of sounds, and is typically divorced conceptually from pitch and loudness" (Wessel, 1979, p. 45). Differences of timbre could be partially described as the sound made by a flute versus that made by a French horn.

Ventilatory Threshold (VT): An index of transition between aerobic and anaerobic metabolism during different modes of exercise. This phenomenon can be observed during the assessment of the respiratory, cardiovascular, and muscular systems.

Wavelet Transform: A mathematical method to reconstruct the time-frequency representation of a signal.

Chapter 2: Review of Literature

The present thesis investigates the effects of sensory modulation on psychophysiological responses to various modes of exercise. Sensory strategies such as music, audiobooks and podcasts were generally used as a means by which to ameliorate the effects of fatigue-related sensations (e.g., limb discomfort and breathlessness). This review was developed in order to critically evaluate the use of sensory modulation during different exercise modes. The theoretical basis of attention, affect, memory, and perceived effort were examined, since these topics are strongly associated with auditory stimuli (Hutchinson et al., 2015; Jones, Karageorghis, & Ekkekakis, 2014; Loizou & Karageorghis, 2015). Particular emphasis was given to the cerebral pathways of attentional switching, including top-down and bottom-up attentional shifts (Buschman & Miller, 2007), given that exercise encompasses various modes of attention depending on its intensity (cf. Hutchinson & Tenenbaum, 2007). Psychophysiological responses to exercise such as brain activity, heart rate variability, and rate of perceived exertion were included in the present review of literature in order to further understanding of the exercising human body.

2.1 Theoretical Backdrop

In the early nineteenth century, John Yelloly (1809) published what would be one of the landmark studies on the influence of the brain on peripheral responses, such as strength and coordination. Ever since his study, the brain has been recognised as the organ responsible for controlling muscles by use of a complex system of electrical signals to produce movements (Penfield, 1954). Most movements that are integral to our daily functioning, such as walking or running, are produced *automatically* because they were already fully developed some 3.6 million years ago (Johanson & Taieb, 1976). While walking, a person is able to appreciate the environment, feel the breeze, and listen to the birds singing in the trees (i.e., environmental sensory signals). During low-intensity exercise, the brain is capable of focusing on external influences while coordinating a simple movement pattern (Hutchinson & Tenenbaum, 2007). However, if the intensity of the exercise increases, the attentional focus may switch to internal processes such as respiration rate and muscular activity, because the brain considers interoceptive sensory cues (e.g., muscle lactic acidosis) as generally more important than external influences.

An increase in exercise intensity causes an increase in afferent signals from the muscles and internal organs to the brain. In such instance, metabolites produced by the working muscles evoke sensations of fatigue and pain (Amann et al., 2013; Pollak et al., 2014). There is a limited channel capacity inside the brain (Pribram & McGuinness, 1992), so the increase in afferent signals forces the “commander” to choose where to focus (theories of fatigue are also explained in section 2.7 Corollary Discharge Model). The brain makes continuous real-time decisions about which signals are most important and gives these the most attention (Treisman, 1964). Unattended signals can still influence attention if their physical features change, such as an increase in loudness (auditory signals) and brightness (visual signals).

The transition in focus between external influences and internal processes is known as *attentional switching*. This transition can occur earlier or later in the exercise cycle, depending on a range of factors (e.g., exercise intensity, mode, and complexity). In recent years, researchers have tested a range of strategies that might cause attentional switching to occur later, in order to assuage the effects of fatigue-related sensations and make the exercise more enjoyable (Lane, Davis, & Devonport, 2011; Stork, Kwan, Gibala, & Martin Ginis, 2015). Exercise enjoyment is positively influenced by sensory strategies such as music (Karageorghis, Terry, Lane, Bishop, & Priest, 2012) and video (Hutchinson et al., 2015; Jones et al., 2014). On the other hand, sensory deprivation has a negative influence on psychological variables (see Boutcher & Trenske, 1990). The relationship between sensory processing and psychobiological systems is evident and capable of influencing exercise performance (see Karageorghis & Priest, 2012a for a review). As an example, Karageorghis and colleagues (2013) demonstrated that collegiate students can swim faster (performance), with more dissociative thoughts, and higher state motivation under the influence of music, which is a simple, safe, and inexpensive sensory strategy.

Interventions using sensory modulation are helpful in exploring the brain circuits that are integral to attentional switching during exercise. The physiological interaction between sensory processing and bodily responses is monitored and controlled by the brain (Lang, Bradley, & Cuthbert, 1998). The cerebral pathways responsible for controlling attentional focus during exercise are hitherto under-researched, because techniques and technology to examine the brain during exercise are relatively new (Aspinall, Mavros, Coyne, & Roe, 2015; Thompson, Steffert, Ros, Leach, & Gruzelier, 2008). The present programme of research set out to employ innovative techniques and methods to process the biological signal in order to shed new light on the activity of neural circuits during attentional switching.

2.2 Attention

In readiness to hunt its prey, the owl must forget the external world and focus on minimal details of movement, in order to act promptly and accurately. Attentional focus is essential for the survival of most species (Darwin, 1859). An inhibitory circuit was identified in the midbrain tegmentum of barn owls, which is responsible for blocking external and internal signals in the optic tectum (Mysore & Knudsen, 2013). Such a mechanism enables the owl to avoid competitive influences on attention, switching the focus only to the target. Similarly, "…the superior colliculus is a bottleneck in the covert selection of signals for perceptual judgments" in monkeys (see Lovejoy & Krauzlis, 2010, p.261). The superior colliculus of mammals seems to be the region of the brain responsible for selecting which stimulus deserves attention.

Attention has also considerable influence on the lives of humans. In 1958, Donald Broadbent published one of the first studies into the phenomenon of selective attention. Broadbent's filter model caused an enormous impact on the scientific world. His model postulates that only relevant signals are processed by the brain in order to prevent information overload, since the brain is not capable of processing signals from multiple sources. In addition, unattended signals remain in the system, but only briefly, after which they are discarded (Broadbent, 1958). In 1964, Anne Marie Treisman improved up on Broadbent's model by introducing the notion of *processes of attenuation*. She suggested that unattended signals are not excluded, but are simply receiving less attention. The unattended signals might receive more attention if the physical features change such as becoming higher in pitch or louder in volume (Treisman, 1964).

The Treisman's attenuation theory also postulates that unattended signals are threshold-dependent, which means that even unattended signals with low-decibel sound can receive attention if they carry important meaning. She proposed this idea based on the strength that different signals can assume. For example, familiar names have strong influence on people's attention. When familiar names are mentioned by others, people tend to focus on this unattended signal, because of the level of importance or familiarity this signal carries. Accordingly, the brain selects a target based on the strength of the message.

The theory proposed by Treisman (1964) has been recently tested by using innovative techniques to analyse the brain. Therefore, controversial results have been found, which means that this topic still remains unclear. In 1999, Rees, Russell, Frith, and Driver, used functional magnetic resonance imaging (*f*MRI; see section 2.10 Functional Magnetic Resonance Imaging) to identify the reason people are not capable of reporting the content of ignored information. They created an experimental design to investigate the difference between inattentional blindness (failure to perceive) and inattentional amnesia (forgetfulness). The results demonstrated that attention is the centre of all sensory processing. The authors also reveal that “When covert attention was directed to other material for a demanding task, even words presented directly at the fovea produced no detectable differential cortical activity whatsoever” (p. 2506). Conversely, when Ruz, Worden, Tudela, and McCandliss (2005) replicated the same procedures using electroencephalography (EEG; see Collura, 1993) and obtained dissimilar results. Several regions such as the left frontal, left posterior, and medial scalp were activated differently between words and scrambled words stimuli. The authors believe this contradiction is associated with the use of different techniques to analyse the brain. Despite the absence of compelling evidence to support the attenuation theory proposed by Treisman (1964), there is insufficient evidence to conclude the brain does not select the target based on the strength of the message.

2.2.1 Aspects of Attention

The human brain works as a leader of the body, controlling actions and reactions. In 1949, Donald Olding Hebb published the first study addressing the close relationship between the central nervous system and psychological responses. Since then, the neurological basis of psychology began to be systematically investigated. To ensure progression, the concepts of psychology were stratified (e.g., differences between affect, emotion, and mood) in order to make cortical correlations possible (Aue, Lavelle, & Cacioppo, 2009). The concept of attention was also re-evaluated, given that attention is associated with various tasks such as attentional control (selective attention; e.g., long-term maintenance of attentional focus) and immediate responses (loud noises; e.g., a sudden shout)

The concept of attention is recently divided into three main components in accord with their neural networks (Petersen & Posner, 2012): *alerting*, *orienting*, and *executive control*. Alerting is an immediate response, induced by sensory input during periods of high sensitivity; for example, when a cyclist wipes the sweat from her eyes in order to allow her to see while cycling. Orienting indicates the selective attention of sensory input based on the signal level of relevance; for example, when a cyclist has to pay attention to instructions provided by the coach during a time trial. Executive control is a cognitive process associated with finding rapid solutions during conflicting tasks; for example, re-organising the peloton while also changing gear.

The aforementioned components of attention activate specific brain regions (Posner, Rothbart, Sheese, & Voelker, 2014). The activity of the prefrontal cortex, parietal lobe, and the thalamus is associated with the alerting system (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005). The activity of the superior parietal lobe, and the temporal parietal junction are associated with the orienting system (Corbetta & Shulman, 2002). The complex activity of executive control is associated with the dorsolateral prefrontal cortex and the anterior cingulate (Yanagisawa et al., 2010). The figures below present some of the brain regions associated with the underlying mechanisms of attention.

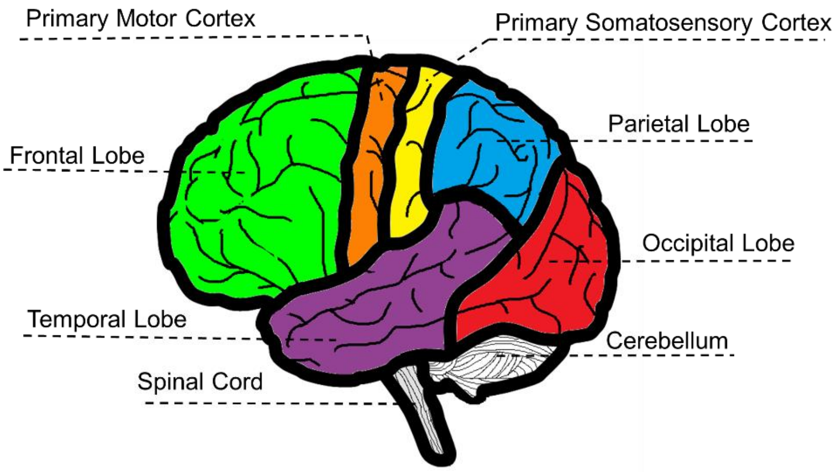


Figure 2.1. Lateral view of the brain.

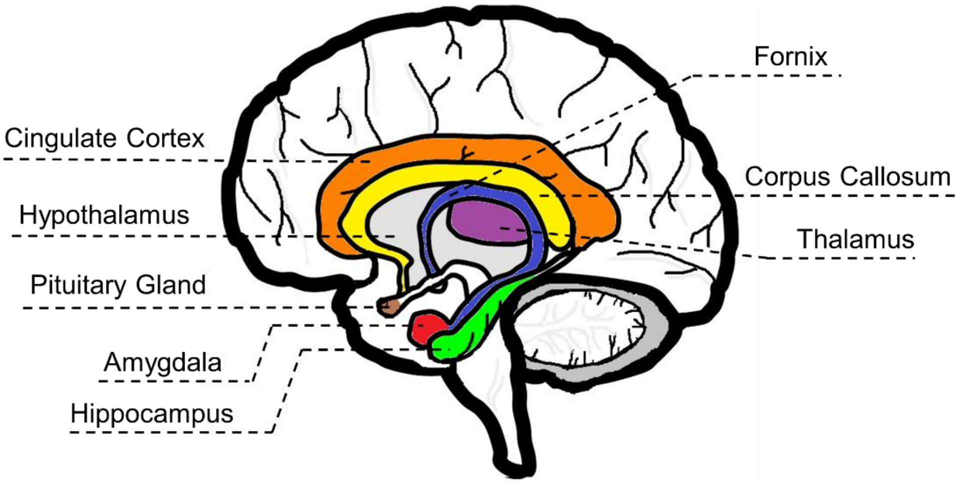


Figure 2.2. Sagittal view of the brain.

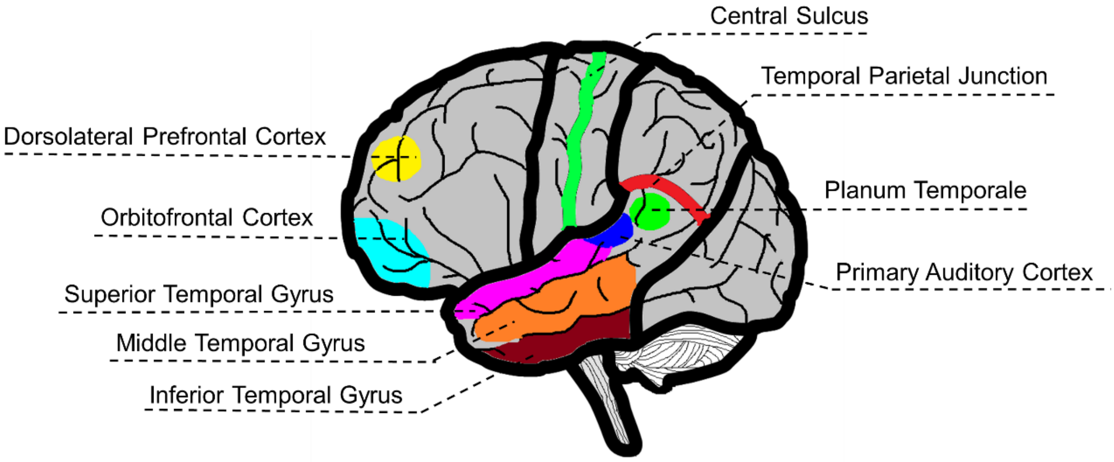


Figure 2.3. Subdivision of superficial regions of the brain.

2.2.2 Influences on Attention

While driving, a man sees a normal landscape with trees and flowers. The image has common features such as colour and brightness, but the man feels astonished by that place. Some aspects of the landscape have reawakened long-term memories, which made the traveller switch the attention to the image. For a short while, the man forgets the real world because of memories from his childhood. It is a simple example that attention is also influenced by brain mechanisms unrelated to the physical features of the signal (see Chun & Turk-Browne, 2007; Desimone, 1996). Psychological responses such as emotions can also strengthen exogenous or endogenous stimuli that affect attention. The relationship between different systems is controlled by specific brain regions. Bush, Luu, and Posner (2000) reviewed the roles of the anterior cingulate cortex (ACC). The authors state that “Lesions of ACC have produced a host of symptoms, which include apathy, inattention, dysregulation of autonomic functions, akinetic mutism, and emotional instability” (p. 216). Therefore, this area of the brain seems to be the hub to integrate and coordinate attention and emotion. Accordingly, neuroimaging studies provided compelling evidence regarding a subdivision of the ACC (see Whalen et al., 1998). This subdivision is directly associated with cognitive and affective processing, which support the notion that this region of the brain represents a hub for attention, behaviour, and emotion (Goldman-Rakic, 1988; Vogt, Finch, & Olson, 1992).

Auditory stimuli such as music can link the “bridges” of the brain and activate numerous brain regions regarding attention, memory, and emotion (Abbott, 2002; Juslin & Västfjäll, 2008; Zatorre & Salimpoor, 2013). While listening to a song, the auditory signal is processed through its physical features such as loudness, tempo, and melody (Liégeois-Chauvel, Peretz, Babaï, Laguitton, & Chauvel, 1998). In addition, music elicits emotions by activating deep regions of the brain (Koelsch, 2014) and can also reawaken old memories associated with events from the past (Jäncke, 2008). Thus, music is an example of an exogenous signal that is capable of capturing attention by activating different neural pathways.

Bishop, Wright, and Karageorghis (2014) manipulated tempo and intensity of music (dBA) in order to identify improvements of reaction time. The hypotheses of this study are based on the assumption that fast reaction times occur at optimal arousal state, and fast-tempo music is expected to increase arousal state by changing patterns of cerebral activity. This study illustrates the extensive interconnection of musical components with diverse neural systems such as attention and motor control. Twelve tennis players were examined by using functional magnetic resonance imaging (*f*MRI). Results confirmed initial hypotheses that fast-tempo music has increased visuomotor activity through the elicitation of emotional responses. This mechanism has improved attentiveness and responsiveness. The subcallosal gyrus was significantly activated during the reaction time task following fast-tempo music. This region of the brain is directly associated with the level of pleasantness of music (see Blood, Zatorre, Bermudez, & Evans, 1999; Brown, Martinez, & Parsons, 2004). Hence, fast-tempo music presumably elicited greater levels of arousal, which modulated reaction time by activating indirect pathways. In this case, arousal dictates the level of readiness and voluntary/involuntary attention of participants. Therefore, voluntary and involuntary types of attention affect reaction time (cf. Prinzmetal, McCool, & Park, 2005). This outcome indicates an indirect effect of music on reaction time of tennis players. This study also sheds new light on the mechanisms underlying the interaction between auditory stimulus, attentional function, and motor control.

2.2.3 Attention and Exercise

Bodily responses change in order to supply energy while exercising. Lungs inflate faster and with more air to bring oxygen into the body, blood flows faster to provide oxygen to organs, and the brain sends and receives more signals to control the body. Acute changes while exercising make the body an adjustable machine able to face diverse situations. When the situation is challenging, the brain works harder in order to accomplish the task (Bigliassi, et al., 2016a; Secher, Seifert, & Van Lieshout, 2008). During exercise, the brain receives signals from many internal receptors such as mechanoreceptors, thermoreceptors, chemoreceptors, and pain receptors (Lynn, 1975). The brain also encodes these signals while coordinating the body (highly-demanding cognitive-motor task). When the intensity of the exercise increases, afferent signals (signals received by the brain) become more relevant than efferent control (signals sent by the brain). In other words, the brain shifts the attentional focus from external influences to internal processes depending on the relevance of the message (Hutchinson & Tenenbaum, 2007; Rejeski, 1985).

When afferent signals are relevant (e.g., the sound of an explosion) the human brain immediately shifts attention to those signals. Based on this assumption, the physical features of the signal influence bottom-up attention (see Katsuki & Constantinidis, 2014). Conversely, attention can be switched according to people's will. Top-down attention is a conscious process to choose the target determined by people's desire (Buschman & Miller, 2007). An example of top-down attention might be attempting to read while people talk. During low-intensity exercise, the brain is able to control attention. At this stage, exercisers can simply appreciate the landscape and feel the breeze. They can also use this moment to prepare themselves for the next stage when the exercise becomes more intense (teleoanticipation mechanism; see Wittekind, Micklewright, & Beneke, 2011). During low-intensity exercise, the brain is able to make choices given that the afferent signals are insufficient to force attention to internal sensory cues.

When the exercise becomes more intense, the number of afferent signals from internal processes increases (e.g., signals from the muscles, heart, and lungs). As a result, attention becomes *uncontrolled* (unconscious reallocation) and the brain is forced to focus on signals considered more relevant (Gabana, Van Raalte, Hutchinson, Brewer, & Petitpas, 2015; Hutchinson & Tenenbaum, 2007). The ability to appreciate the landscape or calculate the best exercise strategy is reduced. During this period, the brain processes what is relevant to finish the trial without shifting attention to task-irrelevant signals such as environmental sensory cues (cf. Bigliassi, León-Domínguez, Buzzachera, Barreto-Silva, & Altimari, 2015a).

2.2.4 Attentional Style

There is consistent evidence in the literature regarding the relationship between attention allocation and exercise intensity (LaCaille, Masters, & Heath, 2004; Gershon

Tenenbaum & Connolly, 2008). The allocation of attention is also influenced by personal factors such as attentional style (Hutchinson & Karageorghis, 2013). Attentional style is a predisposition to use associative or dissociative strategies during exercise (Hutchinson & Tenenbaum, 2007). Associators tend to focus on internal processes during exercise, such as physiological parameters and performance-related indices. Conversely, dissociators tend to focus on external influences during exercise, such as visual and auditory information. There is another attentional style, which involves attentional flexibility; those who can shift attention between associative and dissociative strategies during exercise in accord with situational demands are referred to as switchers (cf. Moran, 1996, p. 71).

There is strong relationship between psychological and physiological responses during exercise (Dasilva et al., 2011). Attentional style is a moderator variable, which can affect perceptions of exercise; therefore, attentional style may influence psychophysiological variables indirectly. Sensory stimuli such as music and video are also expected to positively influence exercisers (Hutchinson et al., 2015; Jones et al., 2014). However, attentional style can moderate the degree to which exercisers are influenced by sensory interventions (see Hutchinson & Karageorghis, 2013).

2.2.5 Attentional Focus and Exercise Performance

Attentional strategies have been extensively applied in the realm of sport and exercise as a means by which to enhance exercise performance and assuage the effects of fatigue (Gershon Tenenbaum & Connolly, 2008; Wulf, Chiviacowsky, Schiller, & Avila, 2010). By focusing on internal or external sensory cues, exercisers can consciously manipulate psychophysiological parameters such as the activity of the autonomous system (Karageorghis & Jones, 2014). External dissociation apparently facilitates the completion of explosive and accurate movements (Lohse & Sherwood, 2011, 2012). In other words, exercisers can perform more accurately when the movements are only partially controlled by conscious processes, meaning that unconscious control can enhance coordination with consequent impact upon performance-related variables.

An internal focus of attention makes the exerciser aware of physiological changes that occur in response to the increasing symptoms of fatigue, and is also effective to improve anticipatory mechanisms (Wittekind et al., 2011). In this instance, the exerciser can focus on physiological changes such as heart and respiration rate and also manipulate those responses through the use of psychological techniques (e.g., imagery; Shafir, Taylor, Atkinson, Langenecker, & Zubieta, 2013). Endurance performance is positively influenced by external dissociation, given that the human brain was developed to make the body capable of overcoming barriers and completing tasks, which means that thinking about muscles and joints is not a natural behaviour (Lohse & Sherwood, 2012; Pourtois, Schettino, & Vuilleumier, 2013).

The human brain naturally forces the attentional focus towards interoceptive sensory cues as a response to the increasing symptoms of fatigue (Hutchinson & Tenenbaum, 2007; Rejeski, 1985). This mechanism is theorised to be a natural response developed through the ages to protect the human body against catastrophic situations such as heart failure, extreme levels of acidosis, and osteoarticular injuries (Noakes, St Clair Gibson, & Lambert, 2005; Timothy David Noakes, 2012). Obese and sedentary people usually focus on the internal sensory cues at the very beginning of the exercise cycle (Deforche & De Bourdeaudhuij, 2015). The mechanism of early attentional switching to internal association prepones fatigue-related sensations and compromises the execution of long-term physical tasks such as walking and cycling (e.g., > 30 min). In such application, external attentional strategies should be trained in order to counteract the detrimental effects of fatigue on task engagement.

2.3 Core Affect, Emotion, and Mood

Conceptual mistakes in studies of psychology-related areas can lead to equivocal results (Beedie, Terry, & Lane, 2005; Ekkekakis, 2013). In this section, a clear difference between core affect, emotion, and mood is presented. Using these terms interchangeably may indicate a threat for the internal validity of research. Taking this into consideration, core affect is the most basic, general, and elementary sensation of humans. It is a feeling perceived at different levels such as excitation and relaxation or pleasure and displeasure. Russell (2009) defines core affect as "a pre-conceptual primitive process, a neurophysiological state, accessible to consciousness as a simple non-reflective feeling: feeling good or bad, feeling lethargic or energised" (p. 1264). Core affect may be the origin of different feelings; however, it can also be felt separately. Russell (2003) also provides an example based on the temperature variation. He explains that variations of temperature occur before the feeling (e.g., hot or cold) associated with such a variation. In this case, the temperature is a primitive and simple experience, but the feeling of cold or hot is a subsequent interpretation. In this example, core affect is analogous to temperature, because this phenomenon precedes more complex feelings.

Emotions, on the other hand, are not easily defined (Fehr & Russell, 1984). Conceptual frameworks were proposed in order to understand the concept of emotion (see Russell, 2003). However, the definition of emotion is commonly explained by using simple examples such as anger, fear, and joy (see Russell, 2009). Emotions are associated with persons, objects, or events from the past, present, or future. Emotional episodes are defining elements, "…involved in the transaction between person and object…" (Ekkekakis, 2012, p. 322). Those elements include cognitive appraisal, which is a mechanism of event-evaluation. Based on this assumption, emotions are psychological responses elicited by real or imagined events (Wierzbicka, 1992). Emotions also require personal appraisal, are of short or very short duration, but high magnitude such as disgust, envy, and happiness.

Emotions and mood have similar roots, but different durations (Beedie et al., 2005). Mood is usually called a state with low intensity and long duration (hours or days) such as feeling apathetic, complacent, and indifferent. Conversely, emotions last for few seconds or minutes (Ekkekakis, 2012). The variation of mood might have no specific causes, and this condition is experienced by humans on a daily basis (see Bellini, Blaime, & Shea, 2002 for a practical example). For instance, when a person wakes up and simply does not feel willing to work. This person does not feel angry or choleric (emotions); actually, it is just an uncomfortable feeling of indisposition. There was no apparent cause to elicit this mood state, but this feeling will probably last for hours or even the entire day. This example demonstrates that moods are not as intense as emotions, there are no specific causes, and last longer than emotional responses.

Affective responses and emotions are produced in the brain (Berridge & Kringelbach, 2013; LeDoux, 2000). Researchers have found many regions of the brain associated with emotional processing (Dalgleish, 2004; Lindquist, Wager, Kober, Bliss-Moreau, & Barrett, 2012). Emotions are complex brain responses, which means that different regions process emotions. Psychological concepts such as attention may comprise cerebral connections with other concepts such as memory; it makes brain analysis, an intriguing area of research. In order to solve this problem, a process of subtraction must be created to isolate cerebral processes for different concepts of psychology (Amaro & Barker, 2006).

In 1868, John M. Harlow identified the prefrontal cortex as an important area in the modulation of emotional responses/mood state. Harlow discovered it because Phineas Gage, one of his patients, suffered a dramatic and famous accident while working; an iron bar went through his head causing serious damage to the prefrontal cortex (front part of the frontal lobe). During his recovery period, emotional aspects such as anger and social behaviour were dramatically changed, which made Harlow able to conclude that the prefrontal cortex had an important influence on emotional responses/mood state. Ever since then, the brain has been assessed exhaustively in order to further understanding of diverse emotions (Davidson, 2004; Sommer & Wurtz, 2008; Tempest, Eston, & Parfitt, 2014).

The limbic system (see Figure 2.2) is also involved in processing and generating emotional responses (Catani, Dell'acqua, & Thiebaut de Schotten, 2013; Morgane, Galler, & Mokler, 2005). Brain networks create a “bridge” between the limbic system and other regions. The temporal-amygdala-orbitofrontal network is connected through the uncinated fasciculus (white matter). This network integrates emotion with behaviour and cognition by linking amygdala and hippocampus with the temporal lobe and the orbitofrontal cortex (Catani et al., 2013). A recent study demonstrated an impaired connection between amygdala and orbitofrontal cortex in psychopaths (cf. Craig et al., 2009). Such evidence suggests that this brain network is also responsible for creating complex emotions through multimodal sensory integration, which, in turn, influences behaviour.

2.3.1 Emotions and Lifespan

Snowdon and colleagues (1999) showed the influence of emotions on the way nuns live. After investigating handwritten autobiographies from the nun study, Danner et al. (2001) discovered a linear trend between positive emotions in early life and longevity. The underlying mechanisms behind the interconnection between emotions and longevity are hitherto under-researched; however, the neural networks of emotion and behaviour (lifestyle) provide a reasonable explanation for this phenomenon. This interplay between emotions and behaviour creates a new theory regarding the effects of music on humans' lives.

Life expectancy increased dramatically some 30,000 years ago (Caspari, 2012); a time close to the epoch when homo sapiens started to create music and other forms of art (Conard, Malina, & Münzel, 2009). The creation of art is hypothesised to be the main reason behind this increase in life expectancy (see Caspari, 2012). In the present thesis, a theory is briefly proposed in order to justify the lifespan difference based on the creation of art. The diagram below depicts the lifespan theory. The theory indicates that life expectancy was greatly influenced by the creation of diverse types of art such as music and sculpture.

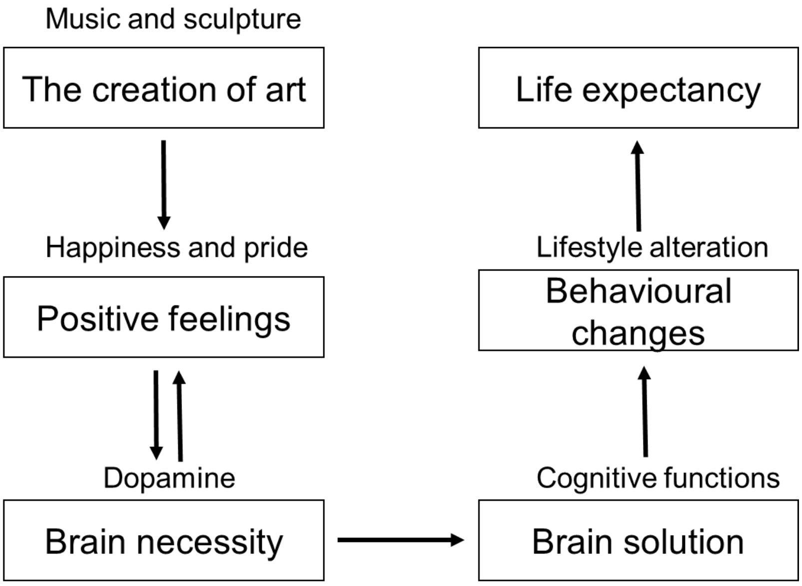


Figure 2.4. The lifespan theory proposed to explain the increase in life expectancy that occurred some 30,000 years ago.

Creativity is highly associated with emotional responses (cf. Averill, Chon, & Hahn, 2001). When humans created music for the first time, emotions evoked by the feeling of creation were added up with the positive emotions elicited by listening to music (Blood et al., 1999). The result of these ingredients created emotions such as happiness and pride. Therefore, the sensations elicited by this phenomenon were so pleasant that the human brain wanted more (dopamine release; see Kringelbach & Berridge, 2009). In order to maintain this dose of pleasure, the brain started to look for solutions. Behavioural changes are unconsciously created by humans in order to maintain good feelings (Holden, 2001). This topic is deeply investigated in the field of gambling and behavioural addiction (for review, see Delfabbro, King, & Griffiths, 2012). Those behavioural adjustments might have led to life expectancy changes, when humans started to care more about their lives. This lifestyle adaptation was a mechanism of protection against premature death. Accordingly, humans altered their lifestyle as a means by which to experience more positive emotions.

2.3.2 Affective Responses to Exercise

Physical exercise has short- and long-term effects on psychological variables such as core affect, cognition, and memory (Beaulac, Carlson, & Boyd, 2011; Hötting & Röder, 2013; Rendi, Szabo, Szabó, Velenczei, & Kovács, 2008; Weinberg, Hasni, Shinohara, & Duarte, 2014). In order to understand the underlying mechanisms of this phenomenon, the relationship between exercise and brain activity must be explored by using brain assessment techniques, such as *f*MRI (e.g., Fontes et al., 2013), functional near-infrared spectroscopy (*f*NIRS; Ekkekakis, 2009) and EEG (e.g., Schneider, Askew, Abel, Mierau, & Strüder, 2010).

Exercising is not an easy task for the human body; the brain has to process all afferent signals from internal receptors and coordinate the musculature in tandem (see section 2.2.3 Attention and Exercise). However, the relationship between exercise and psychological responses is intensity-dependent. Ventilatory threshold is an indicator of transition between aerobic and anaerobic metabolism. Exercising below ventilatory threshold is associated with positive feelings, as suggested by the dual-model theory of affective responses proposed by Ekkekakis (2003). Conversely, exercising above ventilatory threshold is associated with negative feelings. In this context, the ventilatory threshold is a point of transition, not only related to metabolism (from aerobic to anaerobic) but also to psychological responses.

During low-intensity exercise (below ventilatory threshold), the brain is capable of focusing on external influences such as auditory and visual signals (Hutchinson et al., 2015; Loizou & Karageorghis, 2015). This intensity is not difficult for the exerciser to perform. The primary motor cortex and the cerebellar vermis control movement and posture, while the primary somatosensory cortex processes all feedback from internal receptors (Chiel, Ting, Ekeberg, & Hartmann, 2009). Interestingly, perception of exercise intensity is processed in the posterior cingulate gyrus (see Fontes et al., 2013). This evidence supports the direct relationship between exercise intensity and affective responses, because this region of the brain is associated with pain processing, emotion, and memory functions (Vogt, 2005).

2.4 The Mechanisms of Memory

Memory is a cortical plasticity produced when something is learnt (Lamprecht & LeDoux, 2004). When actions of association and repetition are included, memories are consolidated in the brain. Sleeping is also essential to consolidate memories (Stickgold, 2005); but the mechanisms underlying the relationship between memory consolidation and sleeping remain unclear. Memories can be explicit (declarative; conscious recollection) or implicit (non-declarative; without conscious recollection) depending on the level of consciousness involved (see Squire & Zola, 1996). Memories are produced in specific regions of the brain such as the hippocampus and the diencephalon (composed of thalamus, subthalamus, hypothalamus, and epithalamus). These two regions are connected by the hippocampal-diencephalic network (Catani et al., 2013). Ageing and Alzheimer’s disease jeopardise the function and reduce the metabolism of this network, which causes a degradation of memory (Minoshima et al., 1997).

Explicit memories can be subdivided into *episodic*, when people attempt to remember a current event, and *semantic*, when people attempt to remember general information (Squire, 1992). Implicit memories, on the other hand, are broader because non-conscious mechanisms are involved. Riding a bicycle is a common example of implicit memory, when the brain has to produce a certain pattern of movement without conscious recollection.

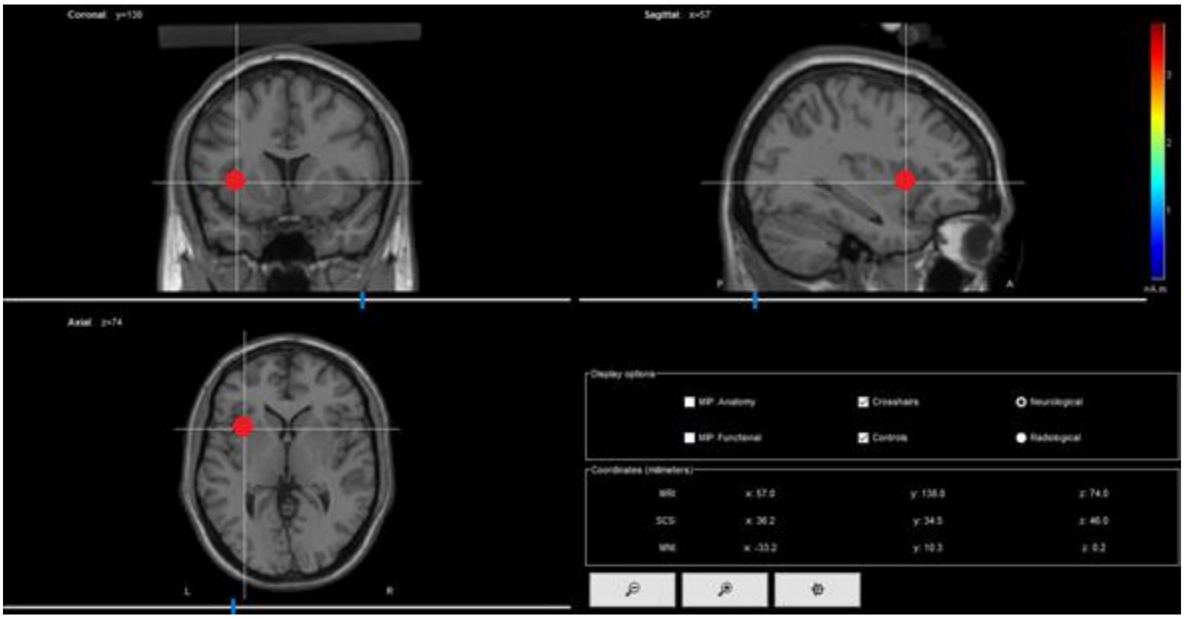
Memories are neural pathways constructed through repetitive association or relevant events (Dudai, 2004). When an important episode occurs, parallel feelings and bodily responses are stored within that event. The moment when a memory is reawakened, all those nostalgic sensations are brought together; for example, if a person witnessed a tragedy during its childhood, that memory can increase heart rate and cause panic, even 20 years after that episode. Childhood is the period of life when humans discover the world; this epoch creates the basis at which personality is developed (Conway & Pleydell-Pearce, 2000). Memories from childhood and youth are stored throughout the lifespan; those deep memories are easily recalled under the effect of sensory stimuli (Juslin & Västfjäll, 2008). If the person who experienced a tragedy during their childhood was listening to a song at that moment, the same song can reawaken those memories by activating old neural pathways. Music can also reawaken positive memories by acting though the same neural circuits (Jäncke, 2008). However, negative memories are more easily recalled by humans than positive memories (see Baumeister, Bratslavsky, Finkenauer, & Vohs, 2001).

2.5 The Musical Brain

Music has many features that can be analysed, such as melody, harmony, tempo, and timbre. However, in considering the effects of music on human behaviour, researchers need to acknowledge that music is more than the sum of its parts. It is not simply a set of auditory signals, but also involves cultural interpretation and human perception (López-Sintas, Cebollada, Filimon, & Gharhaman, 2014). While testing music, researchers tend to be reductionist, breaking it down into its component parts. This method creates an excellent control over the random effects of each musical component; however, the real essence of music is lost (Abbott, 2002; Ball, 2008; Levitin, 2008).

Music acts on the human body by riding over many brain pathways (Zatorre & Salimpoor, 2013). Peretz et al. (1998) found that a patient with extensive brain damage, caused by cerebral aneurysm, could not process melody and rhythm; however, she was able to feel emotions while listening to music. In order to process music, the brain works through a hierarchical sequence. Initially, components such as pitch and melody are processed in the primary auditory cortex, situated in the superior temporal lobe, which is connected to the planum temporale and the superior temporal gyrus. Then, the more complex components, such as timbre and rhythm, are processed. Finally, the emotions and memories evoked by the music are worked through in diverse areas such as the frontal lobe, the parietal lobe, the insular cortex, and the limbic system, which includes the hippocampus, the amygdala, the cingulate gyrus, and the thalamus (Warren, 2008).

Investigating the musical brain is always a challenge, since music evokes emotion according to an idiosyncratic pattern of response (Juslin, 2013). In other words, humans react to music according to personal factors such as personality trait and previous experience. Griffiths et al. (2004) described an interesting case of a man who suffered an infarction in the left amygdala and insula. This patient was a radio announcer and he used to listen to classical music after work in order to relax. Sadly, following the incident, the patient could no longer experience pleasant emotions while listening to Rachmaninov preludes. However, the patient was able to recognise all aspects of the music such as rhythm and interval. This study points out the clear difference between music components and emotions elicited while listening to music.



Display options

☐ MIP Anatomy ☑ Crosshairs ○ Neurological

☐ MIP Functional ☑ Controls ● Radiological

Coordinates (millimeters)

MRI	x: 57.0	y: 138.0	z: 74.0
SCS	x: 36.2	y: 34.5	z: 46.0
MNI	x: -33.2	y: 10.3	z: 0.2

Figure 2.5. Insular cortex presented in the *f*MRI viewer option (3-D).

2.5.1 Exposure to Music

Humans started to create music some 35,000 years ago by using rudimentary bone flutes (Conard et al., 2009), meaning that the musical brain has ancient origins. The application of music to influence humans has attracted considerable interest throughout the history (Nilsson, 2008; Zhang et al., 2012). In 1950, Price and colleagues proposed different types of music to accompany electro-shock therapy, in order to relax patients prior to the required procedures. Recently, physicians have also realised that music could facilitate surgical procedures by enhancing patients' sedation; a cheap and effective method to reduce the use of sedative drugs (Conrad et al., 2007) and lessen negative feelings, such as stress and anxiety (Bradt, Dileo, & Shim, 2013; Tam, Wong, & Twinn, 2008).

Emotions such as joy and fear can be also elicited while listening to music (Koelsch, 2014). The world of entertainment uses soundtracks as a tool for manipulating people's behaviour. The match of music and images present in films can influence the watcher through many brain pathways (see Hasson et al., 2008). Movies use soundtracks as a method to enhance the emotional impact of scenes. In this case, music and movie become a singular structure without dissociation. *The Exorcist* (1973), directed by William Friedkin, is widely considered as one of the most frightening films of all time. In order to elicit feelings of discomfort and suspense, the director included pieces of progressive rock such as the famous *Tubular Bells* (1973) produced by Tom Newman, Simon Heyworth, and Mike Oldfield.

Music can also motivate people by activating the memory system. Before battle, soldiers often listen to music as a means by which to boost self-confidence. Interestingly, a similar intervention is used as therapy with post-traumatic soldiers (Bensimon, Amir, & Wolf, 2008). Hence, music can assume diverse purposes according to components, such as tempo, melody, and harmony. In order to achieve positive results, pieces of music must be precisely chosen by applying appropriate methods of selection. Factors such as extra-musical association and personality trait can influence the way people respond to music (Karageorghis, 2017; López-Sintas et al., 2014; Priest & Karageorghis, 2008).

2.5.2. Music and Exercise

Interventions using music have been widely used in sport and exercise in order to improve athletic performance and regulate mood (Karageorghis, Cheek, Simpson, & Bigliassi, 2018a; Karageorghis, Bigliassi, Tayara, Priest, & Bird, 2018b). The New York city six-day bicycle race provided the first scientific evidence that music might improve athletic performance (Ayres, 1911). The statistician Leonard Ayres investigated the influence of music on cycling performance. An improvement of 1.7 mph was found when athletes cycled under the influence of music. Nevertheless, Ayres mentioned that these results were not surprising, given that soldiers used to run with music to reduce fatigue-related symptoms.

Music can aid exercisers by acting through diverse systems, such as attention and emotion. While exercising, auditory stimuli compete for attention in the human brain (Karageorghis, Ekkekakis, Bird, & Bigliassi, 2017). Using the appropriate volume (75 dBA), auditory signals can shift attention to external influences. This mechanism makes the exerciser focus on the auditory stimulus. Therefore, fatigue-related symptoms are reduced (Karageorghis, 2017). Physiological variables such as blood pressure and heart rate tend to follow a similar trend (Karageorghis et al., 2018c; Szmedra & Bacharach, 1998). Positive affective states can also be evoked by music during exercise (Hutchinson et al., 2018; Laukka & Quick, 2011). Exercise evokes feelings of excitation, alertness, and positive aggression. However, affective responses are intensity-dependent, which means that how someone feels can be more negative with increasing exercise intensity (Ekkekakis, 2003). Music can act upon emotions (Juslin, 2013) by decreasing negative exercise-related symptoms (Stork et al., 2015; Stork & Martin Ginis, 2017), which makes the exercise more enjoyable than under normal circumstances.

Mechanisms of association are common while listening to music. The link between visual and auditory signals is associated with long-term memories in the hippocampus (Watanabe, Yagishita, & Kikyo, 2008). This linear trend makes music capable of eliciting images by activating memory and emotional pathways. Music can also enhance emotional responses evoked by images (Baumgartner, Lutz, Schmidt, & Jäncke, 2006). The interaction between music, memory, and associative images can help people by creating daydream flashes during exercise; those events can also modulate psychophysical responses by switching attention to *internal dissociation* (cognitive strategies; Goode & Roth, 1993; Stevinson & Biddle, 1998).

The human ability to synchronise movements with the rhythmical qualities of music is a different mechanism that music uses to influence performance (Bood, Nijssen, van der Kamp, & Roerdink, 2013). The human brain processes music in the auditory cortex and controls movement in the premotor cortex. The dorsal premotor cortex is the hub responsible for the interconnection between afferent signals and synchronised movements (Zatorre, Chen, & Penhune, 2007). Synchronising movements is a natural skill of people; even young infants can synchronise their movements with excerpts of musical stimuli (cf. Zentner & Eerola, 2010). During exercise, greater efficiency can be developed by integrating synchronous music and repetitive movement (Bacon, Myers, & Karageorghis, 2012; Bood et al., 2013; Lim, Karageorghis, Romer, & Bishop, 2014). The exercise becomes unconscious when music controls its pattern of repetition; therefore, lower levels of energy are required to monitor exercise consciously.

Karageorghis and Terry (1997) reviewed music-related studies in order to understand the psychophysical effects of music in sport and exercise. This work still represents one of the major contributions to the field of music and exercise. The authors identified a series of limitations that appeared to pervade previous research. First, the insufficient methodological description and use of psycho-acoustically diverse pieces of music generated uncontrolled effects on psychophysiological responses. Other aspects such as music intensity and the way music is delivered to exercisers (e.g., headphones or speakers) were also highlighted as a primary concern. Additionally, the sociocultural influences were considered to have been overlooked (i.e., neglected by the scientific community). "…social class, area of residence, ethnic background, and peer group influence are crucial factors in the selection of research participants" (p. 64). Based on the aforementioned limitations, Karageorghis and colleagues have subsequently proposed diverse methodological approaches for the use of music during conditions of exercise (Karageorghis & Priest, 2012b; Karageorghis & Terry, 2008).

The Brunel Music Rating Inventory was developed to assess the motivational qualities of music (Karageorghis, Terry, & Lane, 1999). This assessment was intended to allow researchers and practitioners to use suitable music selections as a means to manipulate exercisers' arousal, rate of perceived exertion (RPE), and mood. The first version of this instrument was created to match the requirements of the four-factor model (rhythm, musicality, cultural impact, and association). However, the instrument was considered difficult to use by non-expert professionals, which led to the development of a second version (Brunel Music Inventory Rating-2; BMRI-2).

> The psychometric properties of the BMRI-2 are stronger than those of the BMRI and it is easier to use. The BMRI-2 provides a valid and internally consistent tool by which music can be selected to accompany a bout of exercise or a training session (Karageorghis et al., 2006, p. 899).

The BMRI-2 has been widely used in the field of sport and exercise. Therefore, consistent results have been found by using the BMRI-2 as a method to standardise the motivational qualities of music for exercise-related tasks (Crust, 2008; Lane et al., 2011; Lopes-Silva, Lima-Silva, Bertuzzi, & Silva-Cavalcante, 2015; Stork et al., 2015). In 2011, an updated version (BMRI-3) was published by Karageorghis and Terry. The BMRI-3 can be rendered highly specific to each exercise context. In other words, the third version of this instrument was designed to make individuals carefully consider exercise training mode while responding the questionnaire. The creation of questionnaires such as the BMRI is intended to help exercisers and researchers to use the most appropriate type of music in order to enhance performance, reduce perception of effort, and increase exercise enjoyment.

2.6 Visual Brain

The visual brain is a complex system, which involves superficial and deep areas of the brain such as the occipital cortex and the thalamus (Creem & Proffitt, 2001). The visual system is able to identify colours, brightness, objects, faces, body parts, and spatial position (Mishkin, Ungerleider, & Macko, 1983). Images initially ride over the optic nerve to the lateral geniculate nucleus, which is the visual region of the thalamus. There is extensive connection between the thalamus and other regions such as the superior colliculi and the suprachiasmatic nucleus. The visual cortex is connected via optic radiation (nerves) from the lateral geniculate nucleus (Tong, 2003). The visual cortex produces the image, which is subsequently processed in other areas according to its physical features such as colour and brightness (Tootell et al., 1998). There are four important networks associated with the visual system: the *occipito–parietal circuit*, the *parieto–prefrontal pathway*, the *parieto–premotor pathway*, and the *parieto–medial temporal pathway* (see Kravitz, Saleem, Baker, & Mishkin, 2011 for a review); those circuits demonstrate the extensive neural connection in the visual system.

The visual system is capable of eliciting emotions (Harrison, Gray, Gianaros, & Critchley, 2010) and memories (Wolfe, 1998) due to its extensive neural network. Emotional pictures have been widely used in order to investigate affective responses to visual stimuli (Mauss & Robinson, 2009). The memory system also has a massive storage capacity for visual stimuli, which means that images can reawaken long-term memories (Brady, Konkle, Alvarez, & Oliva, 2008). Huijbers et al. (2011) showed that emotional pictures can facilitate spatial and item memory of Alzheimer's disease patients; their experiment provides compelling evidence that the visual system is directly connected to the emotional and memory systems. The visual network covers a large area of the brain, from the prefrontal cortex to the occipital lobe (Kravitz et al., 2011). This extensive network might explain the importance of the visual system to capture attention.

2.6.1 Visual Exposure

In 1895, a locomotive approached at full speed and people felt frantic at the *Salon Indien du Grand Café* in Paris. Nevertheless, it was only a series of images edited by the Lumière brothers during 15 s (Loiperdinger & Elzer, 2004). The history of cinema illustrates the emotional power of videos, which capture attention via auditory and visual pathways. The brain processes videos through complex mechanisms, since it involves sound, images, movement and face recognition. Although the brain mechanisms are complex while watching videos, there is a similar pattern of response across different subjects. When people watch *The Good, the Bad and the Ugly* (1966) produced by Sergio Leone, 45% of the cortex (the occipital lobe, temporal lobe, Heschl's gyrus, Wernicke's area, and parietal lobe) activates similarly across different subjects (Hasson, Nir, Levy, Fuhrmann, & Malach, 2004). However, when the movie is broken down into small pieces (scenes) the brain processes it with greater dissimilarity across subjects, which means that the brain exhibits an idiosyncratic response.

There is compelling evidence to suggest that people tend to look at the same places of the screen while watching a movie; it indicates the manipulation of behaviour imposed by films (Hasson et al., 2004). Movies are considered *controllers* (e.g., *Bang Bang*) when the director controls the viewers' behaviour by forcing them to focus on certain scenes. On the other hand, videos with abstract characteristics such as unstructured segments of reality (e.g., people talking in a garden), can allow viewers to focus on different scenes and aspects according to their will. In sum, the brain activity of viewers is greatly influenced by the level of abstraction presented in the movie (Hasson et al., 2008).

2.6.2 Environmental Sensory Stimuli

Indoor exercises such as walking on a treadmill or cycling on an ergometer can be boring and stressful for those who engage in them. A limited array of sensory stimuli are received by the exerciser; therefore, affective responses are usually negative (Bowler, Buyung-Ali, Knight, & Pullin, 2010). People constantly withdraw from indoor activities due to the absence of new challenges. On the other hand, green exercise environments are replete with visual and auditory stimuli; these are capable of capturing attention, which make the exercise more enjoyable and immersive (Gladwell, Brown, Wood, Sandercock, & Barton, 2013). The possible explanation lies in the human history, given that our ancestors conducted physical activities in contact with nature for millennia. Based on this assumption, limited-stimuli environments are perceived as a threat to exercisers, who express negative feelings and the will to disengage from the exercise.

Outdoor activities have positive influences on exercise adherence; however, urban life provides few opportunities for outdoor physical activity. Thus, indoor activities represent achievable options for people to reduce sedentariness. Due to the boredom associated with indoor activities, sensory strategies have been used as a means by which to increase exercise enjoyment. Jones, Karageorghis, and Ekkekakis (2014) tested the influence of different sensory stimuli on psychological responses to indoor exercise. Four experimental conditions were tested (music-only, video-only, music-and-video, and control) in order to elucidate the influence of auditory and visual stimuli on exercise performed at low- and high-intensity. The music-and-video condition caused the greatest level of dissociation, which means that participants switched their attention to external influences, even at intensities above ventilatory threshold. It is important to note that music-only caused greater levels of dissociation than video-only; however, music tracks were chosen according to their motivational characteristics, while video footage only consisted of a pleasant rural scene that was devoid of motivational qualities.

Increasing the amount of sensory stimuli is a common strategy to increase exercise dissociation (Barreto-Silva, Bigliassi, Chierotti, & Altimari, 2018; Hutchinson et al., 2015). When visual and auditory stimuli are used in parallel, attention is shifted to external influences. Hence, the exercise seems more pleasurable under the influence of sensory stimuli (Boutcher & Trenske, 1990), because lower physical exertion is perceived by the exerciser (relationship between physical exertion and affective responses; see Ekkekakis, Parfitt, & Petruzzello, 2011). Hutchinson, Karageorghis, and Jones (2015) recreated a similar experimental design to investigate the effects of music and video on psychological responses at low- and high-intensity exercise. However, congruent videos (music videos) were used in this study. The results show that music-and-video caused greater exercise dissociation and more positive affective valence in comparison with music-only and control conditions, which means that exercisers and exercise professionals must explore diverse sensory strategies in order to positively influence exercise-related responses. Music and video can increase exercise enjoyment, affective valence, and reduce fatigue-related symptoms.

2.6.3 Music and Mental Projections

Music-related interventions have been proven to induce mental projections when the listener visualises her/himself into the story that is depicted by the artist (Bishop, Karageorghis, & Loizou, 2007). Imaginative experiences in the presence of music indicate the close interrelationship among sensory systems and points towards additive effects of music that are not solely related to auditory pathways. Even instrumental music (i.e., no lyrics) has an apparent effect on mental projections as participants tend to recreate their own stories, which is commonly based on recent emotional episodes (see Karageorghis et al. 2018b). It is noteworthy that mental projections and periods of imaginative experiences are taken into consideration when researchers use music as environmental interventions to up-/down-modulate one's affective state. This psychological response might be partially supported by extensive brain area that is active when participants listen to music (Koelsch, 2014; Warren, 2008).

2.7 Corollary Discharge Model

There has been an ongoing discourse regarding the mechanisms that underlie fatigue and task disengagement during whole body modes of exercise (Marcora, 2008; Noakes, 2000). In the present thesis, it was initially assumed that afferent signals from internal organs influence attention by increasing perception of effort; in this case, sensory stimuli are capable of decreasing perception of effort by competing for attention. However, compelling evidence suggests that perception of effort is not influenced by afferent feedback from internal organs. Patients with transplanted heart (without neuronal connection between heart and brain) report similar rate of perceived exertion during exercise (Braith et al., 1992). Similar outcomes were found with double-lung transplantation (see Zhao, Martin, & Davenport, 2003) and epidural anaesthesia, which blocks afferent feedback from active muscles (Fernandes et al., 1990). Peripheral responses to exercise used to be safe places to underpin discussions and hypotheses. Based on this assumption, the necessity to investigate new models of exertion is manifest. The underlying mechanisms of task disengagement during whole-body modes of exercise are apparently disconnected from internal processes such as heart rate, respiration rate, and muscular activity.

The *corollary discharge model* provides reasonable basis to support whole-body modes of exercise. In this model, the central motor command sends signals to control internal organs; in addition, motor areas also emit corollary signals (parallel messages) to regions of the brain associated with exertion. This is intended to modulate perception of effort by riding over brain pathways without interaction with peripheral organs such as heart, lungs, and skeletal muscles. This model has been supported by several studies (de Morree, Klein, & Marcora, 2014; de Morree, Klein, & Marcora, 2012; de Morree & Marcora, 2013); such studies present a strong relationship between perception of effort (RPE), central motor activity (EEG) and muscular activation (electromyography; EMG). The corollary discharge model implicates the brain as the only responsible organ for affecting perception of effort during whole-body exercises.

Theories to explain the mechanisms of fatigue must be carefully examined. Strength was believed to be highly influenced by muscle innervation (Hinsey, 1934) and fibre composition (Maughan & Nimmo, 1984), which means that short-term modes of exercise such as explosive strength (as fast and hard as possible) receive little influence from fatigue-related symptoms, because the brain has insufficient time to process afferent feedback. However, Buckthorpe, Pain, and Folland (2014) demonstrated that even explosive strength is negatively influenced by central fatigue. In this study, a significant reduction of neural output with consequent decrease of motor unit recruitment was evident from the beginning to the end of explosive contractions.

In order to justify the corollary discharge model as responsible for influencing perception of effort, hypnosis was utilised as a means by which to recreate exercise experiences. This technique is expected to exclude the influence of afferent feedback from internal organs by isolating cerebral processes. Cortical activation and cardiovascular responses during sessions of hypnosis are similar to those experienced during real bouts of physical activity (Williamson et al., 2002). Hypnosis-related studies were subsequently used to demonstrate the brain is the organ responsible for creating and controlling exercisers’ perception of effort (Marcora, 2008). Williamson et al. (2001) used hypnosis to simulate uphill and downhill conditions of exercise while measuring cortical and psychophysiological responses; results demonstrated congruent variations of perceived exertion during both experimental conditions. In other words, RPE increased during uphill-simulated condition, and decreased during downhill-simulated condition. The absence of movements indicates that cerebral mechanisms are responsible for altering RPE during sessions of hypnosis. Taking this into consideration, feedback mechanisms could not influence perception of effort; this approach seems to validate the corollary discharge model as a reasonable explanation of fatigue. Furthermore, hypnosis-related experiments indicated that perceived exertion are simply active creations of the human mind (Bigliassi, 2015; Rejeski, 1985).

The corollary discharge model seems to challenge the rationale that underlies the effects of sensory stimuli on exercise conditions (see Sommer & Wurtz, 2008 for a review). In this case, the competition for attention would not occur between afferent feedback and auditory stimuli. Actually, an internal competition between corollary signals from the primary motor cortex and sensory signals from the primary sensory cortex might occur. The level of relevance would be determined by the strength of the message without receiving afferent influences from internal organs.

2.7.1 The Psychobiological Model

The psychobiological model is based on the assumption that corollary signals are responsible for modulating perception of effort and task disengagement. Furthermore, the model lies in the notion that psychological concepts such as motivation and willingness to exercise are capable of influencing perception of effort and exhaustion. In this case, task disengagement occurs

> …when (A) the effort required by the constant-power test is equal to the maximum effort the subject is willing to exert to succeed in the exercise task or (B) when the

> subject believe to have exerted a true maximal effort and continuation of exercise is perceived as impossible. Within the limit set by B, an increase in A (the so-called potential motivation) will improve exercise tolerance (Marcora, 2008, p. 930).

Hence, motivation is an important phenomenon responsible for influencing voluntary control; this variable is also affected by external sensory information and perceived exertion. Corollary signals are sent from the central motor command (precentral and paracentral gyri; Voss, Ingram, Haggard, & Wolpert, 2006) to sensory areas, in order to create the perception of effort. Motivation and perceived exertion affect voluntary control and neural activation of skeletal muscles (central action potentials). This model was originally created because of the incapacity of the *Central Governor Model* (see Noakes, 2000 for a review) to explain task disengagement, which was considered as "…internally inconsistent, unnecessarily complex, and biologically implausible" by Marcora (2008, p. 929).

The psychobiological model underpins whole-body modes of exercise; nevertheless, the function of corollary signals during exercise-related situations is not fully explained. In the present thesis, an update of the psychobiological model is proposed (see Figure 2.6). This update was published in 2015 by the author of this thesis ("Corollary discharges and fatigue-related symptoms: the role of attentional focus"; Bigliassi, 2015). Firstly, it is postulated that exercise conditions turn the brain into an adjustable machine. In order to support exercise, psychophysical phenomena such as motivation, perception of effort, and sensory information act upon voluntary control. Corollary signals are sent from the central areas of the brain to sensory areas; those signals regulate perceived exertion, which negatively influences exercise engagement. However, corollary signals can also act upon motivation and self-belief. In this case, corollary signals assume inhibitory/suppressing characteristics, which decrease neural activation by making perceived exertion the only variable capable of influencing voluntary control.

It is also important to point out that conscious processes can generate positive signals to compete with corollary signals. A similar process was already proposed to explain top-down mechanisms of attention (see 2.1.3 Attention and Exercise). In other words, people can resist this negative influence through the use of motivational strategies (e.g., self-talk; see Blanchfield, Hardy, De Morree, Staiano, & Marcora, 2014). It is noteworthy that awareness and sensory information can also have negative influences on voluntary control; for example, if the exerciser engages in negative self-talk or listens to unpleasant music while running. Those negative influences can decrease motivational state and increase perceived exertion. Therefore, it is postulated that a larger number of corollary discharge might be sent to sensory regions of the brain, reducing efferent signals and thus compromising the recruitment of motor units. In addition, a wide range of psychological constructs, such as self-confidence and state anxiety, can also moderate perception of effort and voluntary control with direct implications for human performance (Parry et al., 2011).

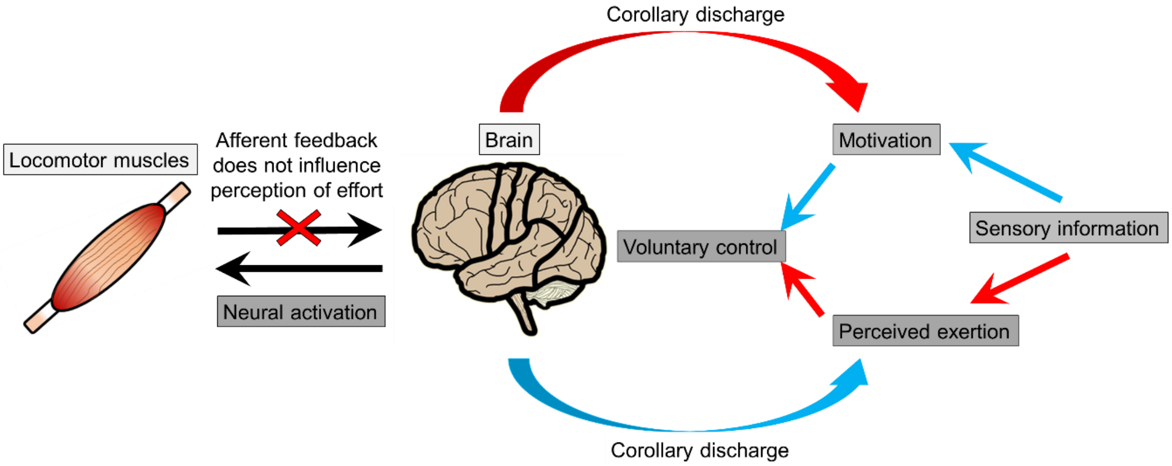


Figure 2.6. An update of the psychobiological model. *Note.* Blue arrows indicate positive influence and red arrows indicate negative influence.

The psychobiological model is a new perspective to support whole-body modes of exercise; nevertheless, there is insufficient empirical evidence to conclude that voluntary control is not influenced by afferent feedback. As previously mentioned, many studies have tested exercise conditions by blocking (e.g., transplantation) different organs such as heart, lungs, and muscles (Braith et al., 1992; Zhao et al., 2003); however, the complete absence of afferent feedback (all peripheral organs) could finally indicate corollary discharges as the only factor responsible for influencing perception of effort and task disengagement (Amann & Secher, 2010). Furthermore, hypnosis is intended to recreate feelings of reality, which means that even sensations associated with afferent feedback might have been felt by participants during hypnosis sessions (Jensen et al., 2015).

Hot environments can increase humans’ perception of effort during exercise or at rest (see Périard et al., 2014). When people are at rest, no efferent signals are produced by the brain in order to modulate perception of effort via corollary signals. In this case, only afferent feedback is responsible for altering perception of effort by acting through peripheral connections. Temperature modulations are worthwhile pathways for researchers to investigate in order to elucidate the mechanisms that underlie perception of effort and task disengagement. Pollak et al. (2014) also demonstrated that the infusion of muscle metabolites can evoke sensations of fatigue and pain at rest, meaning that peripheral changes can influence central fatigue (Amann, Sidhu, Weavil, Mangum, & Venturelli, 2015). Therefore, the brain is not only connected to the periphery but also interacts with visceral and metabolic changes. Despite the intriguing debate about the reasons that underlie task disengagement (Marcora, Staiano, & Manning, 2009; Noakes, 2011; Perrey, 2010), there is no evidence to support the exclusiveness of afferent signals or corollary discharges to modulate perception of effort and task disengagement during long-term and whole-body modes of exercise.

2.7.2 Perception of Effort and Perceived Exertion

Perception of effort and perceived exertion are different concepts and are associated with different brain mechanisms; however, these terms have been used interchangeably in the field of sport and exercise (see Abbiss, Peiffer, Meeusen, & Skorski, 2015). Similarly, dictionaries (e.g., Oxford English Dictionary), relevant pieces of research (e.g., *Psychophysical Bases of Physical Exertion*; Borg, 1982), and scientific societies (e.g., American College of Sports Medicine) are not sufficient sources of information to provide students and researchers with an accurate description of these terms (e.g., "[RPE] is a psychophysiological scale, meaning it calls on the mind and body to rate one's perception of effort"; Utter, Kang, & Robertson, n.d.).

Due to the fact that exertion and effort are dissimilar concepts, misconceptions can lead to misleading results. Effort is defined as the "the amount of mental or physical energy being given to a task"; conversely, exertion can be defined as the "degree of heaviness and strain experienced in physical work" (Borg, 1998, p. 9). In other words, effort is regarded to the energy spent to cognitive or physical tasks, while exertion is associated with the sensations elicited by the physical work. Accordingly, researchers are required to appropriately guide exercisers while using RPE scales, given that perception of effort and perceived exertion differ over time due to the increasing exercise intensity. Despite the fact that effort and exertion follow a linear trend during physical task, exercisers are capable of reaching maximal effort without achieving maximal exertion (Abbiss et al., 2011), meaning that exercisers are also able to differentiate among exertion, effort, and pain (Abbiss et al., 2015). Thus, researchers should explore the effects of psychophysiological interventions on both effort and exertion, given that effort appears to be highly influenced by motivational strategies, whereas exertion appears to be associated with resilience and tolerance.

2.7.3 Psychophysiological Model of Exercise

The heuristic psychophysiological model of exercise proposed herein indicates that fatigue could be associated with a constant *need* to revaluate the importance of the task at hand (St Clair Gibson et al., 2003). Accordingly, one's desire to stop could be indirectly influenced by internal signals, but is primarily controlled by conscious mechanisms. Limited by biomechanical constraints, the human body is, theoretically, capable of exercising to death. However, the worthiness of the action (i.e., a cognitive process) is continually assessed as a means by which to continue or disengage from the task (cf. Pageaux & Lepers, 2016). III-IV muscle afferents could, therefore, increase unpleasant sensations such as discomfort and indirectly induce negative thoughts (e.g., a feeling of despair); these could subsequently lead to a decision to stop (i.e., an indirect mechanism; Amann et al., 2013). In order to resist the negative influences imposed by interoceptive sensory cues, the human brain needs to emit a larger number of neural outputs to the working muscles (Bigliassi et al., 2016a); a functional mechanism responsible for the up-modulation of one’s perceived effort (Marcora, 2009).

Exertional responses might also have the objective to inform the brain about the amount of energy (i.e., metabolic stress) consumed by the working muscle and the likely period of time the body will take to fully recover from that activity (Amann & Secher, 2010; Sommer & Wurtz, 2008). Internal sensory cues are hypothesised to be repeatedly assessed through conscious pathways as a means by which to decide whether the exerciser should continue or stop the activity (Amann et al., 2013). Accordingly, interpretation of fatigue-related sensations is theorised to be a highly advanced faculty developed through the ages with the purpose of facilitating disengagement from unimportant physical tasks and to prevent long-term injuries caused by over-stressed organs (Noakes, 2012).

2.8 Physiological Variables

Physiological sciences encompass the study of human function. Researchers started to become aware of the physiological systems during the 16th century. At that time, there was not clear distinction between body structure and human function (Westerhof, 2011). After years of fairly primitive investigation, physiology became an object of common interest among European researchers. In the mid-1700s, a period of inertia is evident, which paralysed the advance of physiology. This period was mostly influenced by philosophers such as Kant and Schelling who stated that humans were sufficiently intelligent to understand themselves (Westerhof, 2011). Fortunately, in the 18th century, several researchers and physicians realised that physiological sciences could clarify the mechanisms of several diseases and even cure patients. In addition, this advance would only be possible by applying experimental approaches to understand the function of the human body (Marban & Gariepy, 1978). Since that time, physiological breakthroughs have served to help billions of people worldwide.

Physiological systems are divided into nervous, endocrine, cardiovascular, respiratory, digestive, renal, muscular, and skeletal categories. This division is based on the functions each system assumes in the human body (see Barrett, Barman, Boitano, & Brooks, 2009). The first step in analysing these systems is to assess physiological variables. Those variables function as indicators of the system they are taken from. Accordingly, researchers and physicians are able to construct assumptions regarding the conditions of the system. For example, by analysing heart rate variability (see section 2.8.1 Heart Rate Variability), a physician can identify the emotional responses to a given sensory stimulus (e.g., music; Bigliassi et al., 2015b).

With the evolution of science, numerous physiological variables can be assessed by use of simple, inexpensive, and non-invasive techniques. In order to select the appropriate variables to collect, researchers have to be aware of which systems are associated with the problem they are investigating. In this case, the relationship between physiological systems and experimental design must be clear in the researcher’s mind. For example, if a researcher wants to investigate the effects of short-term modes of physical exercise on cardiovascular responses, s/he will have to focus on variables such as heart rate and blood pressure (Gleim, Coplan, & Nicholas, 1986).

As a result of the integration of multiple systems (e.g., nervous and cardiovascular), new areas of research started being investigated. Ivan Pavlov was one of the pioneers in the field of psychophysiology. He discovered that bodily responses were greatly influenced by psychological characteristics such as personality trait (temperament). This evidence indicated the existence of some level of association between visceral and cortical responses (Strelau, 1998). Researching humans is always a challenge because of the complex interconnections among psychological, physiological, and psychophysiological factors. Systems are usually associated as a means to maintain a condition of homeostasis, even during extreme situations of altitude or temperature (Lim, Byrne, & Lee, 2008; Mason, 2000). Therefore, the application of diverse techniques to analyse humans can elucidate the concurrent activity of multiple systems, which allows analyses of association and interaction (see Donina, 2011).

2.8.1 Heart Rate Variability

The human heart starts beating when the foetus is only 6 weeks old and from this moment on, feeds the body incessantly with blood, giving the cells the oxygen they require (Abdulhay et al., 2014). If the heart stops beating, the human body faces a condition of hypoxia, followed by anaerobiosis and pathological conditions or even death (Michiels, 2004). If there is a change in muscular, visceral, or cortical activity, the human heart accelerates or decelerates in response. For example, if a man sitting on a chair suddenly stands up and starts walking, his muscles will demand more oxygen, and so indirectly increase heart rate as a means by which to support such demand (Gregoire, Tuck, Hughson, & Yamamoto, 1996). Therefore, the frequency of the cardiac cycle (cf. Fukuta & Little, 2008) matches the conditions of other physiological systems (e.g., muscular).

The frequency of the cardiac cycle carries the answer for many psychological conditions (cf. ChuDuc, NguyenPhan, & NguyenViet, 2013), due to the strong relationship between central nervous system and heart (Thayer, Ahs, Fredrikson, Sollers, & Wager, 2012).

In order to understand the cardiac cycle, the time between two heartbeats is commonly analysed through the application of time- and frequency-domain methods. Heart rate variability (HRV) is the term referred to the pattern of variation between heartbeats, which is influenced by psychophysiological factors (Sztajzel, 2004).

The sinoatrial node (SA) is a natural pacemaker that controls the frequency of the cardiac cycle (Irisawa, Brown, & Giles, 1993). The SA releases electrical impulses that control the beat-to-beat interval, a phenomenon that occurs unconsciously, and is influenced by autonomic activity. The autonomic nervous system accelerates or decelerates the function of the SA. This system contains two opposite actions, sympathetic and parasympathetic, which act upon several organs of the human body, including the heart (Robinson, Epstein, Beiser, & Braunwald, 2015). The sympathetic activity accelerates heart rate, and the parasympathetic activity decelerates heart rate. Electrical impulses sent by the SA create a rapid depolarization, which make the plasma membrane positively charged and contract the cardiac muscle. This mechanism creates the perfect environment for the muscular cell to contract.

By using relatively simple techniques, researchers are able to capture the electrical activity of the cardiac muscle (e.g., heart rate monitors; Gamelin, Brethoin, & Bosquet, 2006). After analysing the pattern of response produced by the cardiac cycle, researchers can identify the presence of diseases or abnormalities. The use of HRV has been also used to explore the effects of sensory modulation on emotional responses. Bigliassi et al. (2015b) identified a linear trend between cortical activation (prefrontal cortex area; see Figure 2.1), felt arousal, and parasympathetic activity by using different types of music. In this study, the authors demonstrated that nervous and cardiovascular systems respond through a sequence of events to emotional stimuli. Thus, the use of HRV to interpret emotional responses appears to be a promising technique (Lane et al., 2009; Loizou & Karageorghis, 2015; Wang & Wang, 2012).

In order to understand the emotional component presented in the cardiac cycle, some indices must be extracted from the electrical signal. Firstly, sympathetic and parasympathetic activity must be separated by using equations of time, frequency, or non-linear domains (see Rajendra Acharya, Paul Joseph, Kannathal, Lim, & Suri, 2006). Due to the recent development of strategies to process cardiac signals, researchers have faced difficulties to identify the most appropriate domain to operate data. Therefore, the methodological approach dictates the type of analysis the researcher should conduct.

The frequency domain decodes the signal through the Fourier transform method, which may not be suitable for nonstationary signals such as heartbeats (e.g., Kim, Koo, Lee, & Kim, 2014). In addition, conditions of exercise can be a threat for the treatment of HRV signals, since physical effort dramatically modulates the autonomic control, which means that Fourier transform suffers a wide range of limitations (see Rajendra Acharya et al., 2006). In this case, alternative methods such as wavelet transform may be applied to correct possible artefacts (Peters et al., 2011). This technique can be used to change the time extension contained in the signal, without altering the shape. Continuous wavelet transform-based (e.g., Complex Morlet) methods have been used recently in the field of sport and exercise science (cf. Sarmiento et al., 2013). In general, it is highly recommended that researchers apply two or more domain types (e.g., time and frequency) as a means to demonstrate a degree of consistency between distinct parameters (Kocovic, Harada, Shea, Soroff, & Friedman, 1993; Rennie, 2003). Therefore, it is expected that distinct parameters show similar results, which guarantee the pattern of autonomic activity.

HRV is a modern technique to analyse emotional responses to sensory stimuli. Heart rate monitors are portable, inexpensive and non-invasive, which makes this information widely accessible to researchers. By dint of recent developments to analyse the cardiac cycle, autonomic activity can be easily explored with heart rate monitors. Furthermore, cardiac signals are efficiently processed using computational software such as the Kubios HRV – Heart Rate Variability Analysis Software.

> Kubios HRV has become a popular analysis tool for HRV which is attested by over 16000 downloads of the latest version (ver. 2.0) within the past four years that it has been distributed. The new version (ver. 2.1) is a significant upgrade of the previous version including electrocardiogram (ECG) data support, built-in QRS detector accompanied by artefact correction tools, respiratory frequency estimation (ECG derived respiration, EDR), and several usability and functionality improvements (Tarvainen, Niskanen, Lipponen, Ranta-Aho, & Karjalainen, 2014, p. 211).

2.8.2 Respiratory Responses to Exercise

The consumption of oxygen ($\dot{V}O_2$) is directly associated with the cellular metabolism. If an individual's metabolic activity increases, her/his oxygen (O_2) demand increases proportionately. Therefore, the lungs inflate faster and with more air in order to provide the requisite amount of oxygen to the body. By analysing O_2 intake and carbon dioxide (CO_2) production, researchers and physicians are able to estimate the body's metabolic activity. When Claude Gordon Douglas developed a method to analyse respiratory exchange in humans, he also created a powerful means through which to identify cellular metabolism during real exercise conditions by use of a portable and non-invasive technique (see Douglas, 1911). Following a century of systematic research, methods to analyse gas exchange have dramatically changed, however, the main ideas proposed by Douglas remain unchallenged.

The respiratory system has been widely explored by the scientific community in the field of sport and exercise sciences. During the initial phases of moderate exercise, O_2 increases rapidly. This exponential modulation of O_2 consumption reflects the immediate necessity of oxygen required by the human cells. Interestingly, the cardiovascular system presents a delay between O_2 demand and delivery, which causes an O_2 deficit (Barstow, Buchthal, Zanconato, & Cooper, 1994). During this short time period that usually lasts for approximately 2–3 min, part of the energy produced by the cells have anaerobic sources. This mechanism partly accounts for the extreme sensations of exertion at the beginning of exercise bouts, with attendant increase in CO_2 production ($\dot{V}CO_2$). After this period, ventilation starts to stabilise. Concurrently, the cardiovascular system initiates minor adjustments as a means by which to provide the body with the necessary volume of O_2. It is important to emphasise that ventilatory responses to exercise are intensity-dependent, which means that moderate, heavy, severe, and extreme levels of intensity might engender different VO_2 kinetic responses (Burnley & Jones, 2007).

During incremental modes of exercise, intensity varies from low to high extremes. Likewise, the sensations associated with incremental exercise range from very comfortable to totally unbearable (Calbet et al., 2007). Ventilatory responses during incremental exercise present points of inflection, which carry information regarding cellular metabolism (Power, Handrigan, & Basset, 2012). The first inflection point of $\dot{V}CO_2$, which is referred to as *ventilatory threshold* or *anaerobic threshold* (VT), is representative of the point at which anaerobic metabolism initiates the most significant contribution to energy production during whole-body modes of exercise. If the exercise intensity continues to increase, the production of hydrogen ions (H^+) arising from the anaerobic metabolism will permeate the circulatory system. Therefore, a second inflection of $\dot{V}CO_2$ occurs, referred to as respiratory compensation point (RCP) or second ventilatory threshold (Wasserman, Hansen, Sue, Stinger, & Whipp, 2005).

VTs are used as a means by which to evaluate aerobic power and capacity of humans. For example, a good marathon runner must primarily use the aerobic metabolism while training. In this case, VT must occur at high levels in the exercise cycle (Péronnet, Thibault, Rhodes, & McKenzie, 1987). Researchers have also proposed methods of training based on the VT (Londeree, 1997). Such strategies are expected to manipulate the moment at which VT occurs with consequent effects on performance. Due to the linear trend evident among different physiological systems, inflection points induced by metabolic changes may cause modifications in muscular, cardiac, and even cortical responses (Cottin et al., 2007; Hug, Faucher, Kipson, & Jammes, 2003; Tikkanen et al., 2012; William & Kurt, 2013). With this in mind, the use of metabolic transitions extends beyond the assessment of ventilatory or circulatory responses (see Section 2.2.3 Attention and Exercise).

2.8.3 Muscular Activity

The assessment of muscular activity is usually performed through the use of EMG, which is a technique that is used to capture the electrical activity of the muscle. Similar to HRV, EMG identifies the electrical signal of the muscle, which is representative of the contractile properties of the cell. By using metallic electrodes, this technique may indirectly assess mechanisms of fatigue and motor unit recruitment through frequency and time domain, respectively (Farina, Fosci, & Merletti, 2002). The assessment of psychophysiological phenomena is also possible through the assessment of the muscular properties (Künecke, Hildebrandt, Recio, Sommer, & Wilhelm, 2014). For example, the transition between aerobic and anaerobic metabolism increases the amount of H^+ inside the muscle due to the process of glycolysis. This physiological response has the potential to elicit changes of the contractile properties of the skeletal muscle, which prompts an increase in the recruitment of motor units (Mello, Oliveira, & Nadal, 2006). This disproportional increase of motor unit recruitment during exercise is referred to as EMG threshold. This inflection point is strongly associated with other physiological thresholds such as VT during diverse exercise contexts (Hendrix et al., 2009; Hug et al., 2003; Tikkanen et al., 2012).

Motor unit recruitment encompasses the number of cells recruited to produce a certain level of strength. The efferent signals emitted from the brain stimulate the muscle fibres to contract. When the muscle contracts until the point of exhaustion, the recruitment of motor units increases as a means to maintain the same level of work (e.g., Petrofsky, 1979). Conversely, the frequency of electrical output sent by the brain decreases over time as a mechanism of supraspinal fatigue (see Gandevia, 2001). Therefore, performance decreases and sensations of fatigue increase throughout the exercise bout.

Muscular contractions produce clear electrical bursts, which are easily separated from noise such as that caused by bad skin conductance or signals emitted by electronic devices (Reaz, Hussain, & Mohd-Yasin, 2006). The processing of EMG data has rapidly improved (Farfán, Politti, & Felice, 2010). Current strategies involve the use of wavelet families (see Section 2.8.1 Heart Rate Variability) to process dynamic and extremely varied signals (Bigliassi et al., 2014). In spite of the constant development of technology, the application and processing of EMG still varies to a considerable degree across studies (Farfán et al., 2010; Hug & Dorel, 2009).

The identification of motor unit recruitment and fatigue-related mechanisms are the most common responses analysed through the use of EMG (De Luca, 1997). The root mean square (RMS) is an index obtained from the time domain. This variable is applied to quantify the level of physiological activity produced by a range of muscle cells. In addition, the RMS value is representative of the motor unit recruitment. On the other hand, when the researcher wants to analyse signs of central or peripheral fatigue, the frequency domain must be explored. The mean and median frequency of the power spectrum, which is obtained through the Fast Fourier Transform method, indicates the frequency of efferent output emitted by the central command (Chesler & Durfee, 1997). The movement of the central frequency indices to the left side of the graph indicates that lower frequencies have been emitted by the brain in order to maintain that level of contraction. The decrease of central frequencies over the exercise bout is a relevant index of muscular fatigue (Cifrek, Medved, Tonković, & Ostojić, 2009).

EMG data must be carefully processed, as well as all types of biological signals. Some rigorous procedures of filtering, rectification, and smoothing are necessary to polish data before subsequent manipulation (Gazendam & Hof, 2007). When those procedures are strictly followed, useful information can be collected for studies in the area of sport and exercise. EMG devices can be applied through non-invasive approaches (e.g., surface electrodes), furthermore, this technique is usually inexpensive and encompasses diverse modes of communication such as wireless, which allows the execution of exercise during real-life situations. Based on these advantages, the use of surface EMG should be explored further in the area of exercise psychophysiology, because skeletal muscles represent "bridges" to facilitate examination of the link between central command and peripheral responses.

2.9 Brain Analyses

Neuroanatomical sciences were born at the end of the fourth century, when Ptolemy I founded the Ancient Library of Alexandria. Formerly, there was intriguing debate about the organ responsible for creating emotions and processing sensory information. Heart and brain "competed" for hundreds of years in endeavouring to control the body. Aristotle provided doubtful arguments stating the heart was the hub responsible for controlling sensation and movement. However, Hippocratic doctors had already stated many years before that the brain was not influenced by mystic phenomena, and it was the real organ responsible for controlling the whole body, processing sensory information, and producing emotional responses (see Gross, 1995). Following years of investigation, the brain was finally acknowledged as the most important organ of the body. Interestingly, the brain is still considered the great mystery of the universe (e.g., The Orchestrated Objective Reduction Model proposed by Hameroff & Penrose, 2014) because techniques to examine the brain are relatively new (Raichle, 1998).

The great advance of neurophysiology is due to the development of techniques to examine cerebral activity (Raichle, 2003). In 1878, Dr Dodds published a series of manuscripts, which demonstrated that different areas of the brain were presumably associated with specific functions such as vision and audition. This compelling evidence led to the investigation of different brain regions as a means by which to understand and treat brain-related diseases. The relationship between different brain regions and specific cerebral functions was initially determined by case reports (e.g., Baniweicz, 1961). Accidents and cerebral diseases led to the formulation of hypotheses regarding the likely function of different areas of the brain (Allman, 1988). The use of case studies as a means to explain the functions of the brain is still prevalent, since the simulation of accidents and diseases is not ethically possible with human subjects (cf. Weijer et al., 2014).

An interesting aspect of the human brain is the fact that the same cerebral region can assume varied functions such as emotional processing and attention allocation (e.g., the prefrontal cortex; Banks, Eddy, Angstadt, Nathan, & Phan, 2007; Wood & Grafman, 2003). In other words, many brain regions are associated with multiple functions. This assumption led Gage, Parikh, and Markullo (2008) to publish a manuscript stating the cingulate cortex (see Figure 2.2) is associated with all functions of the human brain. The authors used amusing statements to inform researchers about the extrapolation of functions with which each brain region is concerned. Such publications highlight the need to create appropriate methods to identify the real functions of each brain area. Despite the invention of equipment to analyse the human brain, the experimental design is still the most salient aspect of research.

In order to design suitable experiments, researchers must take many variables into account (see Amaro & Barker, 2006). For example, when a long-term (>1 h) experimental design is proposed using *f*MRI (see section 2.10 Functional Magnetic Resonance Imaging), participants can get bored. This feeling can lead to daydream events, which strongly affect neuroimaging results (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Kucyi & Davis, 2014). In other words, the experimental design has a direct impact on the validity of the findings and researchers must strive to design suitable protocols before initiating data collection.

2.9.1 Electroencephalography

In recent years, researchers in the field of sport and exercise sciences have begun to assess brain function as a means by which to understand the mechanisms that underlie complex psychophysiological phenomena during the execution of movements. This is due to the widely-held notion that the brain holds the answers to some of the most intriguing questions that pervade the realm of sport and exercise sciences (e.g., de Morree, Klein, & Marcora, 2012). What causes volitional exhaustion? What are the implications of fatigue-related symptoms? How does one's motivational state influence perceptions of physical exertion? Why do most people disengage from physical activity programmes? These are some of the most pertinent questions in our field and despite recent advances in psychology and physiology, we lack neurophysiological explanations that serve to "connect the dots". This is the reason why brain assessment techniques have attracted a great deal of interest in the last two decades (Jain, Gourab, Schindler-Ivens, & Schmit, 2013; Scanlon, Sieben, Holyk, & Mathewson, 2017).

There are numerous techniques available that facilitate assessment of the brain (e.g., functional magnetic resonance imaging [*f*MRI]); nonetheless, head movements that commonly occur during the execution of gross movements tend to compromise the quality of the biological signal. Accordingly, mobile technology has recently been developed to enable assessment of the brain during real-life situations. Functional near-infrared spectroscopy (*f*NIRS) and EEG are the techniques that currently show the most promise in the fields of sport and exercise sciences. In this section, I will discuss some of the most recent approaches used to measure electrical activity in the brain during exercise. In addition, I will provide guidance on dealing with artefacts elicited by body and cable movements, and on how to process the biological signal.

2.9.2 Measuring Electrical Activity in the Brain

The selection of techniques to assess the brain is based primarily on considerations that pertain to the level of temporal and spatial resolution (Liu, Ding, & He, 2006). EEG and electrocorticography (ECoG; i.e., invasive EEG) present a high level of temporal resolution (i.e., it captures the synchronised activity of neurons); however, such techniques provide a low degree of spatial resolution. EEG is often applied as a means by which to detect temporal events such as attention allocation; when an individual shifts her or his attention from one source of information to another (e.g., Luck, Woodman, & Vogel, 2000). Cognitive mechanisms such as attention allocation occur over brief epochs. Identifying this rapid response represents a significant challenge when employing techniques with poor temporal resolution such as positron emission tomography (PET). Along similar lines, EEG is not recommended as a tool with which to localise activity arising from deep areas of the brain such as the anterior cingulate cortex or the superior colliculus; rather signals that emanate from superficial areas are stronger and more spatially distinguishable (e.g., prefrontal cortex; Dickter & Kieffaber, 2013). Given that EEG activity is recorded from a two-dimensional array of electrodes, the three-dimensional location of deep sources of electrical activity cannot be determined unambiguously (the inverse problem), although it can be modelled (Luck, 2014).

EEG was first recorded non-invasively from the human scalp in 1924 by the German psychiatrist Hans Berger. The early EEG studies adopted the use of brain waves to identify a patient’s arousal state and the delineation of sleep stages (e.g., Loomis, Harvey, & Hobart, 1936; Ray & Cole, 1985). Brain waves have also been investigated extensively in the fields of neurology and psychophysiology to further understanding of a range of disorders and traumas, such as epilepsy and cerebral injuries. The EEG signal derived from brain activity encompasses a range of frequencies. These frequencies are stratified according to different band waves by use of frequency-domain analyses such as Fast Fourier Transform (FFT). Delta (0.5–4 Hz), theta (4.5–8 Hz), alpha (8.5–13 Hz), beta (13.5–30 Hz), and gamma (30.5–100 Hz) are the most commonly designated brain wave bands. In this context, power is the square of the EEG magnitude, and magnitude is the integral average of the EEG signal (Keil et al., 2014). The power of brain frequencies in different wavebands as well as the amplitude (measured in microvolts) of the electrical signal at a particular timepoint can be influenced by sensory stimuli (e.g., Daly et al., 2014a), cognitive tasks (e.g., Twomey, Murphy, Kelly, & O’Connell, 2015), movement execution (e.g., Thompson, Steffert, Ros, Leach, & Gruzelier, 2008), and psychological responses (e.g., Lee & Hsieh, 2014).

The neural origins of the EEG signal. EEG is generated in neural tissue by flows of current in the extracellular space. This current may be influenced by the activity of many thousands of neurons, and can produce effects by volume conduction at a recording electrode distant from the source (Dickter & Kieffaber, 2013). In a wire, electrical current flows in one direction; however, in volume conduction, the current spreads in all directions. The generators of the extracellular current flows are intracellular postsynaptic potentials (Avitan, Teicher, & Abeles, 2009). Both excitatory and inhibitory postsynaptic potentials contribute to EEG, but there is no simple relationship between negative and positive EEG voltages and neural excitation and inhibition.

Electrodes placed on the scalp record EEG predominantly from the underlying cerebral cortex, and the largest contribution to the EEG signal comes from the summed synaptic potentials of pyramidal cells (Olejniczak, 2006). These are the largest cortical cells with their axons forming the main outputs to other cortical and subcortical areas. Their orientation is perpendicular to the cortical surface spanning most of the depth of the grey matter. The bodies of pyramidal cells are typically found in cortical layer 5, close to the base of the grey matter, and their apical dendrites stretch up to layer 1, close to the outer surface of the cortex. Furthermore, they receive their main synaptic inputs in two main regions: thalamic inputs in layer 4 (towards the base), and transcortical inputs in layers 2-3 (nearer the surface).

The pyramidal cell tends to act as a switchable electrical dipole, meaning that the end of the cell that receives an excitatory input is negative, and the other end is positive. For example, consider a small patch of cortex such as 5 x 5 mm. All the pyramidal cells in that patch will be similarly oriented and receive related inputs, so it is likely that the dipoles will be similarly oriented and show some synchronisation, producing a strong EEG signal (Olejniczak, 2006). Conversely, other types of cortical cells have a weak effect on EEG. They are oriented more randomly and their dipoles will thus point in many different directions, so that the net current flow for a cluster of active stellate neurons would probably tend to zero, even if they were stimulated synchronously. Thus, the cortical generator for an EEG signal may be modelled as a set of columns of cortical tissue, each acting as a single dipole source. From an exterior viewpoint, the most striking feature of the human cortex is that it is a continuous but much-folded surface, consisting of furrows (sulci) and convoluted ridges (gyri). Gyri located beneath an electrode will contribute most strongly to the EEG signal, but owing to volume conduction, remote sources will also contribute. This contribution, however, is moderated by distance from the electrode (Olejniczak, 2006).

2.9.3 Electrical Activity in the Brain During Exercise

EEG has been used in numerous scientific domains including the sport and exercise sciences. Schneider, Askew, Abel, Mierau, and Strüder (2010) examined brain function before and after an exhaustive running task. The incremental treadmill test caused an immediate increase in alpha 1 (7.5–10 Hz) activity after exercise. Alpha 1 increase was mainly localised in the left frontal regions of the brain by use of source estimation analysis. The researchers postulated that this increase in low-frequency alpha waves was associated primarily with emotional processing. Their postulate was based on the long-held view that left-hemisphere regions of the brain are linked to positive feelings such as happiness and joy, and that the right hemisphere is associated with negative affect (cf. The Valence Model; Demaree, Everhart, Youngstrom, & Harrison, 2005). Moreover, increases in alpha activity may be indicative of decreases in cortical arousal. Hence, psychological and peripheral physiological responses to exercise (e.g., affective valence and muscle electrical activity) may be investigated in tandem with EEG, as a means by which to elucidate the effects of exercise-related interventions on bodily reactions.

The use of brain assessment techniques during exercise is usually limited to isometric modes of contraction (i.e., when the joints are static) because head and body movements cause artefacts that compromise the quality of the raw data (e.g., Bigliassi et al., 2016a). To address this limitation, researchers have developed EEG systems based on wireless connections, which improve the range of motion and reduce electrical artefacts (for a pioneering study, see Hughes & Hendrix, 1968; for current applications, see Losonczi, Márton, Brassai, & Farkas, 2014; Szu, Hsu, Moon, Yamakawa, & Tran, 2013). Nonetheless, wireless systems are limited in real-life situations; for example, where there are walls present or when a participant needs to travel beyond ~200 m from the signal receiver. Moreover, brisk contractions (e.g., jumping) may generate more artefacts than repetitive movement patterns such as walking. In such instances, EEG devices can be integrated with EMG systems in order to identify and discard movement-related artefacts after data collection. Moreover, new EEG devices such as Muse (Krigolson, Williams, Norton, Hassall, & Colino, 2017) and Emotiv (Duvinage et al., 2013) are attached to triaxial accelerometers that quantify body movements and apply compensatory methods as a form of online correction to protect the biological signal.

Bigliassi, Karageorghis, Wright, Orgs, and Nowicky (2017) investigated the effects of music on brain activity and motor unit recruitment during cycle exercise performed at moderate-to-light intensity. They found that the EEG frequency (i.e., synchronisation of alpha rhythm) over the sensorimotor cortex controlling the working muscles was reduced in the presence of music. The authors postulated that this psychophysiological response could have influenced the electrical activity in the quadriceps given the inference that fewer signals per unit time were reaching the musculature (i.e., a suppression of EEG resynchronisation). The researchers also processed the electromyographic activity in the time-domain (i.e., examining the amplitude of the signal) and identified that more motor units were recruited in the presence of music. This physiological response could potentially indicate that a compensatory mechanism takes place as a means by which to sustain a given exercise intensity (i.e., a reduction in EEG frequency is compensated by increases in EMG amplitude).

The analysis of EEG extends beyond the identification of brain frequencies. For example, the event-related potential (ERP) technique facilitates examination of brain response to sensory stimuli, motor tasks, or cognitive demands (Light et al., 2010). The synchronous samples (i.e., time-locked signals) display a characteristic shape, meaning that modification of the curve profile is indicative of a different phenomenon having occurred over time. Such phenomena are usually introduced by researchers as a means by which to identify the effects of sensory stimuli or cognitive processes on brain responses (e.g., Scanlon, Sieben, Holyk, & Mathewson, 2017). In addition, neuropathological conditions can elicit changes in ERPs. Such changes can be identified through the comparison of diseased and healthy individuals or between dissimilar experimental conditions (see Groppe, Makeig, & Kutas, 2008 for a review).

A variety of sensory stimuli such as music and video have been used to induce ERPs (e.g., Tervaniemi, Just, Koelsch, Widmann, & Schröger, 2005). The modulation of ERP components such as P1 (positive peak that occurs at ~100 ms after the stimulus onset) and N1 (negative peak that occurs at ~100–200 ms after the stimulus onset) varies in accord with the type of stimulus used. It has been proposed that attention allocation modulates the curve design of P1 and N1 during visual tasks (Luck et al., 2000). Interestingly, similar effects are evident during auditory stimulation (Coch, Sanders, & Neville, 2005). Thus, by examining the curve profile of the brain’s electrical activity, researchers are able to identify cerebral responses to different cognitive processes. This technique has been applied extensively in the area of cognitive neuroscience (Landa, Krpoun, Kolarova, & Kasparek, 2014; Sur & Sinha, 2009), and affords a high level of reliability when the guidelines for the application of EEG are followed judiciously (see Keil et al., 2014).

Oscillatory potentials in the motor cortex. The very onset of muscle contractions is generally characterised by a marked drop in signal amplitude at the central electrode sites (Müller-Putz et al., 2007). Oscillatory potentials in the motor cortex have been extensively linked to the execution of active and passive movements (Allen & MacKinnon, 2010; Jain et al., 2013). Event-related perturbation analyses (synchronisation and desynchronisation) serve to identify a combined neuronal purpose to execute cognitive tasks. The brain’s electrical signal represents the extracellular field potentials generated by a group of neurons at the same time (no phase delay). A decrease or increase in a given band frequency has been used to explain desynchronisation or synchronisation of the underlying neuronal population, respectively (Mackay, 2005). Morlet Complex Wavelets are usually applied to extract time-frequency components of the EEG signal and further understanding of brain waves within time-locked phases. Low- and high-frequencies have been repeatedly associated with movement-related tasks (Cheron et al., 2016; Enders & Nigg, 2015). Event-related perturbation (i.e., baseline normalization of time-frequency signals) has been used in the present research programme to elucidate the relationship between oscillatory potentials in the motor cortex and focal awareness (i.e., un/conscious control of movements).

2.9.4 Recording Clean EEG Data

Experienced EEG scientists are well aware of the need for a systematic approach to noise reduction and elimination. It is possible to remove various types of noise from the EEG signal after recording by use of software algorithms such as digital filtering, averaging, threshold-based artefact rejection, and independent components analysis (ICA; Keil et al., 2014). However, each of these methods is characterised by some loss or distortion of the signal. There is really no substitute for recording a clean EEG signal and eliminating artefacts, as far as is possible, at source. We shall consider some of these sources of noise and how they can be reduced or eliminated.

Electrode-related noise. The most critical element in the EEG recording system is the electrode-scalp interface. Good electrical contact with the scalp is essential to obtain clean EEG recordings. Electrodes should be nonpolarizing, which means that they should not build up electrochemical charges in contact with saline fluids, as reactive metals do. Gold (Au), tin (Sn) and silver coated with silver chloride (Ag/AgCl) are considered to be suitable electrode materials (Keil et al., 2014). Laboratories using Ag/AgCl electrodes and conductive gel will generally aim for electrode-scalp impedances of around 5 KΩ. However, good quality modern EEG amplifiers have high input impedances and noise cancelation, and this means that it is possible to record EEG with an electrode impedance of ~50 KΩ, albeit noise risks are increased.

A factor that has a bearing on electrode impedance is the condition of the participant's scalp. The outer epidermis consisting of dead cells is an electrical insulator, plus the skin secretes oils that are nonconducting. Therefore, participants are typically asked to wash their hair the night or morning before the recording, and avoid products such as hair gel, spray, or wax. Brushing the hair vigorously can help in terms of removing loose epidermis. Also, most proprietary electrode gels contain mild detergents that can break up oily films, and pumice powder to help remove dead skin. Perhaps, surprisingly, it is possible to record good EEG data from participants with thick and voluminous hair. Calibrated syringes allow experimenters to determine the optimal amount of gel to fill a disc-type electrode. Electrodes should be filled by continuously extruding gel, starting at the scalp surface and gradually withdrawing the needle towards the top of the electrode.

It is essential to monitor all electrode impedances prior to initiating a recording, and to remedy all electrodes with out-of-range impedances. Before resorting to applying more gel (which can cause bridging between electrodes) an out-of-range electrode should be gently pressed onto the scalp and rocked. This is usually sufficient to establish good contact. It is also important to highlight that recent EEG devices have been designed to measure electrical activity in the brain using dry electrodes, meaning that no gel is necessary to collect the biological signal. Gel-free systems are largely available and active electrode systems can tolerate input impedances up to 100 KΩ. Such devices have been used in a wide variety of contexts and present an acceptable quality for research-related purposes (see Lopez-Gordo, Sanchez Morillo, & Pelayo Valle, 2014).

Mechanical instability of the cap. This problem is largely avoided in a geodesic net, where local tensions automatically adjust the fit of the net to the head. However, the 10-20 style caps come in standard sizes with limited flexibility, so a good fit is not guaranteed and some electrodes may tend to lift away from the scalp. Tubular elastic netting can also be applied to the outside of the cap to improve contact pressure. If mechanical problems are solved, and gel or electrolyte is correctly applied, then recording properties will generally improve over the initial 15–20 min after fitting the cap as the gel or electrolyte acts on the epidermis. It is a good idea, therefore, to ask participants to complete any necessary preliminary questionnaires or other non-EEG data collection while the cap is stabilizing.

External electrical noise. The high-gain amplifiers used in EEG will magnify any tiny voltages present at the scalp regardless of their source. Moreover, the human body, when connected to such an amplifier acts as an excellent aerial that will pick up any radio-frequency electromagnetic signals that are broadcast through the air. The human environment is awash with such signals that emanate from electrical devices. Prominent components of such electromagnetic noise are 50/60Hz mains frequency waves and switching transients (spikes) originating from nearby electrical equipment and lighting.

It is impossible to record clean EEG unless such electrical interference is eliminated. There are three main approaches to eliminating these sources of noise. The first of these is screening; an EEG room should ideally be electrically and acoustically screened. Electrical screening is achieved by a conductive metal mesh embedded in the walls, floor, and ceiling and connected to the ground (earthed). This Faraday cage will prevent any broadcast electrical interference from outside the room reaching the EEG participant, cap, and amplifiers. An effective Faraday cage can be built from steel tubes and connectors, covered in 1-cm steel mesh. The second approach is through amplifier design. EEG amplifiers are differential amplifiers that use three electrodes to record activity: an active electrode (A), a reference electrode (R) and a (virtual) ground electrode (G) placed participant’s head, thus they will subtract the difference from ground of the active and reference voltage (AG-RG).

Since external noise sources will tend to affect AG and RG similarly, this arrangement reduces noise (Luck, 2014). Modern amplifiers can have active noise cancelation and amplifiers that are placed in a headbox as close to the participant as possible. This eliminates cable loss of the unamplified signal. The third approach is to identify and switch off or move possible sources of interference (e.g., fluorescent lights, air conditioning units, or fridges). Some equipment such as computer monitors might, however, need to be placed inside the Faraday cage to present stimuli, and are thus an obvious source of noise. This is particularly a problem with computer screens, which contain large transformers. In such instances, a possible solution is to surround them with a Faraday cage-within-a-cage. Finally, it is important to also ensure that there is no path from the participant to the ground other than via the amplifier. A ground loop system can be a safety issue as well as creating mains-frequency interference.

Physiological noise. The main sources of physiological noise are: eye blinks and eye movements (electro-oculogram: EOG), skin conductance changes (variously known as galvanic skin response: GSR or skin conductance level/response: SCL/SCR), muscle activity (EMG) and heart activity (ECG). Participants should be instructed to blink as little as possible and to keep as still as possible while data are collected; although our experience shows that participants vary greatly in the ability or willingness to suppress blinks. All should be given breaks between blocks of trials in which they can blink, talk, and move. Additionally, vertical and horizontal EOG should be recorded in order to monitor eye movements and blinks, and to assist with the elimination of eye-related artefacts by PCA/ICA methods. GSR can be reduced by good electrode stability and low impedance. EMG interference originates mainly from neck and facial muscles. A relaxed state and comfortable position helps in reducing EMG and given that the dominant frequencies are higher than those of EEG, low-pass filtering is usually sufficient to remove such noises (Kline, Huang, Snyder, & Ferris, 2015). ECG is rarely a problem, but it can also be recorded for purposes of pattern-based artefact reduction.

2.9.5 Dealing with Body and Cable Movements

Dealing with electrical interference caused by external influences such as body and cable movements can present researchers with complications during movement-based protocols (Kline et al., 2015). Some of these electrical noises cannot be removed while processing the data offline, which means that researchers need to reduce the amplitude of electrical artefacts prior to commencement of data collection (Park, Fairweather, & Donaldson, 2015). Notably, recent technological developments have served to reduce the influence of body and cable movements on the EEG signal (e.g., Bigliassi et al., 2017). Mobile EEG devices such as eego™sports make use of active shielding technology to protect the core components of the cables. Consequently, extraneous noise caused by body and cable movements is reduced, which allows researchers to collect EEG data during challenging situations such as outdoor walking and cycling. However, it is important to emphasise that active shielding technology only appears to reduce electrical artefacts during repetitive moments performed at light and light-to-moderate intensities (Bigliassi et al., 2017). This is due to the fact that moderate- and severe-intensity exercise manifests contractions of neck muscles (e.g., trapezius) that are extremely difficult to remove when processing the data; this EMG artefact mainly affects temporal and occipital electrodes.

Some wireless systems reduce movement artefacts by mechanically decoupling the EEG recording cap from the main amplification and recording system, and substituting a radio link from a small transmitter attached to the cap (Losonczi et al., 2014; Szu et al., 2013). Besides portability and accessibility (Mihajlovic, Grundlehner, Vullers, & Penders, 2015), the number of available channels, amplified signal quality, and accessibility of software are salient factors in the choice of a portable system.

It is noteworthy that brisk muscular contractions, even if executed at a moderate-intensity, can severely compromise the quality of the electrical signal. This occurs because some of the artefacts generated by body and cable movements exhibit a similar frequency and amplitude to EEG activity, which means that identification methods such as independent component analysis cannot differentiate artefacts from real brain activity. In such instances, researchers are encouraged to design experimental protocols that prioritise closed kinetic chain exercises (e.g., handgrip and ankle-dorsiflexion tasks) performed at relatively light-intensity with a focus on frontal, central, and parietal electrode sites. Modern EEG devices such as Muse and Emotiv can potentially be used during more realistic settings (e.g., cycling at intensities above ventilatory threshold). However, the number of electrodes is reduced, which consequently limits data processing (e.g., source reconstruction) and interpretation.

It is clear that future research and developmental work is necessary to establish new methods that will mitigate the influence of external factors on the fidelity of EEG data. Offline procedures can only partially remove extraneous noises and should be applied carefully in order to preserve the information carried in the raw signal (see Dickter & Kieffaber, 2013). Researchers are also encouraged to collect EMG signals from facial muscles and the trapezius during movement-based EEG experiments. Analogue triggers can also be created subsequently during the offline data processing stage to identify the very onset of muscle contractions (e.g., Bigliassi et al., 2017). This approach facilitates the removal of muscle bursts from the EEG signal and enhances the internal validity of an experiment.

2.9.6 Methods Used to Analyse Electrical Activity in the Brain

In order to process the biological signal extracted from the electrical activity of the brain, a series of offline procedures need to be conducted in a sequential manner (Olejniczak, 2006). The workflow must be described in the Methods section of an EEG-based research study in sufficient detail to permit replication if required (Picton et al., 2000). The influence of artefacts (e.g., facial muscles and eye blinks) on the electrical signal, filtering processes, epoching, averaging, time-frequency analysis (e.g., wavelet transformations), source reconstruction, and brain connectivity are described herein to provide readers with sufficient background to enable them to interpret the results of EEG experiments in sport and exercise sciences.

Data correction. Firstly, researchers must import the data into computer programs and toolboxes such as Brainstorm (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011) and EEGLab (Delorme & Makeig, 2004) in order to perform offline analytical procedures. These computer programs are open source platforms for EEG analysis with active communities for support and continuous development. Secondly, the signal needs to be re-referenced using consistent reference electrodes across trials and participants (e.g., average mastoid reference, using electrode sites [M1 and M2] or common average reference). In EEG, the signal amplitude recorded at each electrode is compared to voltages recorded at reference electrodes. The choice of reference electrode(s) influences the shape of ERPs recorded at different electrode positions, but referencing may be changed in software during offline processing. After recording, the data are visually checked to identify bad electrodes and bad time-segments (e.g., Wright, Gobet, Chassy, & Ramchandani, 2013). This procedure is normally conducted via a check of the signal amplitude of all electrodes (e.g., using a 2-D layout map). Figure 2.7 provides an example of a bad electrode that has been visually identified at O1 (red signal). This electrode needs to be discarded from further analyses; otherwise its inclusion might compromise final topographical results, estimated sources, and data interpretation. EEG artefacts can also be identified through the application of high-order statistics, frequency decomposition, and ICA; a technique used to separate linearly mixed sources (see Delorme, Sejnowski, & Makeig, 2007).

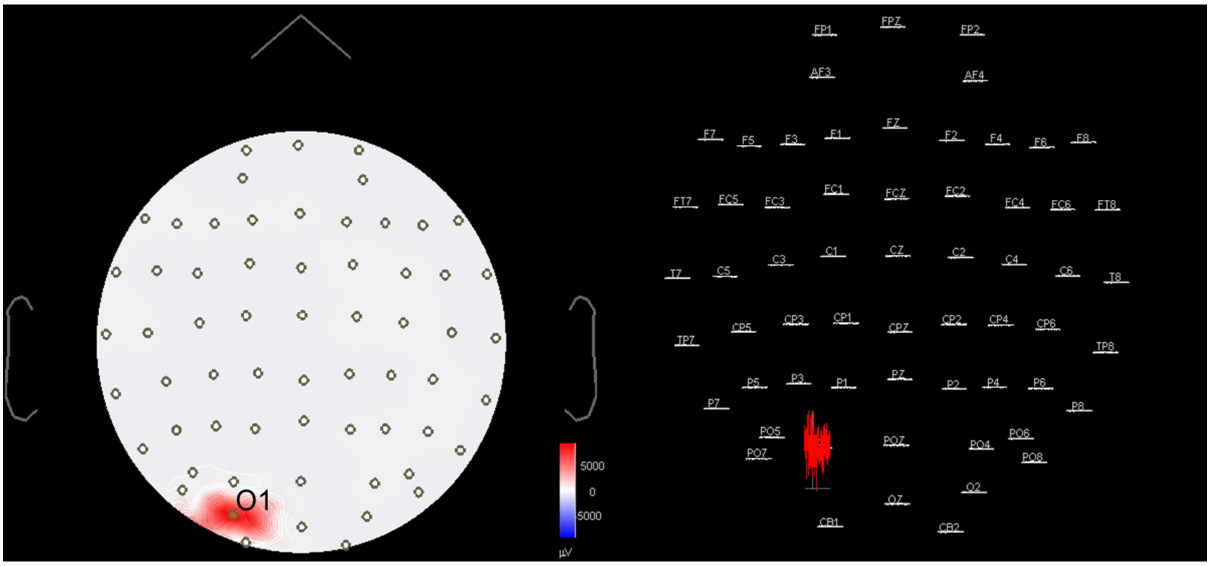


Figure 2.7. Diagrammatic representation of a bad electrode in a 2-D layout, 62-channel EEG map.

Eye blinks and eye movements. The vertical electro-oculogram (VEO) recorded from electrodes above and below the eye scans vertical eye movements and blinks. Blink-related activity needs to be removed from EEG signals in order to negate the influence of orbicular muscular contraction on the activity of frontal electrodes (e.g., Girges, Wright, Spencer, & O'Brien, 2014). Independent component analysis is usually applied by modelling blink activity in the VEO and removing the correlated waveforms of electrical activity from EEG electrodes. This approach possibly represents one of the most necessary methods to be applied during offline EEG procedures (Dickter & Kieffaber, 2013; Keil et al., 2014). This is because signals from both blinks and eye movements are mixed in with the EEG recorded from frontal and frontal-central electrodes. Moreover, ERPs may be confounded by any EOG signals, which have a tendency to occur systematically over time (e.g., where a stimulus trial requires a change in fixation point to complete the task). Consequently, such contractions are epoched and are therefore fully represented in averaged signals. This means that the averaged signals have the potential to indicate false peaks. Similar considerations apply to saccadic eye movements, from both horizontal (HEO) and vertical (VEO) eye movements. The solution requires care at the experimental design stage to eliminate any tendency for stimuli to provoke synchronised eye movements or blinks.

Raw EEG data. The continuous biological signal is imported into the database then broken into smaller time samples (i.e., epochs). These samples can be asynchronous (event-unrelated signals) or event-related windows (epoched by triggers; i.e., time-locked). Pre-processing of the raw (or epoched) EEG data includes DC-offset correction in order to prevent the influence of voltage imbalance problems (i.e., baseline variations). Offline filters (e.g., band-pass filters) are usually applied to exclude artefacts such as muscular contractions and electrical interference from external devices (e.g., computers and smartphones). Methods of independent component analysis and signal space projection have also been developed to remove cardiac and respiratory artefacts (e.g., Castellanos & Makarov, 2006).

Averaging. The pre-processed EEG signal usually needs to be averaged in time and/or frequency domains. The time-locked signal can be successfully averaged in time; in this case, amplitude is summed across different samples (Picton et al., 2000). However, event-unrelated samples, referred to as *asynchronous samples*, need to be averaged in the frequency-domain (i.e., FFT is conducted for each segment), otherwise, the time-amplitude average of all the samples will tend towards zero volts because the stimulus onset is random in relation to the EEG signal. In such instances, the brain does not “know” the times at which the samples were taken. This is the mathematical fact that underpins the principle of ERP averaging (Picton et al., 2000). Time-locked signals can be easily averaged using grand average methods; conversely, asynchronous samples are required to be processed in the frequency-domain through the application of methods that decompose the power spectrum into different band waves. It is also important to make clear the main differences between FFT and wavelet transformations. FFT methods provide the size of the component of frequency but no detail regarding the spatial duration. Conversely, wavelet transformations can derive a characteristic time and frequency. For example, time-frequency decomposition methods such as Morlet Complex Wavelets can indicate not only whether the power of theta waves were up-/down-regulated but also precisely when this modulation occurred (Bigliassi et al., 2014).

Topography and source estimation. Asynchronous samples can only be processed in the frequency-domain and present changes in different band frequencies over the cortex surface. Two-dimensional topographical maps are usually generated to illustrate the distribution of various frequencies at different electrodes (Pfurtscheller & Lopes Da Silva, 1999). Time-locked signals are directly linked to triggered stimuli/cognitive processes. When averaged, time-locked signals can be processed in both time- and frequency-domains, and allow the reconstruction of estimated sources. Source reconstruction is more accurate for focal sources in the superficial regions of the cortex than it is for extended sources (Wennberg & Cheyne, 2013) or for sources in medial or subcortical regions (Koessler et al., 2014). The source of the brain’s electrical signal can subsequently be reconstructed by applying different methods, such as the Minimum Norm Method (wMNE; Grech et al., 2008) or Standardised Low Resolution Brain Electromagnetic Tomography (sLORETA; Pascual-Marqui, 2002). sLORETA is based on current source density (i.e., a current flowing towards the electrode is a source, and a current flowing away from the electrode is a sink; see Kamarajan, Pandey, Chorlian, Porjesz, & Begleiter, 2016). In addition, researchers are required to select the neural orientation of the reconstructed sources. Source orientation is a biophysical postulate that suggests that each vertex of the cortex surface contains one, two, or three dipoles with orthogonal directions. This anatomical observation is based on the fact that neurons are organised in different macro-columns that are perpendicular to the cortex surface. Unconstrained sources are recommended during EEG-related studies given its poor spatial resolution and the considerable challenge associated with the estimation of precise source locations.

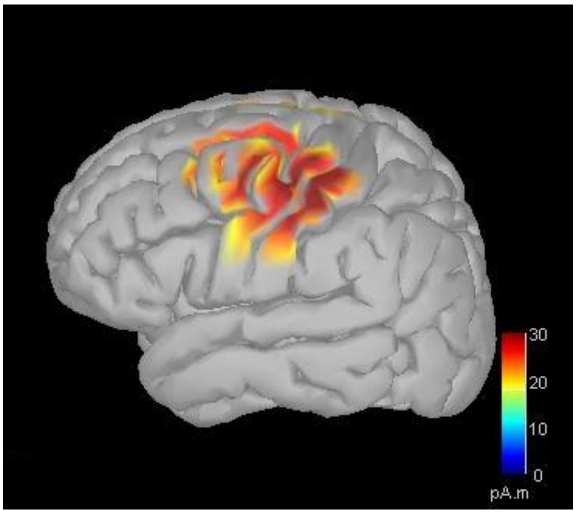


Figure 2.8. Time-locked EEG signals and source reconstruction analysis through the use of the wMNE method.

Brain atlas. The final step in identifying the sources of an event-related potential entails the application of atlases to identify the brain regions that exhibit an increase in signal amplitude (e.g., Jain, Gourab, Schindler-Ivens, & Schmit, 2013). Brain atlases are subdivisions of the cortex surface that were created to explore the anatomy of the brain (i.e., brain labelling; see Klein & Hirsch, 2005) and its activation patterns. Computer programs such as Brainstorm provide users with numerous atlases that can be applied to extract amplitude and frequency changes from specific brain regions (see Figure 2.9).

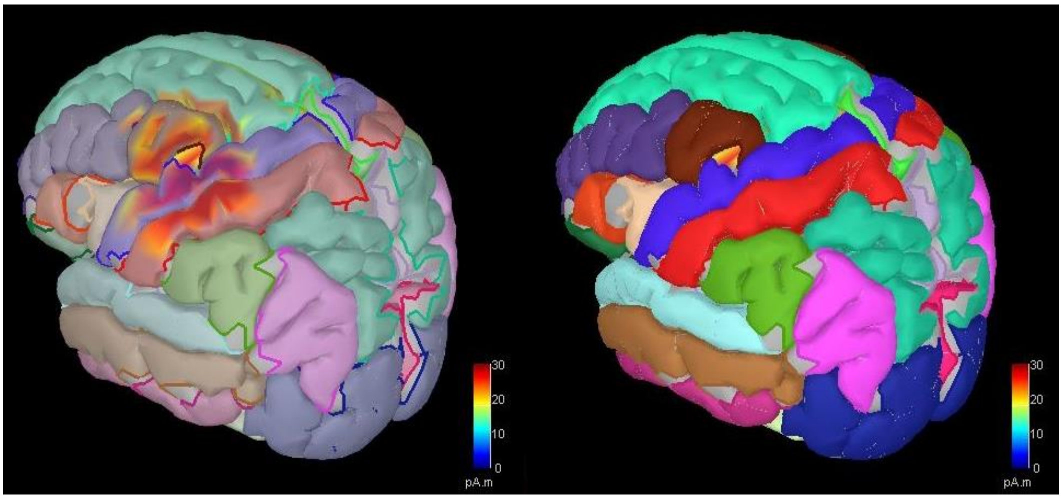


Figure 2.9. An example of source reconstruction (wMNE) and localisation (Mindboggle).

Note. An increase in signal amplitude can be identified in the left superior parietal gyrus and adjacent areas, such as the left superior parietal, left supramarginal, and left postcentral gyri. The signal amplitude threshold was set at 60% as a means by which to only present the highest values (cf. Jain et al., 2013).

Brain connectivity. Analyses of brain connectivity by statistical methods (e.g., correlation) have been used extensively in the fields of psychophysiology and neuroscience to further understanding of the neural networks that connect different brain regions (Jovanović, Perović, & Borovčanin, 2013). Spectral coherence analysis represents one of the most common methods to analyse brain connectivity and is applied to further understanding of the relationship between two electrical signals in the frequency-domain (Friston, 2011). Signal coherence is usually applied to estimate the means by which different brain regions/electrode sites respond in tandem. The magnitude of signal coherence varies from 0 to 1 and similar to correlational approaches, 1 represents a maximal level of coherence between electrical sources. Other methods such as Bivariate Granger causality analysis have been applied in the field of neuroscience to estimate not only the relationship between two brain regions but also the in-and-out connectivity between two electrical sources (Haufe, Nikulin, & Nolte, 2011). Put another way, this method has been used to indicate the influence of one electrode site on another (see Figure 2.10). Cortico-muscular coherence (EEG–EMG) is another approach widely used in the field of exercise sciences. By calculating the degree of connectivity between the electrical activity in the brain and muscles, researchers are able to indirectly assess the neural control of working muscles (e.g., Petersen, Willerslev-Olsen, Conway, & Nielsen, 2012).

Partial directed coherence (Baccalá & Sameshima, 2001) and directed transfer function (Kamiński & Blinowska, 1991) are also methods developed to investigate information flow in the brain structures and can be used for very similar purposes in the field of human movement sciences. For example, Mierau et al. (2017) demonstrated how different brain regions communicate during a balance control task through the use of partial directed coherence, which is a time-variant, frequency-selective and directed functional connectivity analysis tool. The authors suggested that balance control is primarily supported by functional networks. In the alpha network, the occipital lobe acts as a source, and the communication with other brain regions propagate towards parietal and central areas. This study demonstrates how brain connectivity analysis can be used to explore how different brain regions are connected during complex physical tasks and facilitate the proposition of theoretical frameworks that are primarily supported by neurophysiological measures.

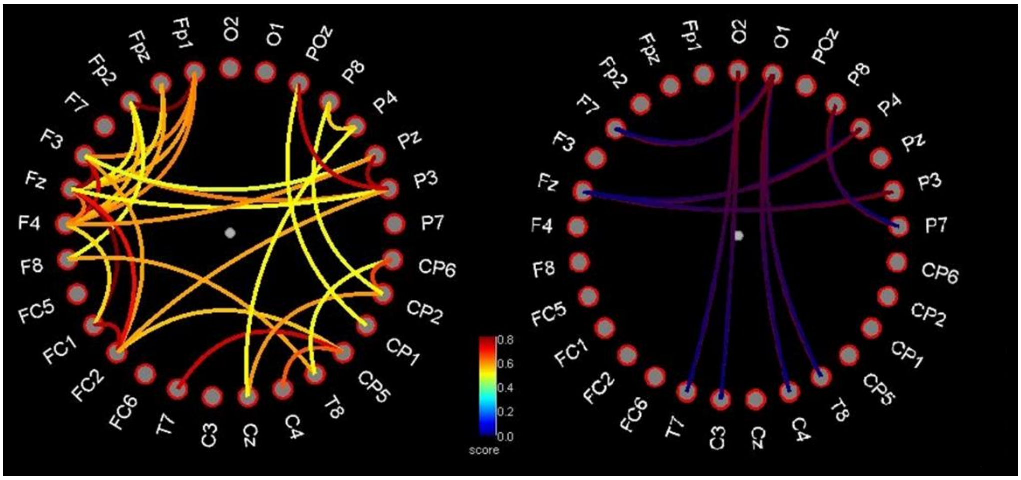


Figure 2.10. Examples of brain connectivity analyses across 62 electrode sites.
Note. The left figure presents the signal coherence method, while the right figure presents the Bivariate Granger Casualty analysis method. The blue areas of the link between two regions represent the electrical output from one electrode site; conversely, the red area represents the electrical input from other electrode sites (i.e., being influenced by other regions).

2.9.7 Interpreting the EEG Data

Interpretation of the EEG data depends primarily on the design of a study and the information available in the extant literature. Correlational analysis can also be implemented at this juncture as a means by which to identify whether changes in the brain’s electrical activity are associated with psychological responses (e.g., enjoyment or perceived activation) and/or peripheral physiological reactions (e.g., changes in heart rate variability or muscle electrical activity). It is noteworthy that the temporal resolution of the measures included in a correlational analysis can be slightly different, meaning that strong or weak relationships might not be particularly meaningful. For example, 1-s EEG epochs collected during the execution of movements are unlikely to correlate well with changes in affective valence that were measured immediately after an exercise bout. This is because the 1-s synchronous samples will be potentially linked to the neural control of working muscles, whereas affective responses will be indicative of a much longer timeframe. In such instances, decomposing the electrical signal by use of frequency-domain analysis appears to be a suitable approach in detecting changes in brain activity associated with psychophysical (e.g., perceived exertion) and psychological (e.g., motivation) responses.

2.9.8 Safety Issues

When used properly, EEG is a very safe and non-invasive technique. All EEG equipment should meet current safety standards for use with human participants, be properly maintained and installed, and tested for electrical safety. Operators should ensure that participants are protected from ground loops. Particular risk of ground loops may occur if the participant is physically connected to more than one recording and/or stimulating system. Other potential risks to be controlled for include skin irritation or cross-infection from gels and caps. The laboratory environment and cap storage area should be kept clean and tidy at all times. All electrode caps and electrodes should be washed meticulously after use. Water and antibacterial detergent should be used, as recommended by the manufacturer, to gently remove gel residues from electrodes. Blunt needles should always be sterilised. Gel should be hypoallergenic and transferred to a separate container for exclusive use with each participant. Operators should wash hands thoroughly for each testing session and use antibacterial hand gel.

2.10 Functional Magnetic Resonance Imaging

*f*MRI has excellent spatial resolution, which means that it can identify cerebral activity in deep areas of the brain (e.g., brainstem and amygdala). Unlike EEG, *f*MRI captures the haemodynamic response of the brain to a certain event. From the electrical impulse until the increase in blood flow to the active areas, there is considerable delay. This physiological response explains the relatively poor temporal resolution of *f*MRI. The blood-oxygen-level dependent (BOLD) response lies in the fact that neural activity consumes oxygen, which is supplied by oxygenated haemoglobin (see Logothetis, 2002). Therefore, the increase in electrical impulses emitted by the neurons must increase the necessity for blood and oxygen at that brain region. *f*MRI captures a high frame rate sequence of images and identifies the variation in blood flow over time as a response to sensory, cognitive, and motor events.

*f*MRI scanners allow researchers and physicians to examine inner parts of the human brain through the use of an efficient and non-invasive method. Images are initially displayed in greyscale, but the magnetic properties of the cell create a clear differentiation between grey and white matter. The brain is analysed in terms of anatomical and functional properties. Extreme cases of brain tumours and cerebral injuries can be easily identified with *f*MRI. This examination allows the application of medical procedures during the initial phases of the problem, increasing the chance of complete recovery. *f*MRI scanners allow the use of visual and auditory stimuli during data collection. Images are displayed in front of participants' eyes and compatible earphones make the use of auditory stimuli possible. Therefore, an extensive range of experimental designs can be developed to explore the human brain.

A series of limitations are associated with the use of *f*MRI scanners. Firstly, this technique is extremely expensive, which makes its use very limited and available for few institutions. Furthermore, the collection of brain images must be free of head and body movements. In other words, participants are expected to lie down and stay still during the complete period of data collection. Head movements produce noises, which can be only partially corrected by computational procedures (i.e., realignment). Thirdly, *f*MRI scanners rely on the quality of the magnetic properties of human cells. This assumption makes the use of metallic components impossible during examination. The necessity to stay still during relatively long periods of time during *f*MRI procedures can also elicit drowsiness and daydreaming, which modulate brain activity in a randomised manner. Despite the aforementioned limitations, *f*MRI is still the cutting-edge technology to examine brain-related responses to sensory, cognitive, and even motor (simple patterns of movement; e.g., finger tapping tasks) events.

The first studies on the use of magnetic resonance machines to produce images date from few years ago, meaning that this technique is fairly recent (cf. Henderson, 1983). Ever since then, the use of this equipment has become prevalent amongst researchers and physicians, because of the manifold advantages associated with the use of *f*MRI (e.g., excellent spatial resolution). The human brain is the most complex organ of the body, and this fact complicates the establishment of experimental designs. The use of simple visual tasks, including the use of dots and moving dots have been applied extensively as a means to explore the areas of the brain associated with motion recognition (e.g., Ho & Giaschi, 2009; O'Craven, Rosen, Kwong, Treisman, & Savoy, 1997). A subtraction method (i.e., contrast) must be applied to isolate the activation of a certain brain region (Amaro & Barker, 2006; Aue et al., 2009). In other words, to make sure that the activity of the brain is related to a certain event, researchers have to create opposite experimental conditions (i.e., *counterproof* methods; regress problem). For example, if a researcher wishes to investigate which brain regions activate in response to the combined effects of exercise and music, music-only and exercise-only conditions need to be administered in order to explore the sole effects of music and exercise on brain activity.

The use of *f*MRI scanners is applied to diverse contexts such as attention tasks and visual stimulation. However, exercise interventions are scarce inside the scanner due to head movements, which produce noise that compromises the fidelity of the data. Therefore, simple exercises such as hand grip-squeezing tasks have been used inside the scanner to elucidate the cerebral responses to isometric contractions (cf. Thickbroom, Phillips, Morris, Byrnes, & Mastaglia, 1998). Other physiological systems such as the cardiovascular and respiratory are seldom investigated using *f*MRI. However, Fontes et al. (2013) created a compatible cycle ergometer to evaluate how the brain responds to various exercise intensities using *f*MRI. Cycling caused activation in the cerebellar vermis, precentral gyrus, and postcentral gyrus. Furthermore, high-intensity exercises increased the BOLD response of the posterior cingulate gyrus and precuneus. Despite a wide range of difficulties to replicate similar protocols, this study demonstrates the viability of using *f*MRI to examine the cardiorespiratory system during the execution of movements.

The *f*MRI data is processed offline and a sequence of procedures must be conducted in order to extract meaningful information. However, the steps to process brain images are relatively straightforward and generally easier to follow when compared to EEG analysis. The images are initially imported into computer programs such as SPM12 and head motion is realigned based on the functional volume of the first image. Subsequently, the functional files are 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) is commonly used to normalise the anatomical and functional properties of the brain images. Finally, functional scans are smoothed to increase the signal-to-noise ratio and increase the validity of the statistical procedures. In order to identify the statistical differences associated with each experimental condition, *t* and *F* test contrasts are conducted and brain atlases such as Pickatlas toolbox (Maldjian, Laurienti, Kraft, & Burdette, 2003) can be used to identify the active brain regions and extract statistical values from significant voxels.

Original Studies

The chapters that follow present five original studies that were designed and conducted as a means by which to elucidate the brain mechanisms that underlie the use of music during exercise-related situations. The EEG studies purposefully progress from a laboratory-based approach to more realistic settings. The author also employed two research techniques – EEG and *f*MRI – to investigate the same paradigm from different perspectives. In the first study (Chapter 3), the author explored the positive effects of music that are very commonly observed (e.g., enhancement of task performance) in real-life situations. The author decided to start such line of investigation by exploring the effects of motivational music during the execution of part-body exercises performed to the point of exhaustion. Interestingly, music can also have a negative effect when individuals execute highly-demanding cognitive motor tasks. This prompted the author to conduct the second original study. In Chapter 4, the author demonstrates how the brain activates in response to auditory distractions that have the potential to disrupt task performance and compromise the execution of movements.

The third original study (Chapter 5) of this thesis was undertaken to explore the effects of music on neural activation during cycle ergometer exercises. This study represents the first scientific attempt to investigate the effects of music during more realistic types of exercise. Subsequently, the author conducted a fourth study (Chapter 6) where participants walked 400 m at a pace of their choosing on an outdoor running track. This experiment was purposefully designed to recreate a real-life scenario wherein participants could experience an everyday form of physical activity while they listened to music. Finally, the fifth study (Chapter 7) was conducted using an *f*MRI scanner to explore the subcortical brain regions that activate in response to exercise and music, and further understanding of complex psychophysical phenomena such as attention and fatigue.

Chapter 3: Cerebral Mechanisms Underlying the Effects of Music During a Fatiguing Isometric Ankle-Dorsiflexion Task

Study 1 was published in *Psychophysiology*

(see section Manuscripts Published in Peer-Reviewed Journals During the PhD Programme)

3.1 Introduction

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

3.1.1 Attentional Focus

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

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

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

3.1.2 Sensory Modulation

Sensory strategies such as auditory stimuli have been extensively used as a means by which to ameliorate the effects of fatigue-related symptoms during exercise (Karageorghis & Priest, 2012b). Through the purposeful use of sensory stimuli, individuals experience more pleasant sensations and lower perceived exertion than under normal circumstances. In such applications, sensory stimuli force one’s attentional focus to external sensory cues, causing significant psychophysiological effects (see Karageorghis & Priest, 2012a, 2012b for a review). A recent study indicates that even at high exercise intensities, affective responses are more positive under conditions of auditory and audiovisual stimulation (Jones et al., 2014).

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

3.1.3 Cerebral Mechanisms Underlying Attentional Switching

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

> The psychobiological model is an effort-based decision making model based on motivational intensity theory, and postulates that the conscious regulation of pace is determined primarily by five different cognitive/motivational factors: Perception of effort; potential motivation; knowledge of the distance/time to cover; knowledge of the distance/time remaining; previous experience/memory of perception of effort during exercise of varying intensity and duration. (p. 1319)

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

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

3.1.4 Brain Waves During Exercise

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

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

3.2 Aims of Study 1

EEG was used in Study 1 in order to shed new light on the mechanisms that underlie AS during a physically demanding motor task and ascertain key cortical areas/networks that activate in response to music through frequency analyses. An auditory stimulus (musical excerpt) was used to manipulate AS and thus further understanding of the attentional processes that occur during an exhaustive isometric ankle-dorsiflexion task.

3.3 Hypotheses

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

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

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

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

3.4 Method

3.4.1 Participants

Ethical clearance was secured from the first author’s institutional ethics committee and written informed consent was obtained from all participants. Undergraduate students were invited to participate via institutional email. Participants who demonstrated an interest in taking part were initially surveyed by the first author to collate demographic data such as age, gender, ethnicity, and sociocultural background. Furthermore, participants were administered the Attentional Focusing Questionnaire (AFQ; Brewer et al., 1996) in order to assess their dominant attentional style during exercise. The inclusion criteria were that participants needed to be: right-handed, music listeners, non-musicians, and apparently healthy. Sample size was calculated using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) for a one-way analysis of variance (ANOVA; within-subject factors; three experimental conditions). Alpha level was set at 0.5 and 1- β at 0.8 (Cohen, 1994). Based on a large effect size of sensory modulation on attentional focus (f = 1; Hutchinson et al., 2015), 15 participants were required. An additional four participants were included in order to account for the likelihood of experimental attrition. In total, 19 participants (10 men and 9 women; M_{age} = 26.4, SD = 3.6 years; M_{height} = 170.3, SD = 9.4 cm; M_{weight} = 67.0, SD = 11.5 kg; $M_{physicalactivity}$ = 203.1, SD = 5 min/week) completed each experimental phase of the study.

3.4.2 Experimental Design

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

EEG electrodes (Quik Cap; Compumedics Neuromedical Supplies) were placed on her/his scalp.

Participants were instructed that exercise should be sustained until the point of volitional exhaustion or when the participant could no longer tolerate the proposed exercise intensity for more than 3 s. The period of time that participants sustained the contraction was recorded by use of a handheld stopwatch (Casio, model HS-80TW-1EF) and variations in produced force ≤ 10% were permitted. The same piece of music used in the sensory stimulation condition (see 3.4.3 Music Selection section) was administered again 5 min after the final experimental condition, as a means by which to identify the sole effects of music that are not evident during exercise. The music-only effects (MO) were subsequently compared with the control condition (CO; no intervention) and music-during-movement condition (MM) in order to explore the brain activity that is exclusively representative of the interaction between music and motor task.

[redacted]

[redacted]

Figure 3.1. Experimental set-up of Study 1. Figure 3.1A: Force transducer used to quantify the level of pressure generated by the participant against the load cell; Figure 3.1B: Participant wearing the EEG cap and headphone; Figure 3.1C: Participant's vision from outside the Faraday cage; the cage was assembled to prevent the electrical interference of external devices.

3.4.3 Music Selection

Eye Of The Tiger by Survivor (109 bpm) was used in Study 1 as a means by which to ameliorate the effects of fatigue-related symptoms that occur during the execution of exhaustive motor tasks. The rationale underlying this choice was predicated on participants' likely extramusical associations and level of familiarity with this particular track (North, Hargreaves, & Hargreaves, 2004). The track was expected to awaken long-term memories (Watanabe et al., 2008) of the *Rocky* film series and evoke positive emotions (Juslin, 2013) during exercise-related situations (Karageorghis & Priest, 2012a). Participants were asked about their level of familiarity with the stimulus after completing all the experimental phases; all were familiar with the auditory stimulus and related the piece of music to the *Rocky* film series.

3.4.4 Procedure

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

A 6-8 min interval was used to induce appropriate recovery between experimental conditions. It was intended that the participant started their next experimental condition when psychophysiological indices returned to baseline levels. Thus, the category ratio (CR10) was administered to assess the limb discomfort and the participant was required to perform a new MVC test. The menstrual cycle of women was not monitored in Study 1, because there is strong evidence to suggest that this variable does not influence isometric strength (Nicolay, Kenney, & Lucki, 2007) regardless of the use of contraceptive medication (Elliott, Cable, & Reilly, 2005).

3.4.5 Electromyography

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

3.4.6 Electroencephalography

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

3.4.7 In-task Measures

Selective attention was assessed every 30 s by use of the Tammen’s (1996) Single-Item State Attention Scale (SIAS). The SIAS measures the allocation of attentional focus to internal and external sensory information during the execution of physical tasks. Limb discomfort (CR10; Borg, 1982), situational motivation (MOT, Tenenbaum, Kamata, &

Hayashi, 2007), affective valence (Feeling Scale [FS]; Hardy & Rejeski, 1989) and felt arousal (Felt Arousal Scale [FAS], Svebak & Murgatroyd, 1985) were assessed prior to and immediately after the exercise bout. An order of administration was established and applied consistently throughout the experiment (1st SIAS, 2nd CR10, 3rd MOT, 4th FS, and 5th FAS). The CR10 was used to measure the level of limb discomfort associated with the active limb during the execution of a fatiguing task using the response set "How much discomfort are you feeling in your leg?" Situational motivation was used to measure how motivated participants were feeling at that moment using the response set "How motivated are you feeling?" The FS was applied to assess participants' affective state using the response set "How are you feeling right now?" The FAS was used to measure the level of perceived activation/arousal that one experiences using the response set "How aroused are you feeling right now?"

3.4.8 Data Analysis

Electromyography. Spike2 (v4.11; Cambridge Electronic Design) was used to obtain time and frequency indices from the muscle electrical signal, which was initially filtered, rectified, and smoothed. Time and frequency domains were used to identify the motor unit recruitment and fatigue-related symptoms, respectively. The RMS value obtained from the raw EMG data is representative of the motor units necessary to produce a certain level of contractile strength. The mean frequency (MF) obtained from the frequency spectrum was used as an index of fatigue (Arendt-Nielsen & Mills, 1988). Fatigue-related symptoms usually increase over time as a response to increasing exercise intensity. Accordingly, MF is expected to decrease, because the firing rate of electrical signals emitted by the brain also decreases over time as a response of increasing RPE (Cifrek et al., 2009; de Morree et al., 2012). Fast Fourier Transform was used to decompose the EEG signals into different wave frequencies. MF was calculated as a means to compare experimental conditions and identify the trend by which fatigue occurs over time (De Luca, Sabbahi, & Roy, 1986). The RMS was used to identify the motor unit recruitment. The recruitment of motor units is expected to increase over time as a means by which to compensate the increasing exercise intensity (Chesler & Durfee, 1997). The agonist–antagonist ratio was calculated by dividing the average of the anterior tibialis RMS value by the average of the gastrocnemius RMS value.

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

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

3.4.9 Statistical Analysis

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

3.5 Results

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

3.5.1 Psychological Responses and Task Performance

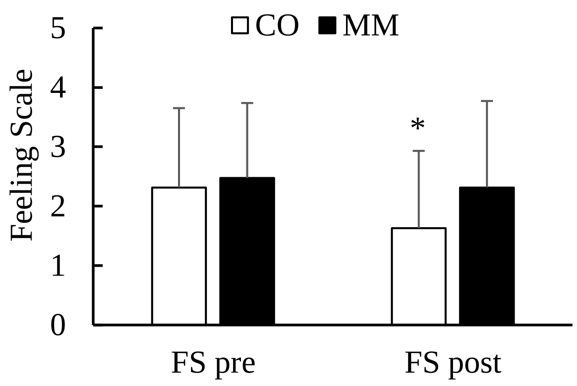
ANOVA and *t* test results are presented in Table 3.1. Participants' attentional style had no influence on the dependent variables (*p* > .05). The fatigue test elicited detrimental effects in terms of participants' affective states; however, values for this variable did not change when participants executed the motor task under the influence of music (CO: FSpre *M* = 2.31, *SD* = 1.33, FSpost *M* = 1.63, *SD* = 1.30; MM: FSpre *M* = 2.47, *SD* = 1.26, FSpost *M* = 2.31, *SD* = 1.45). There were no statistically significant differences between MM and CO for felt arousal, situational motivation, and limb discomfort measures (see Figure 3.2). Changes in AS were analysed over time by calculating the rate of change along the regression line; the attentional slope represents the magnitude by which fatigue-related symptoms force the reallocation of attentional focus to associative thoughts (attentional shift). Participants who performed the task under the influence of music demonstrated greater levels of dissociation throughout the exercise bout (CO: *M* = -16.36, *SD* = 9.19; MM: *M* = -12.61, *SD* = 6.34). Task performance was significantly different between MM and CO (CO: *M* =167.58, *SD* = 81.39 s; MM: *M* = 196.53, *SD* = 103.32 s; ~15% of difference).

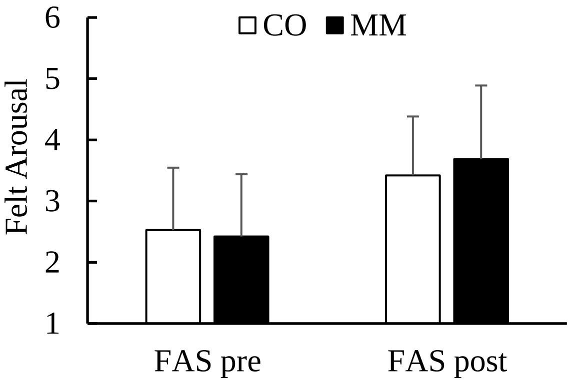
Table 3.1

Mixed-Model Repeated-Measures (RM) ANOVA and t Test Results.

Affective Valence – Within-subjects effects	*F*	*p*	η_p^2
Experimental Condition	7.45	.014	.29
Time	3.01	.100	.14
Experimental Condition x Time	2.32	.145	.11
Felt Arousal – Within-subjects effects	*F*	*p*	η_p^2
Experimental Condition	.681	.420	.03
Time	53.5	.000	.74
Experimental Condition x Time	.656	.428	.03
Situational Motivation – Within-subjects effects	*F*	*p*	η_p^2
Experimental Condition	2.85	.108	.13
Time	.007	.933	.00
Experimental Condition x Time	1.67	.213	.08
Limb Discomfort – Within-subjects effects	*F*	*p*	η_p^2
Experimental Condition	.000	1.00	.00
Time	101	.000	.84
Experimental Condition x Time	1.69	.209	.08
	t	*p*	
Time to exhaustion (s)	-2.25	.037	
Attentional shift (slope)	-2.49	.023	

Note. η_p^2 = partial eta squared; Power = Observed power (computed using an alpha of .05).





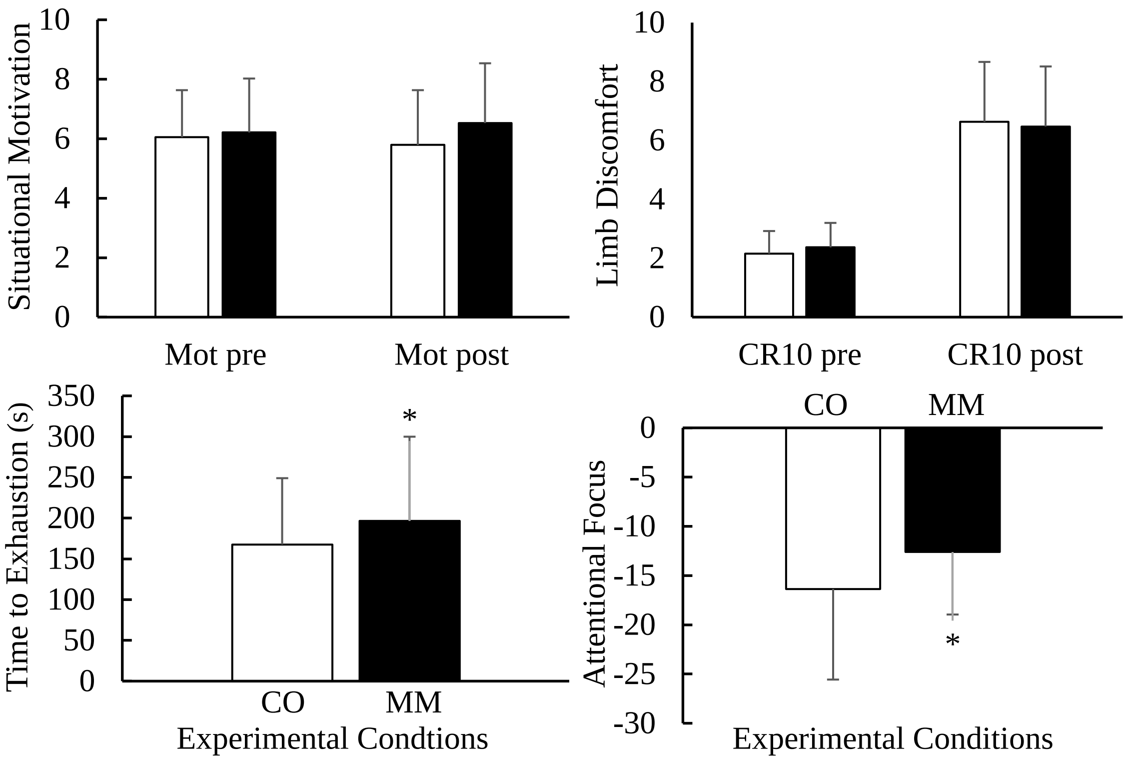


Figure 3.2. Psychological responses and exercise performance compared between CO and MM. Means and standard deviations are presented. *Note.* CO = Control condition; MM = Music condition; FS = Feeling Scale; FAS = Felt Arousal Scale; MOT = Situational motivation; CR10 = Limb discomfort; * = $p < .05$.

3.5.2 Electrical Activity in the Muscles

No statistical differences were identified in the mean frequency of the power spectrum when comparing CO and MM (CO: *M* = 74.20, *SD* = 16.85; MM: *M* = 73.65, *SD* = 17.13; *t* = .218; *p* = .830); correspondingly, the agonist–antagonist ratio was similar between CO and MM (CO: *M* = 184.07, *SD* = 71.19; MM: *M* = 181.92, *SD* = 65.57; *t* = .039; *p* = .969). The electrical activity in the muscles was similar on time and frequency domains, but those results need to be analysed in tandem with indices of task performance, given that participants who executed the motor task under the influence of music had significant improvements in time to exhaustion, meaning that the auditory stimulus partially *controlled* fatigue and the recruitment of motor units (see Figure 3.3).

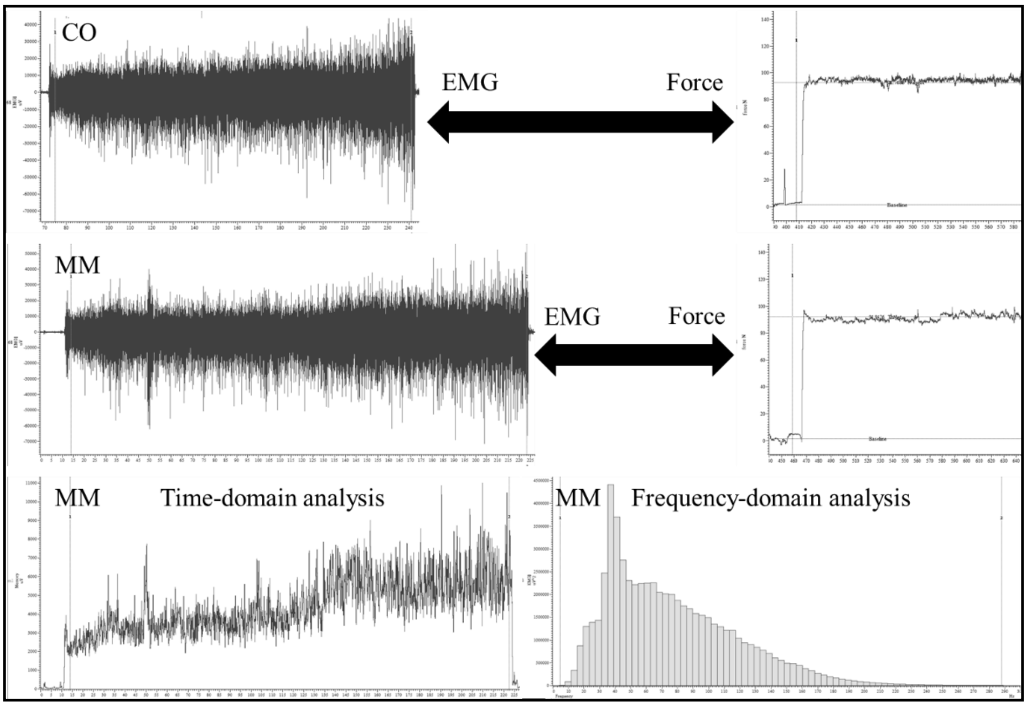


Figure 3.3. Electromyographic measures taken in Study 1. Music prolonged time-to-exhaustion and maintained the output frequency and recruitment of motor units during the execution of a fatiguing motor task. *Note.* CO = Control condition; MM = Music condition; EMG = Electromyography.

3.5.3 Electrical Activity in the Brain

The brain electrical activity was analysed on frequency domain at each electrode site. Results indicated statistically significant differences between CO, MM, and MO (see Table 3.2). A difference was identified at low-frequency components of the power spectrum. When participants executed the motor task in the absence of music, an increase in low-frequency waves (mostly theta rhythm) was evident in the frontal, central, and parietal regions of the cortex. Conversely, listening to music elicited a decrease in theta waves through the entire surface of the brain compared to CO (see Figure 3.4 and Figure 3.5). The same pattern of response was identified when participants exercised in the presence of music; low-frequency waves in the frontal, central and parietal areas were partially suppressed in MM, but the magnitude of the differences was moderated by exercise-related signals. AF3 was the only electrode site that MM differed statistically from both CO and MO (*p* < .05). In other words, the results of Study 1 indicated that theta waves in MM were partially suppressed/inhibited by music and partially stimulated by exertion-related cues (parallel processing of internal and external sensory information).

Table 3.2

One-way ANOVA (F and p values) Results.

Electrodes	Theta (*F*)	Theta (*p*)	Alpha (*F*)	Alpha (*p*)	Beta (*F*)	Beta (*p*)
FP1	3.327	.044*	2.215	.120	.791	.459
FPZ	3.017	.058	1.977	.150	.889	.418
FP2	2.866	.067	1.839	.170	.849	.434
AF3	3.940	.026*	4.430	.017*	.780	.464
AF4	2.589	.086	1.755	.184	.345	.710
F7	2.080	.136	2.049	.140	.602	.552
F5	3.467	.039*	2.468	.095	1.240	.299
F3	3.517	.038*	2.493	.093	1.403	.256
F1	3.296	.046*	1.419	.252	1.543	.224
FZ	2.437	.098	.747	.479	1.145	.327
F2	2.509	.092	.978	.384	1.117	.336
F4	2.317	.110	.907	.411	.874	.424
F6	2.301	.111	.601	.553	.902	.413
F8	1.637	.205	1.836	.171	.827	.443
FT7	1.949	.154	1.127	.332	.665	.519
FC5	2.813	.070	1.624	.208	.721	.491
FC3	2.893	.065	1.302	.281	1.227	.302
FC1	3.056	.056	1.589	.215	1.696	.194
FCZ	3.134	.053	1.244	.297	1.707	.192
FC2	3.458	.040*	1.354	.268	1.901	.161
FC4	2.982	.060	1.345	.270	.276	.760
FC6	2.143	.128	1.313	.278	.204	.816
FT8	2.325	.109	1.665	.200	.583	.562
T7	2.058	.139	1.200	.310	.840	.438
C5	2.310	.110	.740	.482	.585	.561
C3	2.761	.073	.494	.613	1.088	.345
C1	3.698	.032*	1.655	.202	1.290	.285
CZ	3.888	.027*	1.639	.205	1.285	.286
C2	3.903	.027*	1.404	.256	1.374	.263
C4	3.181	.050*	.883	.420	.313	.733
C6	2.799	.071	1.034	.363	.584	.562
T8	3.085	.055	1.245	.297	.615	.545
TP7	2.210	.121	.997	.376	1.563	.220
CP5	2.686	.078	1.171	.319	.619	.543
CP3	2.887	.065	.882	.421	1.079	.348
CP1	1.999	.147	1.355	.268	1.049	.358
CPZ	3.678	.033*	1.040	.361	.939	.398
CP2	3.897	.027*	1.262	.292	1.224	.303
CP4	3.901	.027*	1.554	.222	.678	.512
CP6	3.828	.029*	1.788	.178	.670	.516
TP8	3.404	.041*	1.437	.248	.754	.476

Table 3.2 continues

Table 3.2 continued

P7	3.074	.055	2.549	.089	3.153	.052
P5	3.132	.053	2.671	.079	2.085	.135
P3	3.309	.045*	2.388	.103	2.035	.142
P1	3.792	.030*	2.539	.089	1.669	.199
PZ	3.804	.029*	1.820	.173	1.665	.200
P2	3.706	.032*	1.820	.173	1.296	.283
P4	4.137	.022*	2.743	.074	1.768	.182
P6	4.136	.022*	2.466	.096	1.162	.322
P8	3.561	.036*	1.473	.239	1.957	.152
PO7	3.483	.039*	1.964	.151	1.411	.254
PO5	2.747	.074	1.584	.216	1.896	.161
PO3	2.718	.076	1.564	.220	1.904	.160
POZ	3.441	.040*	1.961	.152	2.205	.121
PO4	3.829	.029*	2.749	.074	2.581	.086
PO6	3.766	.030*	2.527	.090	2.419	.100
PO8	3.800	.029*	2.424	.099	2.427	.099
CB1	2.598	.085	1.395	.258	1.933	.156
O1	.821	.447	.370	.693	.826	.445
OZ	3.900	.027*	2.227	.119	3.019	.058
O2	3.742	.031*	2.709	.077	2.678	.079
CB2	2.105	.133	1.242	.298	1.007	.373

* *p* < .05.

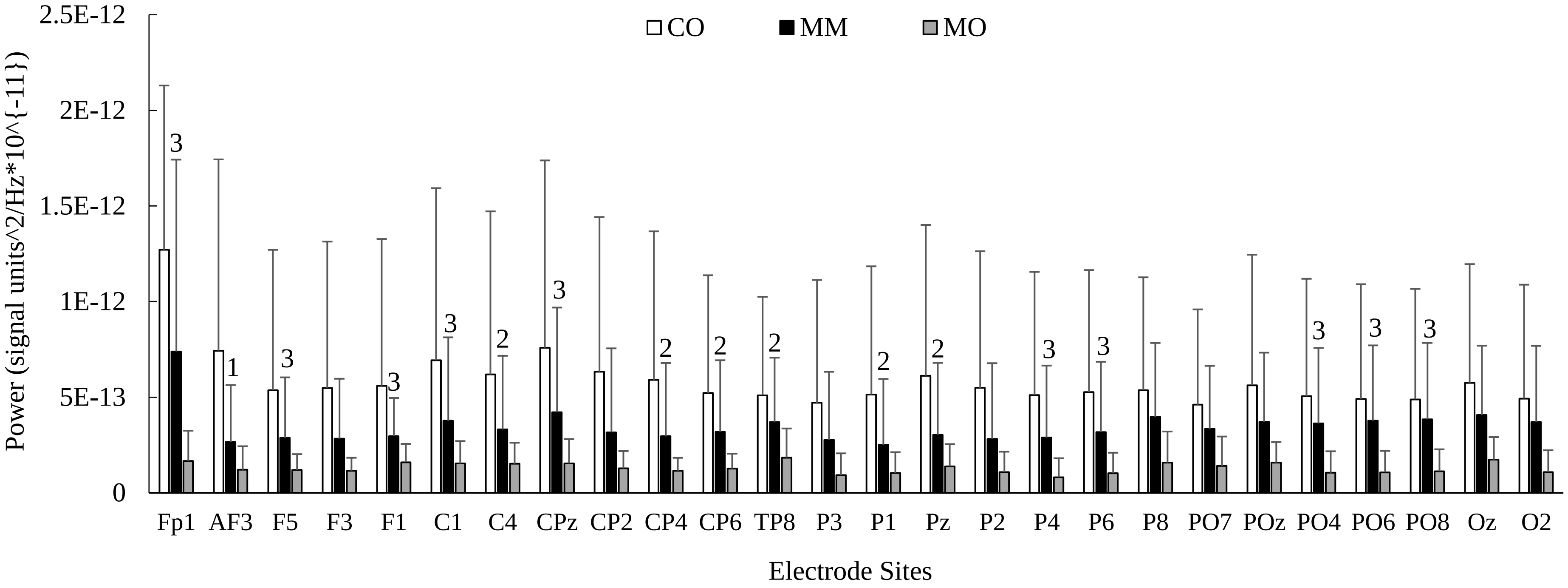


Figure 3.4. Theta rhythm power results for each electrode which differences were statistically significant (*p* < .05) between CO, MM, and MO (Bonferroni adjustment). Means and standard deviations are presented. *Note.* CO = Control condition; MM = Music condition; MO = Music-Only condition; 1 = MM differed statistically from CO and MO; 2 = MM differed statistically from CO; 3 = MM differed statistically from MO; the absence of data label indicates that CO differed statistically from MO.

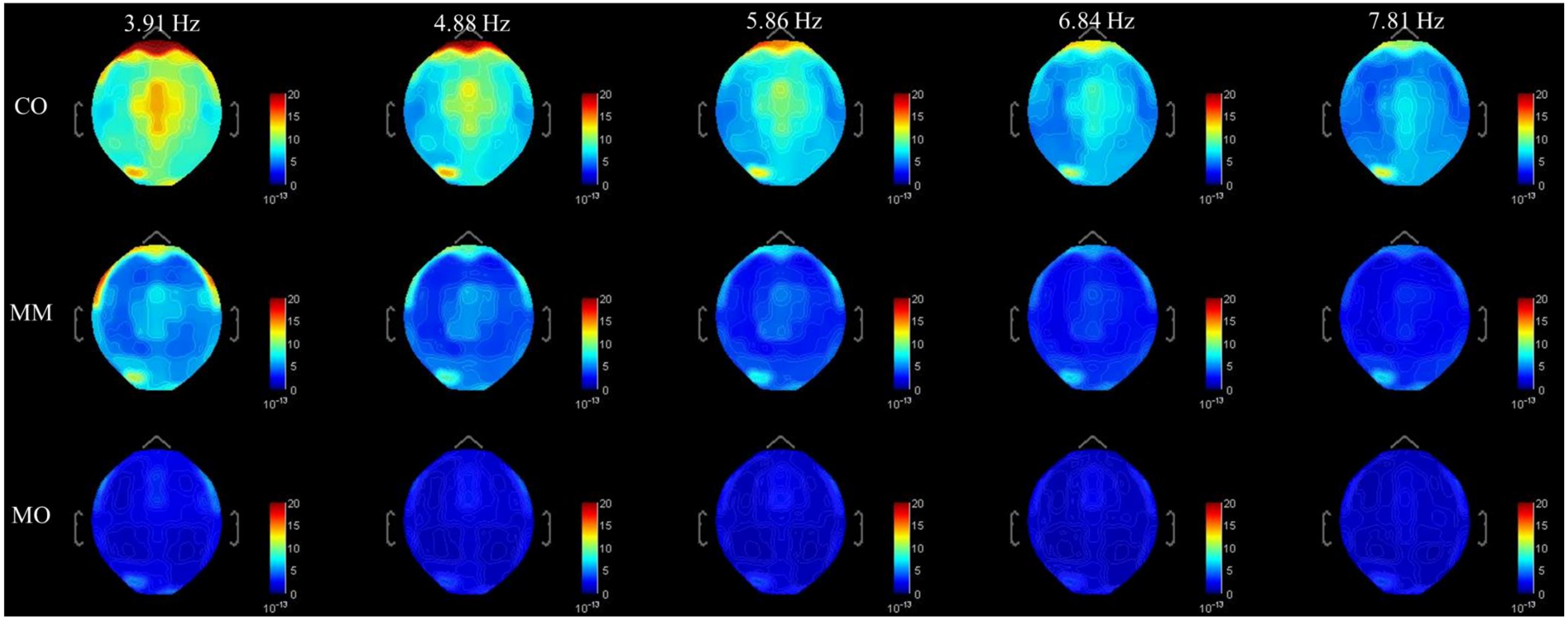


Figure 3.5. Low-frequency components (theta waves) of the power spectrum presented for CO, MM, and MO. *Note.* The coloured scale indicates the power of the band frequency (power [signal units^^{2}/Hz*10^{$^{-11}$}]); CO = Control condition; MM = Music condition; MO = Music-only condition.

3.6 Discussion

The main objective of Study 1 was to further understanding of the attentional processes that occur during a fatiguing isometric ankle-dorsiflexion task by applying music as a potential external distractor. The presence of music was expected to partially reallocate the participants' attentional focus to task-unrelated factors and subsequently ameliorate the effects of peripheral fatigue (Rejeski, 1985; Treisman, 1964; Van Duinen, Renken, Maurits, & Zijdewind, 2007). Due to the multifaceted effects of music on brain activation (Levitin, 2008), a more positive affective state coupled with improvements in task performance was expected.

3.6.1 Affective and Perceptual Responses

The author predicted that music would promote a dissociative attentional style, with consequent effects on psychophysiological responses, affect, and task performance. This hypothesis was supported by the results. The findings indicate that music primarily forces attention to auditory areas and therefore evokes positive affective responses. This response is subsequently overcome by the detrimental effects of peripheral discomfort that naturally lead to volitional exhaustion. However, participants sustained the task for a longer period of time under the influence of music, meaning that the reallocation of attentional focus to task-unrelated information led to improvements in task performance when the symptoms of fatigue were fairly light or moderate. Limb discomfort, felt arousal, and situational motivation were similar when compared between MM and CO. These results are also surprising given that participants who executed the motor task under the influence of music were able to sustain the contraction for a longer duration, which, in accord with the dual-mode theory of affective responses, should lead to more negative affective responses (see Ekkekakis, 2003). The dual-mode theory suggests that affective valence is influenced by cognitive processes and interoceptive cues. Therefore, the increasing exercise intensity is hypothesised to up-regulate afferent feedback from peripheral organs and down-regulate protective cognitive processes such as self-efficacy. This combination of peripheral and central processes is hypothesised to generate negative affective responses during exercises performed at high intensities. The results support the notion that task disengagement relies on the *worthiness* of the action (i.e., one's desire to persist), which is assessed continuously via conscious pathways (Pageaux, 2014). Music-related interventions reduce focal awareness and render reflexive control of movement execution (Kiefer, 2012). The upshot of this is a partial reduction in the interpretation of fatigue-related sensations and consequent increase in time-to-exhaustion.

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

3.6.2 Electrical Activity in the Muscles

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

Based on the electrical signal extracted from the anterior tibialis and gastrocnemius (see Figure 3.3), the present authors were able to identify a physiological index of attentional distraction; participants presumably fell into a partial "trance" (e.g., resting state and meditation; Aftanas & Golocheikine, 2001) during the execution of the motor task. During various periods of time, participants were only partially aware of the fatigue-related symptoms because the auditory stimulus reallocated attentional focus towards somatosensory regions, and the execution of the movements was reflexively controlled by the central motor command. This result is supported by the notion that simple motor tasks can be performed with partial focal awareness if they do not involve extreme symptoms of fatigue or pain (e.g., Kiefer, 2012).

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

3.6.3 Cerebral Responses

The central motor command (precentral and paracentral gyri; Voss et al., 2006) was expected to reduce action potentials to the working muscles and possibly generate an increase in low-frequency waves such as theta and alpha (initial hypotheses; e.g., Cao, Wan, Wong, da Cruz, & Hu, 2014). The effects of music were expected to partially block the processing of internal sensory cues and enhance exercise performance with possible effects on the brain electrical activity (Bigliassi, et al., 2016a). The results indicated that music not only reallocated the participants’ attentional focus towards sensory regions but also re-arranged the brain activity throughout the exercise bout. Music suppressed the sharp increase of low-frequency waves in the frontal, central, and parietal regions (see Figure 3.5). For a short period of time, fatigue-related symptoms were somewhat inhibited by the *defensive* effects of music. The *barrier* imposed by music to reduce exertional responses was initially triggered by attentional processes, because participants were only partially aware of internal sensory cues at light-to-moderate levels of exertion (attentional shift; see Figure 3.2).

The fatiguing test used in Study 1 was rather challenging to execute and participants had to control numerous internal (e.g., sensations of fatigue) and external factors (e.g., level of strength produced). The increasing symptoms of fatigue compromised task performance and participants had to maintain force at the target level (40% of MVC), which means that the difficulty should increase over time due to a presumed increase in lactic acidosis and other biochemical metabolic markers. An increase in low-frequency waves in the frontal, central, and parietal regions is possibly associated with the effects of fatigue-related symptoms on executive control during the execution of fatiguing motor tasks (Pires et al., 2018). The considerable complexity of the physical task and necessary control to sustain the contraction at the target level naturally reallocated attentional focus towards associative thoughts such as internal sensory cues and task-related information (Hutchinson & Karageorghis, 2013).

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

3.6.4 Limitations of Study 1

The piece of music used in the present experiment was chosen by the researchers and might not elicit precisely the same cluster of psychophysiological responses across participants, given that music preference is highly personal (North et al., 2004). However, different pieces of music could pose a threat to the internal validity of the experiment due to differences in the psychoacoustic properties of the stimulus (Karageorghis & Priest, 2012b). Based on this assumption, the author decided to partially compromise the ecological validity of the experiment given its laboratory-based approach. Secondly, the motor task used in Study 1 can only induce peripheral fatigue (limb discomfort) and might not be sufficiently effective to discharge a large number of corollary signals to sensory regions. Whole-body modes of physical activity can possibly cause substantial discharges of corollary signals from the central motor command and increase the input of afferent feedback; in such instances, the brain regions that activate in response to the sensory stimulus would be possibly different from those identified in the present experiment. However, Study 1 represents the first scientific attempt to illuminate the complex effects of music and exercise on cerebral activity. It is noteworthy that the carry-over effects of fatigue might have influenced task performance across conditions, despite the physiological (cardiac stress), neural (MVC), and perceptual (limb discomfort) parameters that were monitored to ensure that participants had regained homeostasis. Moreover, a randomised, counterbalanced design was employed to address the potential confound of fatigue carry-over on EEG activity, task performance, and psychophysiological responses.

3.7 Conclusions

Study 1 was undertaken as a means by which to further understanding of the effects of music on electrical activity in the brain and psychophysiological responses during the execution of a fatiguing isometric ankle-dorsiflexion task. The findings indicate that music induces a partial attentional switching from associative thoughts to task-unrelated factors during exercise, which leads to improvements in task performance. Participants also experienced a more positive affective state under the influence of music. These psychological responses are possibly associated with a mechanism pertaining to suppression of fatigue-related symptoms that are triggered by attentional processes (corollary discharges/afferent feedback; Bigliassi, 2015). The stimulative piece of music used in Study 1 down-regulated theta waves in the frontal, central, and parietal regions of the brain when participants executed a fatiguing motor tasks. The effects of music on electrical activity in the brain are possibly associated with a mechanism of attention reallocation, wherein exercise-related afferent cues remain outside of focal awareness over a broader range of intensity.

Chapter 4: Effects of Auditory Distraction on Voluntary Movements: Exploring the Underlying Mechanisms Associated with Parallel Processing

Study 2 was published in *Psychological Research*

(see section Manuscripts Published in Peer-Reviewed Journals During the PhD Programme)

4.1 Introduction

Selective attention is among the most fundamental and important functions of the human brain (Driver, 2001). In 1958, Daniel Broadbent proposed that attention allocation was generally defined by the physical features of an environmental signal. Broadbent's filter model had enormous impact on the scientific world, given that its main postulate was that only relevant signals are processed by the brain. Broadbent's assertion was predicated on the fact that the brain has limited capacity to process sensory signals from multiple sources; thus, strong sensory signals from one's environment were hypothesised to force attention towards external influences. For example, the sound constituents of loudness and pitch can elicit rapid shifts of attention (see Lee et al., 2013), given that they are directly relevant to the survival of the organism (Walker, Bizley, King, & Schnupp, 2011).

The human cortex is able to process the physical features of a range of stimuli and initiate actions that are predicated on the stimulus relevance. The sound of an explosion nearby immediately reallocates one's attentional focus towards auditory pathways in order to initiate an action that mitigates any potential harm (Petersen & Posner, 2012). In such instances, auditory stimuli appear to initiate cascade reactions that activate brain regions (e.g., amygdala and hypothalamus) that are associated with survival functions (see LeDoux, 2012). Irrelevant stimuli, on the other hand, are routinely dismissed through a process of sensory blockage (Mysore & Knudsen, 2013). The blocking of such stimuli allows humans to focus more intently on task-relevant information, avoiding the influence of potential distractors that might compromise task performance (e.g., Garrison & Williams, 2013).

During the execution of movements, the brain attempts to select the most salient signals and duly allocate the most attentional capacity towards them in order to complete a given task successfully (Hutchinson & Tenenbaum, 2007). However, there are multifarious internal and external sensory cues during conditions of physical effort (Katsuki & Constantinidis, 2014). The muscles, heart, and lungs emit signals to the brain as a means by which to facilitate one's sense of exertion (Noakes et al., 2005). In order to cope with the prophylactic influences of interoceptive sensory cues, the brain needs to engage in dissociative strategies (e.g., directing attention to surrounding scenery). The reallocation of attentional focus towards task-unrelated information (e.g., an aesthetically-pleasing landscape) allows fatigue-related symptoms (e.g., limb discomfort) to remain outside of focal awareness and renders the execution of simple movements partially automatic (Kal, van der Kamp, & Houdijk, 2013; Lohse & Sherwood, 2012; McNevin, Shea, & Wulf, 2003). This is owing to the fact that interoceptive sensory cues are not sufficiently potent to increase the use of associative thoughts (Hutchinson et al., 2015). However, the execution of complex movements usually requires high levels of concentration and generally entails only mild symptoms of fatigue, meaning that attentional focus has to be entirely allocated to task-related information (e.g., target shooting performance; Pashler et al., 2001). In such instances, irrelevant stimuli need to be suppressed (Geng, 2014) or processed in such a way that task performance is not compromised (i.e., parallel processing; see Rejeski, 1985; Wilson et al., 2009).

Music-related interventions have been used in the field of exercise and sport as a means by which to promote the use of dissociative thoughts and improve exercise performance (see Karageorghis & Priest, 2012a, 2012b for review). However, the use of music is hypothesised to have a detrimental effect on motor performance if the exercise mode demands high levels of concentration. In such instances, the human brain attempts to partially suppress or parallel process potential distractors to enable the organism to engage with the task. The underlying mechanisms of parallel processing have been researched extensively in the field of visual sciences (see Thornton & Gilden, 2007 for a review), but remain uncharted during the execution of motor tasks (e.g., Bullock & Giesbrecht, 2014).

4.1.1 Processing of Potential Distractors

The human brain houses an extensive neural network that enables multifaceted connectivity across different areas, which leads to the manifestation of complex emotions and decisions (Bassett & Gazzaniga, 2011). The brain is capable of processing and suppressing a variety of signals (i.e., internal [e.g., muscle afferents] and external [e.g., music] sensory cues) in tandem; this organ does not function on a *stop-and-go* basis. In actuality, there is a constant flow of information between peripheral and central nervous systems (Hernández-Peón et al., 1961). The parietal lobe of the brain has been identified to be the region responsible for selecting the most salient signals and informing other areas about the relevance of the signal (see Yantis, 2008). However, other regions of the cortex such as the frontal lobe can also play a central role in the partial suppression of attentional distractors (Suzuki & Gottlieb, 2013). The frontal and parietal lobes are integrated (Brunetti et al., 2008) and appear to operate in tandem as a means by which to define which pieces of information are most relevant (Ptak, 2012).

The brain mechanisms associated with attentional shifts can be rendered more complex under exercise conditions when compared to a resting state; this is due to the fact that a larger proportion of the brain is active (Secher et al., 2008). In order to generate movement, the primary motor cortex has to send neural messages to the spinal cord, which subsequently causes skeletal muscles to contract. Concurrently, the brain needs to process interoceptive (e.g., muscle afferents; Pollak et al., 2014) and environmental (e.g., visual information; Hutchinson et al., 2015) sensory cues. Thus, attentional mechanisms bear substantial influence over the gamut of factors that underlie task performance (Lohse & Sherwood, 2012).

4.1.2 Rationale for Study 2

In 1985, Rejeski developed a theory predicated on Broadbent's (1958) idea (i.e., attention depends on the physical features of the signal) to explain the integrative processes that take place when individuals need to cope with internal (bodily) and external (environmental) cues during movement execution. Rejeski advanced the parallel processing theory, which posits that interoceptive signals compete for attention with external, environmental cues because the brain is limited in its capacity to process sensory information from multiple sources. Accordingly, even strong sensory signals, as previously proposed by Broadbent (1958), could be partially suppressed given that internal cues are deemed to be more relevant than external influences during the execution of movements. This theory has been tested extensively in the field of exercise science by use of music as an ecologically-valid stimulus that directs attention towards an external influence and ameliorates the effects of fatigue (see Karageorghis & Priest, 2012a, 2012b).

Subsequently, Tenenbaum (2001) suggested that attentional focus is moderated primarily by exercise intensity and complexity (e.g., Stroop test). His theoretical propositions advanced Broadbent's idea and introduced a number of moderators (e.g., exercise intensity and mode) through which attention could be influenced during the execution of movements. During exercise, individuals are able to focus outwardly if task-related factors (e.g., muscle acidosis) do not enter focal awareness. Highly-demanding motor tasks, in terms of intensity and/or complexity, have the potential to partially suppress task-irrelevant signals, such as environmental distractions. This is essentially a means by which attention can be guided inwardly.

Collectively, the theoretical contributions of Rejeski (1985) and Tenenbaum (2001) support the notion that sensory signals are processed by the brain in parallel channels, and that exercise intensity and complexity can moderate the degree to which attention is reallocated towards internal and external sensory cues. In the present context, the interaction of exercise intensity and complexity constitutes the “relevant signals” to which Broadbent (1958) was alluding. Accordingly, auditory distractions can disrupt task performance if the exercise mode and/or intensity demand high levels of concentration (Lavie, 2005). In such instances, the brain appears to parallel process potential distractors in order to enable the organism to fully engage with the task at hand (Geng, 2014). Put another way, attentional processes mediate the perception-action cycle as a means by which to facilitate movement execution (cf. Cutsuridis, 2013). These attentional processes also have a direct effect on decision-making functions, allowing the organism to execute a motor plan and sustain neural control of working muscles (Lohse & Sherwood, 2012; Lohse, Sherwood, & Healy, 2011).

Once an external stimulus enters focal awareness, it could potentially disrupt an action and thus force the organism to re-arrange the motor plan (e.g., Wood &Wilson, 2010). Parallel processing and attentional suppression mechanisms can prevent the detrimental effects of sensory distraction on voluntary control when the physical features of the stimulus are not overbearing (Quartana, Burns, & Lofland, 2007). Strong sensory signals (e.g., startling auditory stimuli), on the other hand, can override this attentional threshold, enter focal awareness, and force individuals to re-organise the task, in accord with the new situational demands imposed by the stimuli (Hommel, 2010).

4.2 Aim of Study 2

This was an exploratory study intended to further understanding of the neural systems that activate in response to auditory stimuli during the execution of attention-demanding tasks. It was hypothesised that highly demanding cognitive-motor tasks would guide attentional focus towards task-related information and reduce the processing of external influences to some extent. Parallel processing mechanisms were also hypothesised to prevent the disruption of the motor action and protect higher-order cognitive functions (i.e., reduced activity in the frontal lobe) against potential distractors (Suzuki & Gottlieb, 2013). An auditory stimulus was used to manipulate attention and thus assist in furthering understanding of the attentional processes that underlie movement execution. An event-related potential study was developed using a simple motor task (isometric ankle-dorsiflexion). Brain reconstruction analyses were used to identify the neural networks that activate to prevent sensory signals from entering focal awareness.

4.3 Event-Related Potential Analysis

Event-related potential experiments have been a common means to further understanding of attentional mechanisms associated with sensory stimulation (e.g., Popovich & Staines, 2015). Attentional responses occur for very short periods of time and researchers generally require high-temporal resolution techniques to acquire meaningful data (Light et al., 2010). Reallocation of attentional focus from one source of sensory information to another has been repeatedly linked to changes in the electroencephalographic waveform (e.g., Rapela et al., 2012; Spielmann et al., 2014). Luck et al. (2000) suggested that waveform changes caused by attention modulation might be moderated by situational demands and type of sensory information. For example, auditory distractions have been commonly associated with up-/down-modulations in the EEG waveform following ~300 ms of stimulus onset. It has been hypothesised that P3 (~350 ms) is primarily induced by stimulus-driven attentional processes that originate in the frontal cortex (Polich, 2007). Conversely, recent evidence indicates that up-modulations in P3 could also be associated with stimulus evaluation and decision-making processes (e.g., Twomey et al., 2015). In the context of Study 2, the reception of sensory stimuli during the execution of motor tasks might impose greater challenges for the brain and ERP components might differ owing to the amount of internal and external sensory information that needs to be processed in tandem.

4.4 Research Hypotheses

Muscle electrical activity. It was hypothesised that the auditory stimulus would not modulate the neural activation of the working muscle and voluntary control because the brain could easily process potential distractors during a simple cognitive-motor dual task (Caputo & Guerra, 1998; Geng, 2014). Participants were expected to partially inhibit the processing of extremely irrelevant information as a means by which to execute the task successfully. Simple auditory distractions are hypothesised to be not sufficiently challenging to compromise the force produced and possibly ineffective in modulating the electrical activity in the muscles. In such instances, a parallel processing mechanism could be identified using the premise that participants are able to sustain the muscle contraction at the required level regardless of the presence of auditory distraction.

Brain activity. When participants receive auditory stimulation at rest processing of potential distractors has been shown to occur at approximately 300 ms after the stimulus onset (Horváth, Sussman, Winkler, & Schröger, 2011; Polich, 2007). However, the reception of sensory stimuli during the execution of motor tasks might impose greater challenges for the brain. In such instances, the evoked response could be influenced by task-related factors. It was hypothesised that the presence of task-related factors, such as interoceptive sensory cues and visual feedback, would up-regulate the electroencephalographic waveform at ~300 ms following stimulus onset to a greater degree than a no-exercise condition (cf. Berti & Schröger, 2003). In order to cope with the detrimental effects of auditory distractions, participants would need to parallel process the stimulus in such a way that it does not enter focal awareness and disrupt task performance. Furthermore, the parietal and frontal lobes have been implicated in the processing of attentional distractors (Suzuki & Gottlieb, 2013).

The parietal and posterior temporal regions of the cortex were hypothesised to assume a similar function during the execution of isometric motor tasks performed at low intensity. Differences in the frontal and parietal lobes are thought to be associated with the brain's electrical activity, which oscillates during the processing of attentional distractors when individuals execute attentionally demanding tasks (see Foxe & Snyder, 2011 for a review).

4.5 Method

4.5.1 Participants

The institutional ethics committee of the first four authors approved the study. Undergraduate and postgraduate students were contacted via email and invited to participate. Those who expressed an interest were subjected to an initial survey to capture key demographic details (e.g., age and gender). The inclusion criteria were that potential participants were healthy and right-handed. Sample size was calculated by use of G*Power 3.1 (Faul et al., 2007) and based on a large effect size of sensory modulation on attentional focus ($f = 1$; Hutchinson et al., 2015), 15 participants were required. Four additional participants were recruited to protect the study against participant attrition and deletions due to outliers. Accordingly, the sample comprised 19 participants (9 women and 10 men; $M_{\text{age}} = 26.4$, $SD = 3.6$ years; $M_{\text{height}} = 170.4$, $SD = 9.5$ cm; $M_{\text{weight}} = 67.1$, $SD = 11.6$ kg).

4.5.2 Experimental Procedures

A researcher initially explained the psychometric measures and addressed any queries from participants. A researcher cleaned the participant's legs and face with preparation pads saturated with 70% isopropyl alcohol. Thereafter, five EMG surface electrodes (Goldy Karaya Gel electrodes, 28 mm diameter, silver/silver chloride, Arbo, Henley Medical, Stevenage, UK) were placed on the participant's right leg, and 64 EEG electrodes (Quik Gel; Compumedics Neuromedical Supplies) were placed on the participant's scalp. Each participant was asked to perform isometric ankle-dorsiflexion contractions at 20% of their maximal voluntary contraction (MVC).

A force transducer (Model 615, S-Type Load Cell, Tedea-Huntleigh Electronics, UK, max 100 kg) was used to measure the foot pressure produced. The participant was able to observe the strength line (Spike 2 v4.11; Cambridge Electronic Design) as a means to apply the required force. The MVC was assessed three times in order to identify the peak value prior to commencement of the experimental exercise bouts. The participant was asked to perform a maximal ankle-dorsiflexion contraction for 5 s and there was a 2-min interval in between each attempt in order to negate the effects of fatigue on task performance. The force signal was amplified 1000 times, low-pass filtered at 2 KHz, and digitised at 1 KHz.

The experiment consisted of five sets of 30 trials (total = 150 trials). Each trial consisted of 10 s of contraction followed by 10 s of rest and each participant was instructed to control the length and intensity of contraction by following the time and strength line, respectively. The sets could only recommence when the participant fully recovered, which was objectively assessed by means of the MVC and level of limb discomfort (CR10; Borg, 1982). A short musical excerpt (2.8 s of the chorus of *Fancy* by Iggy Azalea, feat. Charli XCX. 95 bpm, 75 dBA) was used as an auditory distraction and to *possibly* degrade task performance levels. The musical excerpt was delivered by use of noise-cancelling headphones (Sennheiser HD201). Two experimental conditions were administered: Auditory distraction (AD; auditory stimulus applied during exercise) and stimulus-only (SO; auditory stimulus applied at rest), in addition to a control condition (CO; no intervention). During the first 20 trials of the set, AD and CO were randomised, as well as the moment at which AD started, which varied across 3, 4, and 5 s following initiation of the contraction. This approach was adopted in order to circumvent the potential confound of expectation (Aue et al., 2009). During the last 10 trials of the set, SO was used at random times as a means by which to isolate effects of the auditory stimulus that were not associated with exercise attentional shifts. E-Prime 2.0 was used to design the present experiment and deliver the auditory stimulus. The electronic devices were synchronised by use of a parallel port and the stimulus triggered an immediate mark in the EEG signal; the stimulus was subsequently used to epoch and average the trials (see 4.5.3 Data Analysis section).

Electromyography. Muscle electrical activity was measured by use of EMG, which identifies the electrical potential generated by muscle cells. Surface electrodes were placed on the tibialis anterior and lateral gastrocnemius in accord with the recommendations of the SENIAM project (Stegeman and Hermens, 1999). The ground electrode was placed on the lateral malleolus. The EMG signal was amplified 1000 times, low-pass filtered at 20 Hz, and digitised at 1 KHz.

Electroencephalography. Brain electrical activity was assessed by means of a 64-channel Quik-cap. The 64 Ag/AgCl electrodes were attached to the participant’s scalp, based on the international 10–20 system and filled with Quik gel (Compumedics Neuromedical Supplies). The mastoids were used to digitally reference the brain electrical signal. Two pairs of electrodes captured the horizontal and vertical eye movements. Impedance was kept below 5 kΩ. The brain electrical signal was amplified at a gain of 1000. Online bandpass filters 0.1 – 100 Hz were used to avoid electrical interference and muscle artefacts. The signal was acquired through the use of the software Scan 4.4 acquisition and digitised at 1000 Hz by using Synamps amplifier (Compumedics Neuroscan).

4.5.3 Data Analysis

Spike2 (v4.11; Cambridge Electronic Design) was used to obtain time-domain indices (RMS) from the muscle electrical signal, which was initially filtered, rectified, and smoothed (Altimari et al., 2012). The RMS value obtained from the EMG data is representative of the motor units necessary to produce a given level of contractile force (Farina et al., 2002). The electrical activity in the anterior tibialis was used to quantify the influence of auditory distraction on motor unit recruitment during each trial.

Bad EEG electrodes were visually checked and those not working reliably were discarded before epoching methods. Independent component analysis was used to remove eye blinks by tracking down the activity of vertical eye movements (Zhou & Gotman, 2009). The raw data were imported into the database by epoching the original file into 4.5-s windows (.5 s before and 4 s after the auditory stimulus onset). The signal was DC-offset corrected in order to prevent the influence of voltage imbalance problems. Subsequently, the electrical signal in the brain was submitted to bandpass filters 0.5–30 Hz, 24 dB/octave and the time-amplitude signals were averaged for each experimental condition (i.e., grand average). The head model was computed through the use of OpenMEEG (Gramfort, Papadopoulo, Olivi, & Clerc, 2010) based on the EEG cap that was used. The source of the brain electrical signal was reconstructed by applying the Minimum Norm Method (Pinto & Silva, 2007). The source orientation was unconstrained, meaning that each vertex of the cortex surface contained three dipoles with orthogonal directions. This anatomical observation is based on the premise that neurons are not only organised in macro-columns perpendicular to the cortex surface. The signal-to-noise ratio was conventionally set at 3. The computed sources were averaged across participants and the Mindboggle Atlas (Klein & Hirsch, 2005) was used to identify the brain regions associated with the activity.

The source reconstruction was initially performed using full-frequency spectrum analysis. The results are presented for group data ensemble-averaged waveforms. A magnitude threshold was used to localise the sources of the brain electrical activity at approximately 35% of the peak (Jain et al., 2013). The EEG procedures were performed by use of Brainstorm (Tadel et al., 2011), which is freely downloadable under the GNU public license (http://neuroimage.usc.edu/brainstorm). The EMG and EEG signals were compared using a paired-samples *t* test (controlled over time dimensions) on Brainstorm, and the *p* value thresholds were corrected dynamically for multiple comparisons using the Bonferroni method. This method allowed the author to compare the entire epoch across conditions and delineate the overall dimension of the waveform in the averaged samples (i.e., all peaks).

4.6 Results

4.6.1 Electrical Activity in the Muscle

The electrical activity in the muscles produced by participants was used as an index of attentional distraction. Figure 4.1 serves to illustrate three experimental trials in the absence and presence of the auditory stimulus and the grand average for both conditions, where EMG data were compared by use of paired-samples *t* tests. Results indicated that no statistical differences existed between AD and CO ($p > .05$), meaning that the auditory stimulus was not sufficient to have a detrimental effect on motor unit recruitment as hypothesised herein (see Figure 4.1). A magnifying glass approach was used to zoom in on the force produced and the electrical activity in the anterior tibialis at the moment the auditory stimulus was introduced. The electrical activity in the anterior tibialis was not affected by the attentional distraction. No statistical differences existed between AD and SO when the exercise trials were epoched and averaged.

4.6.2 Electrical Activity in the Brain

In comparing AD and SO, the author expected to identify the electrode sites that activated in response to the processing of auditory distractions during the execution of a motor task. Accordingly, task-related information (i.e., pertaining to control and execution) was the only methodological factor responsible for inducing statistical differences in the EEG waveform pattern. Statistically significant differences were identified in the left frontal, central, central parietal, right parietal, and parietal-occipital regions of the cortex (Figure 4.2; $p < .05$). A very similar EEG waveform pattern was identified in the right posterior/central

(CPZ, CP2, CP4, CP6, TP8, PZ, P2, P4, P6, P8, POZ, PO4, PO6, PO8, and OZ) and anterior (AF3, F5, F3, F1, Fz, F2, and FC2) electrodes. Statistically significant differences between AD and SO occurred approximately .360 s after the stimulus onset and are possibly associated with the attentional demands imposed by sensory stimuli during the execution of motor tasks. The presence of task-related factors modulated N2 at .368 s after the stimulus onset. The signal amplitude in AD remained positive at approximately .360 s, while a sharp decrease was identified in the absence of muscular contractions (SO). The evoked potentials are presented in Figure 4.3 for some of the electrode sites in which statistical differences were identified between AD and SO.

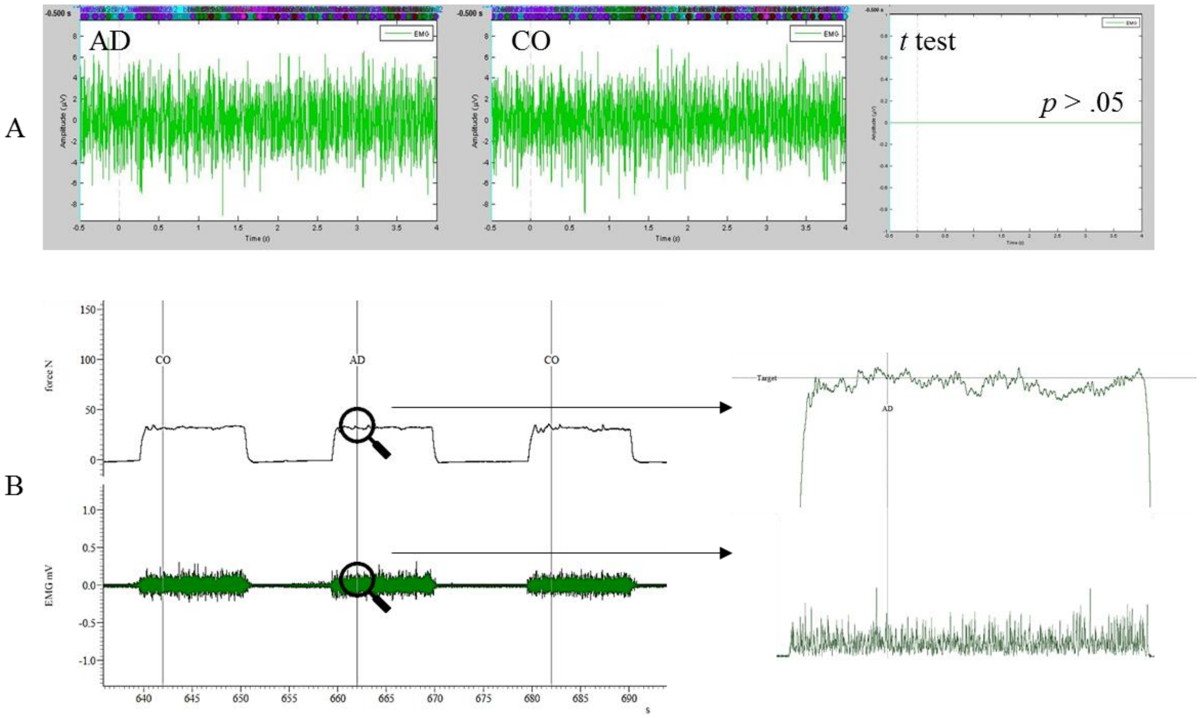


Figure 4.1. Comparison of EMG activity between AD and CO. *Note.* AD = Auditory distraction; CO = Control; Row A = Grand average waveforms compared between AD and CO; Row B = Force and raw EMG data of participant 1 across three exercise trials.

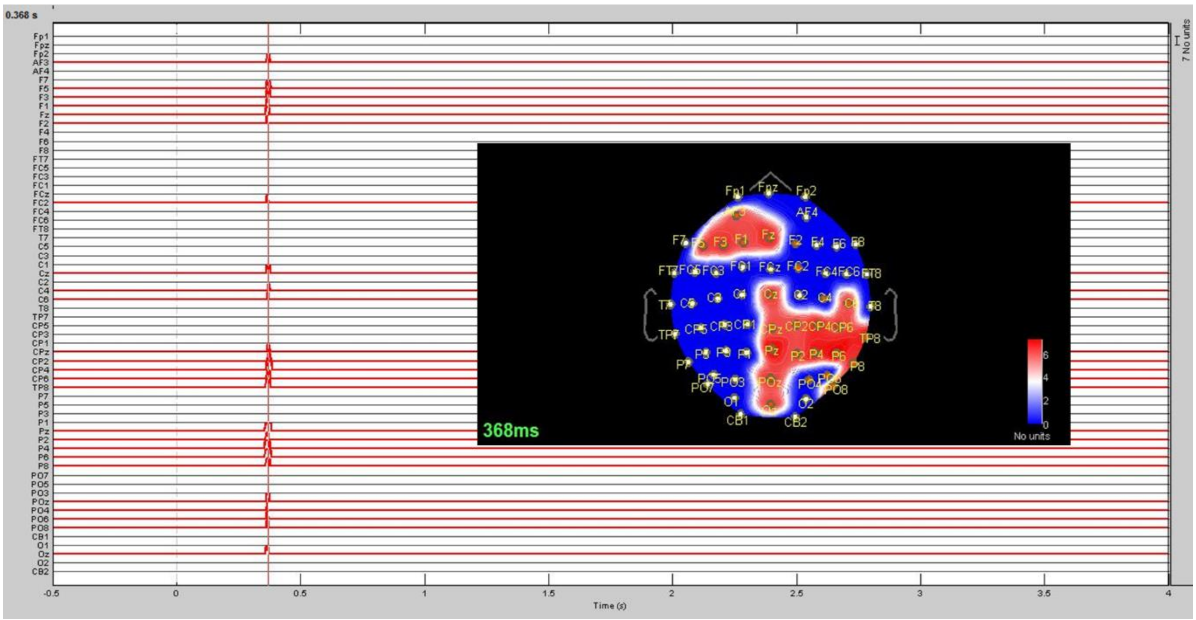


Figure 4.2. Paired-samples *t* test comparing AD and SO. *Note.* Spikes in the graph indicate statistically significant differences between conditions. A 2-D topographical map was created to anatomically localise the differences on the cortex surface. AD = Auditory distraction; SO = Stimulus-only.

The distributed current source maps were reconstructed at .368 s ($p < .05$). The 2-D topography maps and estimated sources represent the group-averaged data. The sources of the brain electrical signal indicated a conspicuous difference between anterior and posterior regions of the cortex. The presence of task-related factors increased the activity of the inferior and posterior parietal gyri at .368 s after the onset of the stimulus. The Mindboggle Atlas was used to locate and identify the brain regions that activated in response to attentional processing. Activity in the left superior frontal gyrus was evident when the stimulus was delivered in the absence of muscular contractions. Task-related factors reallocated the brain activity from left anterior to right and central posterior regions of the brain at .368 s after the stimulus onset (see Figure 4.4).

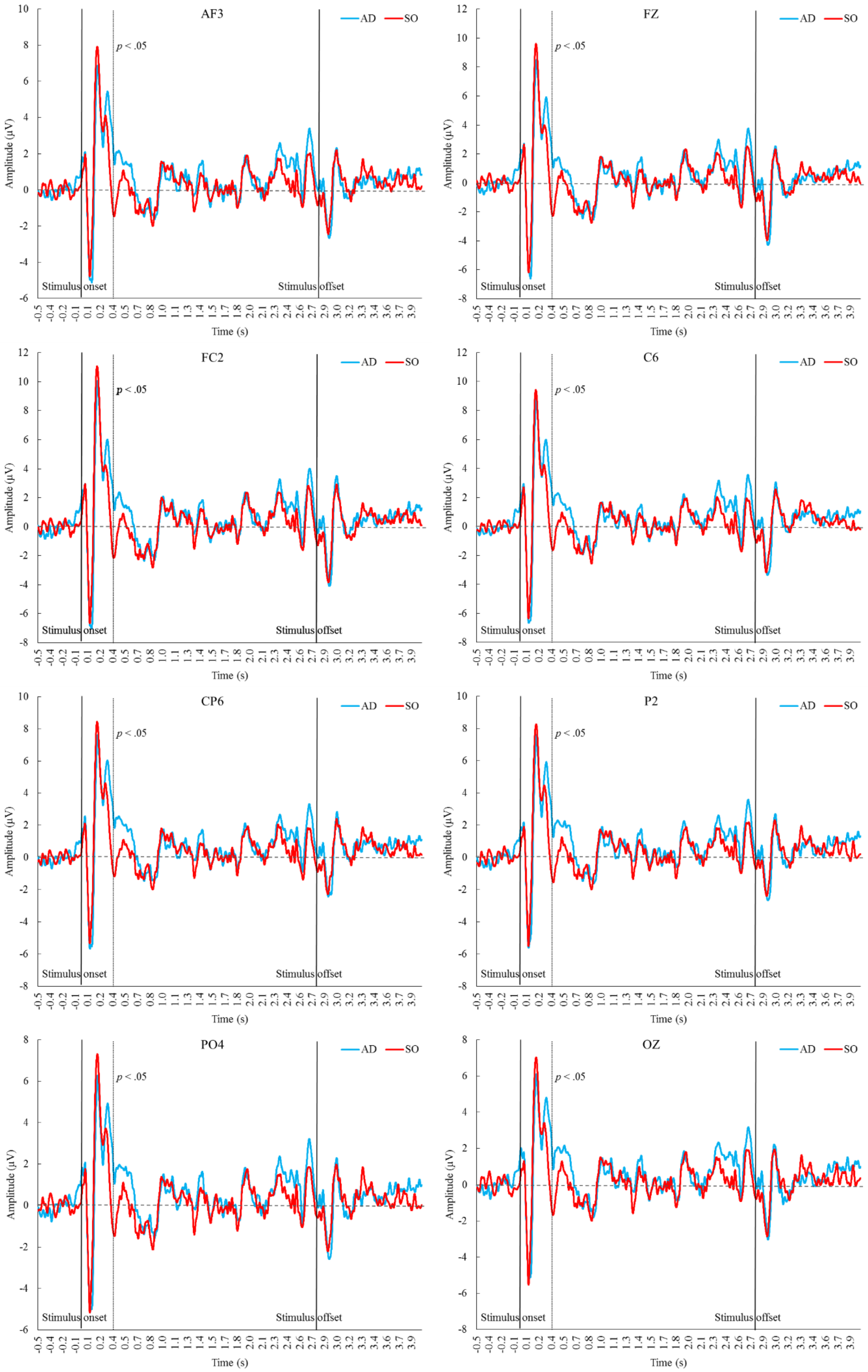


Figure 4.3. Grand average waveforms recorded at AF3, Fz, FC2, C6, CP6, P2, PO4, and Oz electrode sites presented for AD and SO. AD = Auditory distraction; SO = Stimulus-only.

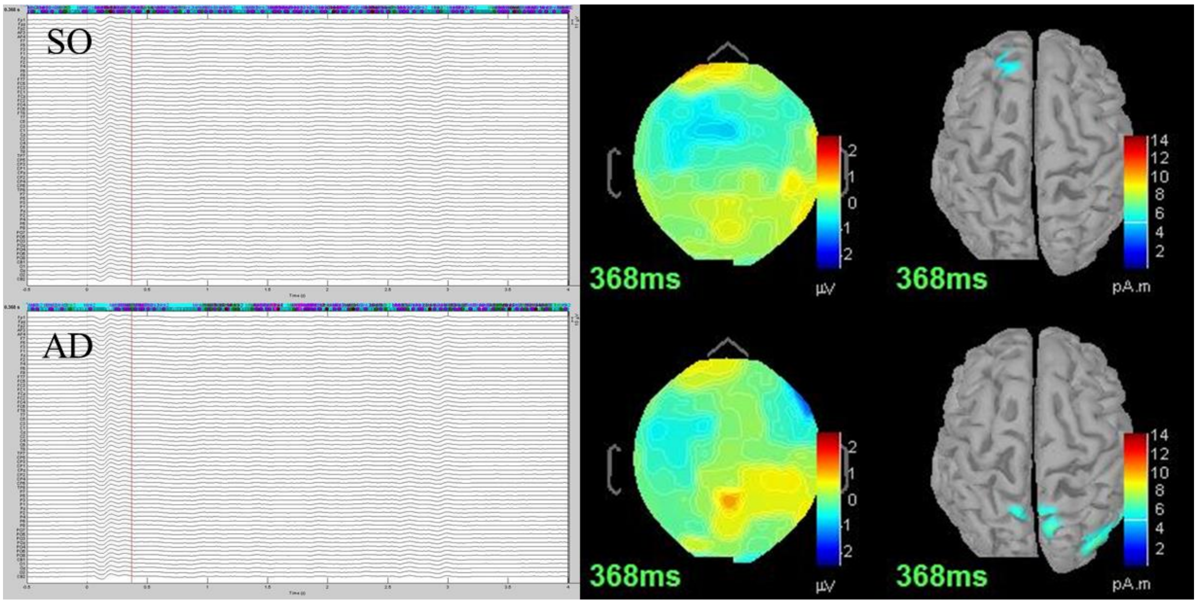


Figure 4.4. The reconstructed sources of the brain electrical activity for AD and SO at .368 s. Mindboggle Atlas was used to identify active brain regions. AD = Auditory distraction; SO = Stimulus-only.

4.7 Discussion

This experiment attempted to further understanding of the neural systems that activate in response to auditory stimuli during the execution of an isometric ankle-dorsiflexion task. A brief musical excerpt was used to draw participants' attentional focus towards task-irrelevant stimuli. In line with Rejeski's (1985) conceptualization, the author expected a parallel processing mechanism to emerge given that participants were required to monitor a range of task-relevant factors, such as the force generated and work duration (10 s of contraction and rest). Accordingly, the alerting system (i.e., immediate reallocation of attentional focus to the auditory stimulus; Fan et al., 2005) would influence selective attention. Nonetheless, parallel information processing was expected to have immediate bearing over attentional focus in order to prevent likely detriments in neural activation of the working muscles.

The present results appear to uphold the veracity of Rejeski's (1985) and Tenenbaum's (2001) theoretical propositions, as parallel channels partially suppressed the processing of task-irrelevant signals, allowing participants to focus more intently on the task at hand. Moreover, the findings indicate that exercise complexity and intensity could have similar effects on selective attention, given that a distractive auditory stimulus was not sufficiently potent to disrupt task performance. In such instances, the frontoparietal network appears to activate at ~360 ms following stimulus onset. This is a means by which task-unrelated signals can be blocked and the neural activation of working muscles can be maintained. Nonetheless, auditory stimuli could have a more potent effect on the execution of low-demanding cognitive motor tasks such as self-paced walking. Everyday tasks performed at a light intensity only require partial awareness to be executed successfully, meaning that environmental sensory stimuli have a strong bearing on attentional focus, which subsequently forces individuals to re-arrange the motor plan (e.g., Haga et al., 2015).

According to Broadbent's (1958) theoretical proposition, low-demanding cognitive tasks leave greater capacity for parallel processing and thus there is a reduced likelihood of task disruption to a primary task. Interestingly, recent evidence indicates that even walking tasks can be negatively affected by the presence of environmental distractions (e.g., smartphones), leading to detriments in task performance (Haga et al., 2015; Vredeveldt & Perfect, 2014). This is predicated on the notion that low-demanding cognitive tasks only require partial awareness to be executed, leaving scope for environmental distractions to guide attentional focus towards task-irrelevant cues. Attentional shifts that are prompted by the presence of internal and external sensory cues appear to force the prefrontal cortex to inhibit inappropriate actions and maintain the motor plan. Nonetheless, this proposed mechanism does not appear to prevent auditory stimuli from entering focal awareness and disrupting task performance (e.g., during walking; Takeuchi, Mori, Suzukamo, Tanaka, & Izumi, 2016).

4.7.1 Electrical Activity in the Muscle

The electrical activity produced by the anterior tibialis was assessed in order to identify the likely negative effects of the auditory stimulus on neural activation and voluntary control. Electrical activity in the muscle was used as the primary index of attentional distraction given that the experimental task only required participants to contract the anterior tibialis at 20% of MVC. Minimal differences caused by attentional distractions should have elicited immediate changes in the neural control of movements with subsequent influence on EMG activity. Accordingly, a hypothetical decrease in the recruitment of motor units (i.e., measured by RMS) caused by the auditory stimulus would indicate that participants were only partially capable of processing task-irrelevant information during the execution of an isometric ankle-dorsiflexion task performed at low intensity (Petersen & Posner, 2012). However, EMG signals were not influenced by the auditory stimuli, indicating that the immediate electrical signals evoked by the stimuli were rapidly inhibited via the mechanism of attentional suppression (Geng, 2014) or parallel processed by alternative brain networks (Caputo & Guerra, 1998).

The number of task-related factors can also influence the attentional system (Lavie et al., 2004). For example, if the motor task involves fine motor control of movements and high levels of concentration, even insignificant sensory stimuli can compromise the neural activation of the working muscles (see Bernstein & Bernstein, 2015). Fortunately, the attentional system is trainable and humans have developed psychological techniques that normally involve the control of physiological indices as a means by which to avoid the detrimental effects of task-irrelevant factors on task performance (Bernier, Codron, Thienot, & Fournier, 2011; Desbordes et al., 2012). Tenenbaum (2001) suggested that exercise intensity can moderate the processing of environmental sensory stimuli. For example, whole-body exercises performed at high intensity force attentional focus towards interoceptive sensory cues and increase the prevalence of associative thoughts. In such instances, task-irrelevant factors remain outside of focal awareness because the brain has limited capacity to process signals from multiple sources. It is noteworthy that the execution of repetitive movements appears to reallocate the organism’s attentional resources in accord with the relevance of both internal and external sensory stimuli; a potential confound that Broadbent (1958) did not contemplate in his original theoretical contribution.

4.7.2 Cerebral Responses

Electrical activity in the brain was compared primarily between AD and SO; thus, only task-related factors could be responsible for the differences in the evoked potential. Luck, Woodman, and Vogel (2000) pointed out that attentional processes would only suppress perceptual pathways if the sensory system is overloaded. In Study 2, a highly demanding cognitive-motor task was used as a means by which to guide attentional focus towards task-relevant information. Statistically significant differences were identified in the left frontal, frontal-central, central, central-parietal, right parietal, parietal-occipital, and occipital regions of the cortex. The presence of task-related factors (e.g., executing the motor task and monitoring the level of force produced) modulated N2 at .368 s after the onset of the stimulus. Such differences might be attributed to a parallel processing mechanism that initially manifested in the superior and inferior parietal regions of the cortex (Corbetta & Shulman, 2002; Katsuki & Constantinidis, 2014; Lee et al., 2013). No statistical differences were identified *during* the stimulus cessation; I contend that this cerebral response occurred owing to the fact that the auditory stimulus had already been partially suppressed approximately .360 s after the stimulus onset (Berti & Schröger, 2003; Polich, 2007). Therefore, the stimulus cessation would not have differed between AD and SO.

The high or low activity in the parietal lobe is primarily influenced by the number of task-related factors (Yin et al., 2012). The control of produced force and time duration serve to reallocate one’s attentional focus to task-related information. Irrelevant auditory stimuli are therefore supposed to force one’s attentional focus towards sensory pathways. This reallocation of attentional focus could possibly explain the differences in N2. Time-domain analysis indicated that the presence of task-related factors prevented the sharp decrease of the EEG activity after approximately .360 s.

Auditory distractions have been commonly associated with changes in P300. Previous authors have suggested that up-/down-modulations in the time-series waveform that occur at ~350 ms following stimulus onset are induced primarily by stimulus-driven attentional processes originated in the frontal cortex (Berti & Schröger, 2003; Polich, 2007). There is evidence emerging to suggest that up-modulations in P300 reflect a direct response to stimulus evaluation and decision-making processes (see Nieuwenhuis et al. 2005; Twomey et al. 2015). P300 amplitude tends to increase during NoGo tasks (i.e., requiring self-control to elicit successful outcomes) as a form of response inhibition (Salisbury, Griggs, Shenton, & McCarley, 2004), and similar responses have been successfully replicated in social contexts (see Nash et al., 2013). Accordingly, the neural faculties and cognitive processes associated with up-/down-modulations in P300 appear to be far more complex than previously thought. The results of Study 2 are in line with the extant literature (Linden, 2005; Wang, Zheng, Huang, & Sun, 2015). It is speculated that changes in AD could have been caused by the presence of task-related factors, such as afferent feedback from working muscles and performance-related information, such as visual feedback (Vredeveldt & Perfect, 2014). Up-regulation of the EEG waveform at ~360 ms following stimulus onset might be indicative of a swift decision strategy to reduce processing of potential distractors (for review, see Linden 2005). It is hypothesised that up-modulations at ~360 ms following stimulus onset could represent neurophysiological mechanisms that underlie Rejeski’s (1985) and Tenenbaum’s (2001) theoretical propositions. This electrophysiological response would partially block task-irrelevant information from entering focal awareness and thus causing disruption to exercise performance.

It is hypothesised that the parietal lobe initially evaluated and successively reduced the processing of irrelevant stimuli such as a distracting musical excerpt (cf. Suzuki & Gottlieb, 2013). The frontal lobe possibly received the signals from the parietal regions of the cortex and initiated appropriate action (i.e., stimulus interpretation; see Chadick & Gazzaley, 2011; Prado et al., 2011). Reduced activity in the left frontal regions induced by the presence of task-related factors (see Figure 4.3) is believed to be caused by the previous suppression of irrelevant information in the parietal lobe. In summary, motor tasks performed in the presence of sensory stimuli appear to activate the parietal-frontal pathways. The parietal cortex functions as an informant in the parietal-frontal neural connection, but also performs initial evaluation of sensory signals (Bisley & Goldberg, 2010) and thus may partially suppress or enable future processing in the frontal lobe, not only at rest, but also during exercise-related situations.

4.7.3 Limitations of Study 2

It was hypothesised that statistical differences at .368 s after stimulus onset were possibly associated with parallel processing-related mechanisms (cf. Rejeski, 1985) that activate as a means by which to reduce the influence of attentional distractions on motor control. The present experiment was designed to mitigate the influence of potential confounds such as arousal-related responses caused by the execution of movements (Svebak & Murgatroyd, 1985). Three methods were applied to isolate attention-related mechanisms from arousal-induced changes: (a) use of light intensity exercise bouts performed at 20% of MVC for short periods of time and separated by 10-s rest periods, (b) delivery of an auditory stimulus at random times after 3, 4, or 5 s of the contraction onset, and (c) delivery of an auditory stimulus at the end of block sessions (i.e., after 20 contractions). Therefore, arousal-induced modulations should bear minimal influence upon ERPs.

The author decided to use *Fancy* by Iggy Azalea as a means by which to demonstrate that real exercise modes could be partially compromised by external sensory cues such as the chorus of a popular song. Interestingly, the stimulus was fully inhibited/parallel processed and no physiological effects were identified. However, affective and perceptual responses were not analysed in Study 2; I believe that the repetition of the auditory stimulus might have caused negative affective responses during the execution of isometric motor tasks. Accordingly, the brain's electrical activity would have been influenced by such negative psychological responses (independent interference). The repetitive nature of event-related potential studies is a common problem in neuroscience (Picton et al., 2000), but the author attempted to select a reasonable number of trials that would facilitate the acquisition of meaningful data but also avoid the negative influence of extreme repetition.

It should also be highlighted that the experiment did not include a manipulation check by which to gauge participants' notion of perceived relevance of the task-demand characteristics and auditory stimuli that were presented in the experimental conditions. Furthermore, the motor task used in Study 2 does not represent a real-world mode of exercise such as cycling or running. Whole-body modes of exercise usually involve an extensive control of movements (Novacheck, 1998) and could potentially involve different brain networks, generating dissimilar ERPs.

Changes in exercise intensity and complexity could also induce different ERPs. However, it is important to point out that this is the first study to address the brain mechanisms that underlie parallel attentional processing during exercise and therefore the control of external interferences such as a complex motor tasks and powerful muscular contractions should be maximised. Future research might aim to replicate the design of the Study 2 in order to investigate the brain networks that activate during the execution of exercise performed at moderate and high intensities (i.e., fatiguing tasks). Such work would extend the neuroscientific examination of Rejeski's (1985) and Tenenbaum's (2001) theoretical propositions.

4.8 Conclusions

Study 2 adopted a theory-based approach to address the attentional neural systems that activate in response to potential distractors during the execution of an isometric task. The findings appear to support Rejeski's (1985) and Tenenbaum's (2001) models given that parallel channels partially inhibited the processing of environmental sensory cues, thus allowing participants to execute the motor task. The recruitment of motor units in the anterior tibialis was not affected by external sensory cues, meaning that processing of auditory distractions was possibly suppressed during the execution of a demanding motor task. This neural faculty might have been developed through the ages as a means by which to prevent the influence of task-irrelevant factors on motor performance and enable humans to maintain the control of a task. Motor tasks performed in the presence of irrelevant sensory stimuli appear to activate the parietal-frontal network (Fan et al., 2005) as indicated by source reconstruction analysis. The presence of task-related factors (e.g., need to execute movements at precise intensities) during a highly demanding cognitive-motor task moderated the sharp decrease of EEG activity through the entire brain surface after approximately .360 s of the onset of the stimulus. This neurophysiological response could be associated with a decision-making strategy to reduce processing of external influences and thus prevent the disruption of task performance.

Chapter 5: Effects of Auditory Stimuli on Electrical Activity in the Brain During Cycle Ergometry

Study 3 was published in *Physiology & Behavior*

(see section Manuscripts Published in Peer-Reviewed Journals During the PhD Programme)

5.1 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 (Boutcher & Trenske, 1990; Jones et al., 2014). Music-related interventions have been widely used in a range of contexts and exercise modalities such as running (Terry, Karageorghis, Mecozzi Saha, & D'Auria, 2012) and swimming (Karageorghis et al., 2013). 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; Karageorghis & Jones, 2014). 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 Bigliassi, 2015). However, the cerebral mechanisms that underpin the effects of environmental distractions on psychophysiological parameters during exercise remain unclear.

5.1.1 Music: From the Brain to the Heart

The effects of music-related interventions on brain activity have been studied in non-exercise-related settings (e.g., Koelsch, 2011; Shahabi & Moghimi, 2016). 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 Zatorre & Salimpoor, 2013). The brain appears to process music through a hierarchical sequence of neural events (Peretz et al., 1998). 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 (Baumgartner et al., 2006; Koelsch, 2014). The emotions elicited by music are characterised by an idiosyncratic response pattern (Juslin, 2013). In other words, an individual’s response to a piece of music is partly governed by personal factors such as sociocultural background and pre-existing mood.

5.1.2 Exercise and Brain Activity

The effects of physical exercise on brain activity have been investigated extensively (e.g., Popovich & Staines, 2015; Den’etsu Sutoo & Akiyama, 2003; van Praag, 2009). 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., Sutoo & Akiyama, 1996). Interestingly, the examination of the brain function during physical tasks has been conducted relatively recently (Fumoto et al., 2010), because limb movements and muscular contractions usually elicit artefacts in the biological data that severely compromise its quality (Kline et al., 2015; Thompson et al., 2008). With the benefits afforded by technological advances, researchers are now able to investigate the brain during exercise (e.g., Enders et al., 2016). The modulation of brain frequencies has been examined extensively and linked to diverse cognitive processes (e.g., Luck et al., 2000), sensory stimuli (e.g., Sammler et al., 2007), and physical tasks (e.g., Gennaro & de Bruin, 2018; Schneider et al., 2010).

Using a stationary isometric exertion task in combination with a traditional EEG system, Bigliassi et al. (2016a) demonstrated that environmental sensory cues serve to down-regulate low-frequency waves (i.e., theta) in the frontal regions (F8 electrode site) and up-regulate 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 hypothesised 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 towards external influences and make the execution of movements reflexively controlled by the central motor command (i.e., precentral and paracentral gyri; Zénon et al., 2015), a mechanism that has been coined as *partial trance* (Study 1).

5.1.3 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 (Gandevia, 2001) 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 (McCormick, Meijen, & Marcora, 2015; Pageaux, 2014). 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 (McCormick et al., 2015; Pageaux, 2014). The greater signal output emitted by the brain is also hypothesised to produce larger corollary discharges (efference copies) to areas of the brain associated with perceptions of effort (Pageaux, Marcora, Rozand, & Lepers, 2015). This physiological response appears to be consequent to the large proportion of working muscles that characterise whole-body modes of exercise (Marcora, 2009).

Afferent feedback from working muscles increases fatigue-related sensations during exercise (Pollak et al., 2014) by reallocating one's attentional focus towards task-related information (i.e., indirect effect determined by selective attention; see Bigliassi, 2015). Therefore, exertional responses are simply active creations of the human brain (Rejeski, 1985); 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 towards 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 (Hutchinson et al., 2015; Jones et al., 2014). The underlying mechanisms of attention reallocation during exercise are related to the fact that dissociative thoughts (i.e., focusing outwardly towards environmental cues) induce a more restful state (e.g., meditation), that renders the exercise more automatic and unconscious (Karageorghis & Jones, 2014); thereby reducing perceived exertion and enhancing pleasure.

5.2 Aim of Study 3

For a period spanning over a century, researchers have scrutinised the effects of music using a diversity of exercise modalities (Ayres, 1911; Stork et al., 2015). Musical components have been thoroughly investigated (Bishop et al., 2007; Bood et al., 2013; Fritz et al., 2013) and conceptual frameworks developed (e.g., Karageorghis, 2016). However, the neural underpinnings of music-related interventions during real-life exercise modes (e.g., cycling) are relatively unchartered waters for investigators. Study 3 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.

5.3 Research Hypotheses

The execution of whole-body modes of exercise in the presence of music is hypothesised to increase the number of dissociative thoughts and induce a more positive affective state (Hutchinson et al., 2015; Stork & Martin Ginis, 2017). Music is also hypothesised to ameliorate the effects of fatigue-related symptoms during exercise performed at light-to-moderate-intensities (Karageorghis, 2017). In turn, these exertional responses (e.g., increase of limb discomfort) modulate the activity of the autonomous system during exercise (Sarmiento et al., 2013). 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 (Pageaux, 2014). Therefore, sensory stimuli are hypothesised 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; Ekkekakis, 2003), because mechanoreceptors strongly redirect the outflow of blood pumped by the heart to the working muscles (De Meersman, Zion, Weir, Lieberman, & Downey, 1998) and generate numerous electrical outputs to the brain which, in theory, force attentional focus towards fatigue-related sensations (Karageorghis & Jones, 2014; Rejeski, 1985).

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 (Bigliassi et al., 2016a). 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 towards pleasant environmental cues, and optimise the neural activation of working muscles; thus inducing a more autonomous control of movement (Bigliassi et al., 2016b).

5.4 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 characterise 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 Study 3 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.

5.4.1 Participants

The sample size required for the present experiment was calculated using G*Power 3.1 (Faul et al., 2007). Results of the study by Lim, Karageorghis, Romer, and Bishop (2014) were used as group parameters to estimate the effect size. It was indicated that 18 participants would be required ($d = .71$; $\alpha = .05$; $1 - \beta = .80$). 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 and nationality in addition to 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.

5.4.2 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 centres and thus represented an ecologically valid exercise mode. Moreover, the author was 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.

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; Warburton et al., 2011). The psychological measures (see 5.4.5 Perceptual and Affective Measures section) were also presented at this juncture as a familiarisation 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 familiarise them with the laboratory/experimental procedures and establish VT. During the experimental phase, this physiological index was used to determine the relative exercise intensity.

Participants pedalled at 50 W and the exercise intensity was increased by 25 W every 3 min (Karapetian, Engels, & Gretebeck, 2008) up to 75% of maximal heart rate (~145 bpm) estimated by use of the age-predicted maximal heart rate equation (i.e., 208 - 07 x age; Tanaka, Monahan, & Seals, 2001). VT was expected to occur at a heart rate of ~135 bpm in healthy young participants (see Lim et al., 2014). A heart rate monitor (V800 Polar; H7 Polar strap; Boudreaux et al., 2018; Giles, Draper, & Neil, 2016) 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 nonlinear domain (e.g., standard deviation 1 [SD1; short-term variability]) analyses were applied to detect VT through the use of deflection points of HRV (see Karapetian, Engels, & Gretebeck, 2008).

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 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 randomised 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 Figure 5.1).

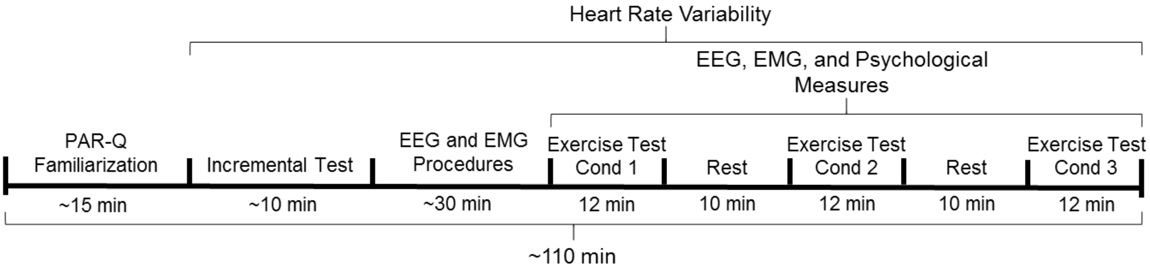


Figure 5.1. Diagrammatic representation of experimental procedures for which conditions were randomised and counterbalanced. *Note.* PAR-Q = Physical Activity Readiness Questionnaire; EMG = Electromyography; EEG = Electroencephalography; Cond = Condition (control, audiobook, or music).

5.4.3 Music Selection

The author 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 towards auditory pathways, evoke positive emotional responses, and assuage the mild effects of fatigue-related symptoms (Karageorghis & Priest, 2012a, 2012b). 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 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 (Model 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 (Karageorghis, Jones, & Stuart, 2008).

5.4.4 Audiobook Selection

Alice's Adventures in Wonderland (Carroll, 1865) 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 similarly employed at the very end of the experiment to identify the degree to which participants liked the AB.

5.4.5 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). Selective attention was assessed by use of Tammen's (1996) single-item attention scale (SIAS). 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; Hardy & Rejeski, 1989). This is a psychological instrument that examines the hedonic tone of emotional responses, and has been used extensively in exercise science (e.g., Dasilva et al., 2011; Karageorghis et al., 2010). Perceived activation was assessed using the Felt Arousal Scale (FAS; Svebak & Murgatroyd, 1985) and tapped core affect intensity according to Russell's (1980) circumplex model of affect. Perceived exertion was assessed using Borg's (1982) RPE scale, which was developed to assess exertional responses during exercise. For each trial, the psychological instruments were administered in the same order (1st SIAS, 2nd RPE, 3rd FS, and 4th FAS).

5.4.6 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 (Bigliassi et al., 2015a). The signal was initially transferred to Polar Flow and subsequently imported into Kubios HRV for analysis (Tarvainen et al., 2014). 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 (Billman, 2011): Standard deviation of normal-to-normal intervals (SDNN) and 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 (Rajendra Acharya et al., 2006).

5.4.7 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 Cheron et al., 2016). The compact EEG amplifier was placed in a compatible backpack where the signal was digitised 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 (Tadel et al., 2011). 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 EMG electrodes were placed on the participant's right vastus lateralis (Jain et al., 2013) in accord with the SENIAM project recommendations (Stegeman & Hermens, 1999). 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 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 Figure 5.2).

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 (.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 (Bailey et al., 2008; Enders et al., 2016; Jain et al., 2013). 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. Bigliassi et al., 2016a; Bigliassi et al., 2016b).

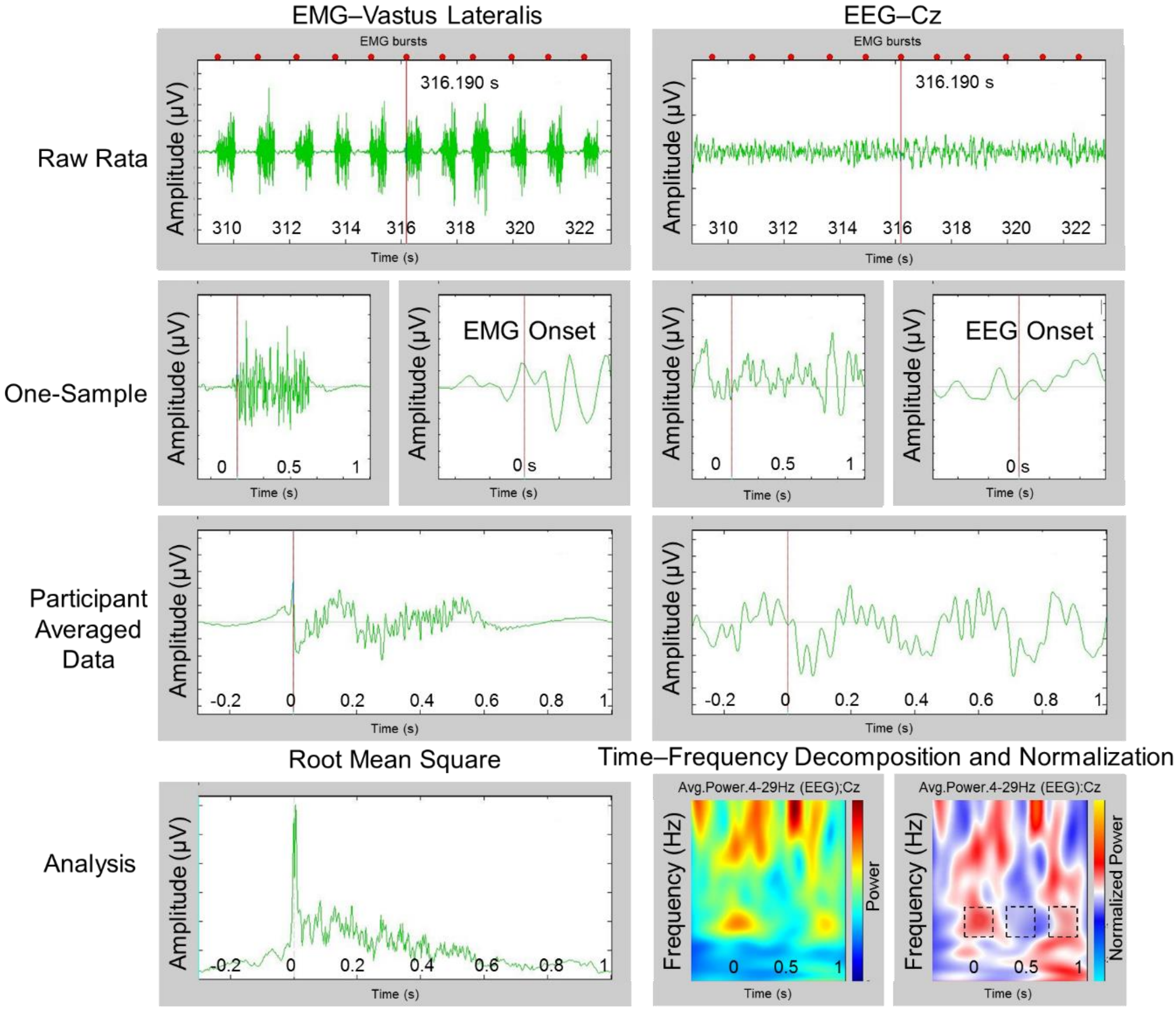


Figure 5.2. Offline procedures conducted to process the biological signal. This figure is divided into two columns: The left column indicates the procedures undertaken to process the EMG data; the right column indicates the procedures undertaken to process the EEG data. The first row illustrates the 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 normalised using event-related perturbation (i.e., synchronisation–desynchronisation analysis). Values within the windows represent the synchronisation-desynchronisation-resynchronisation cycle; these were averaged for each participant and compared across conditions. *Note.* EMG = Electromyography; EEG = Electroencephalography.

Oscillatory potentials at the Cz electrode site (Enders et al., 2016; Jain et al., 2013) were used to further understanding of time–frequency changes influenced by voluntary control of movements (Mackay, 2005). 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 (Müller-Putz et al., 2007). Time–frequency maps were decomposed by use of Morlet Complex Wavelets (central frequency = 1 Hz; time resolution = 3 ms; Tadel et al., 2011) 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; Makeig, 1993; Tadel et al., 2011) was calculated to investigate temporal changes in spectral power associated with the pedalling. The advantage of this measure for Study 3 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 pedal cycle.

I used the average power for each frequency band as a form of baseline index to normalise the data. I decided to use the average power for each band frequency as a baseline index with which to normalise the data given that cycle ergometry phases were constant and evoked potentials were oscillatory in nature (i.e., continuous control of lower limbs and stabilising muscles). Alpha frequencies were selected to extract the synchronisation-desynchronisation-resynchronisation cycle (see Figure 5.2). 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 (Park et al., 2015; Weisz et al., 2014). Alpha magnitude-squared coherence values were analysed throughout the epoch (Jovanović et al., 2013).

5.4.8 Data Analysis

For all statistical analyses, univariate outliers were identified through use of the standardised scores (*z*-scores) method on SPSS 17.0. Accordingly, data points lying beyond three standard deviations (i.e., $z > \pm 3.29$; Tabachnick & Fidell, 2014) 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 (Rasch & Guiard, 2004). A repeated-measures (RM) general linear model was used to compare the perceptual (attentional focus and perceived exertion; 3 [Conditions] x 5 [Timepoints]), affective (affective valence and felt arousal; 3 [Conditions] x 5 [Timepoints]), and cardiac (SDNN and RMSSD; 3 [Conditions] x 4 [Timepoints]) variables over time followed by Bonferroni-adjusted pairwise comparisons. Post hoc results were included in the figures in cases where significant Condition x 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 one-way RM ANOVA accompanied by Bonferroni-adjusted post hoc tests. A paired-samples *t* test was used to compare liking scores between the audiobook and music selection.

5.5 Results

Analysis of *z*-scores indicated that there were no univariate outliers. The piece of music selected for the present experiment was considered to be moderately pleasant while the audiobook was considered to be moderately unpleasant (M_{MU} = 6.72, SE = .28; M_{AB} = 4.50, SE = .50; t_{17} = 3.79; $p < .001$).

5.5.1 Perceptual Responses

Attentional focus was, for the most part, externally allocated at 20% below VT. An increase in associative thoughts was manifest when participants exercised at 10% below VT (see Table 5.1). The audiobook was not sufficiently engaging to guide participants' attentional focus towards 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 Study 3 increased the use of dissociative thoughts throughout the execution of cycle exercise performed at light-to-moderate-intensities (see Figure 5.3A). 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 (η_p^2 = .27), while the audiobook had no significant effect. Rate of perceived exertion was not influenced by either condition or time factors.

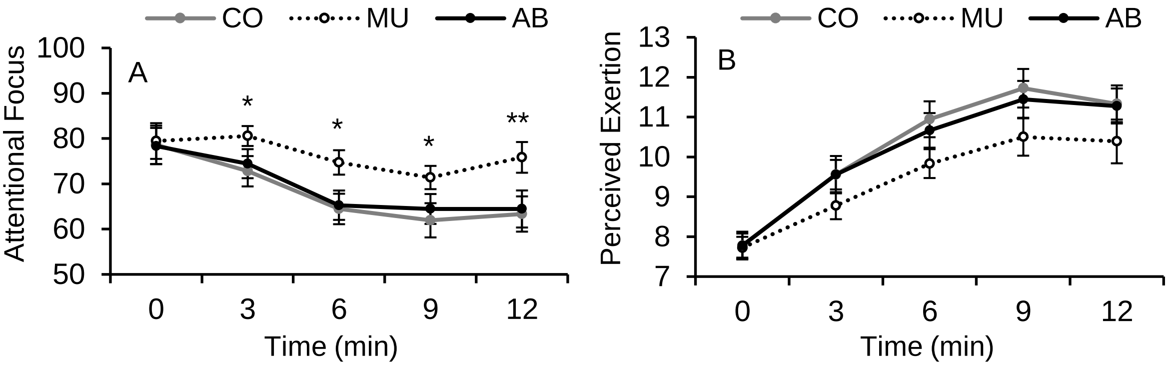


Figure 5.3. Psychophysical responses compared across CO, MU, and AB. A = Attentional focus compared across CO, MU, and AB; B = Rating of perceived exertion compared across CO, MU, and AB. Means and standard errors are presented. *Note.* CO = Control condition; MU = Music condition; AB = Audiobook condition; * = MU was statistically different ($p < .05$) to CO. ** = MU was statistically different to both CO ($p = .001$) and AB ($p = .034$).

5.5.2 Affective Responses

Execution of the cycle task led to reductions in participants' affective states (see Table 5.1). When compared with CO and AB the music condition up-regulated participants' affective states to a greater degree ($\eta_p^2 = .33$). However, no significant Condition x 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.

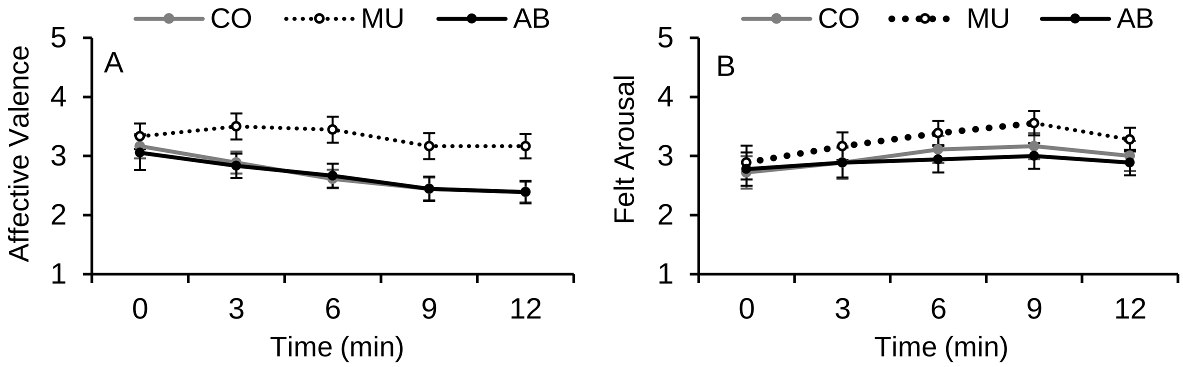


Figure 5.4. Affective responses compared across CO, MU, and AB. A = Affective valence compared across CO, MU, and AB; B = Felt arousal compared across CO, MU, and AB. Means and standard errors are presented. *Note.* CO = Control condition; MU = Music condition; AB = Audiobook condition.

5.5.3 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 5.1 and Figure 5.5A; $\eta_p^2 = .77$); nonetheless, no differences were evident across conditions. No Condition x Time interaction effects were identified. A similar temporal response to SDNN was evident for a parasympathetic index (RMSSD; $\eta_p^2 = .58$) of the autonomic control (see Figure 5.5B), and no differences were identified across conditions. No Condition x Time interactions were evident for RMSSD.

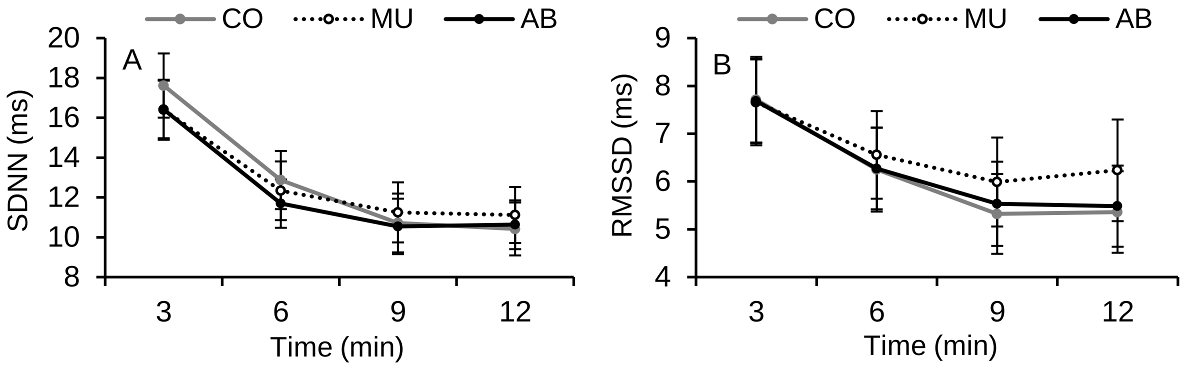


Figure 5.5. Sympathovagal indices compared across CO, MU, and AB. A = SDNN compared across CO, MU, and AB; B = RMSSD compared across CO, MU, and AB. Means and standard error are presented. *Note.* CO = Control condition; MU = Music condition; AB = Audiobook condition; SDNN = Standard deviation of normal-to-normal intervals; RMSSD = Root mean square of the successive differences.

Table 5.1

Two-way 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	.008	.001	.355	5.95	1.42, 24.15	.014	.26
Condition	.751	.101	.801	7.53	2, 34	.002	.30
Time x Condition	.003	.001	.425	2.69	3.4, 57.80	.048	.13
Perceived Exertion							
Time	.009	.001	.333	34.55	1.3, 22.63	.001	.67
Condition	.890	.392	.901	6.26	2, 34	.005	.27
Time x Condition	.022	.029	.544	1.94	4.35, 73.99	.107	.10
Affective Valence							
Time	.029	.001	.384	6.06	1.53, 26.08	.011	.26
Condition	.351	.001	.606	8.57	1.21, 20.61	.006	.33
Time x Condition	.058	.275	.632	1.93	8, 136	.060	.10
Felt Arousal							
Time	.159	.001	.528	3.81	2.11, 35.90	.029	.18
Condition	.632	.025	.731	3.17	1.46, 24.84	.073	.15
Time x Condition	.032	.078	.684	1.00	8, 136	.434	.05
SDNN							
Time	.134	.001	.494	57.21	1.48, 25.20	.001	.77
Condition	.965	.752	.966	1.39	2, 34	.262	.07
Time x Condition	.126	.065	.544	1.79	6, 102	.107	.09
RMSSD							
Time	.169	.001	.486	23.72	1.46, 24.79	.001	.58
Condition	.947	.646	.950	1.90	2, 34	.165	.10
Time x Condition	.004	.001	.430	.98	2.58, 43.90	.399	.05

5.5.4 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 up-regulated in the central, central-parietal, and parietal regions of the brain when participants exercised with the audiobook (see Table 5.2 and Figure 5.6). SMR frequency bands were also up-regulated in the frontal regions in MU and AB when compared to CO. Averaging of the power spectra partially equalised time-related changes caused by auditory cues (see 5.5.5 Time–Frequency Oscillatory Potentials section).

Table 5.2

One-way Repeated-Measures (RM) ANOVA Results for Time-Averaged Band Frequencies, Time-Frequency Oscillatory Components, Root Mean Square Amplitude, and Magnitude-Squared Coherence.

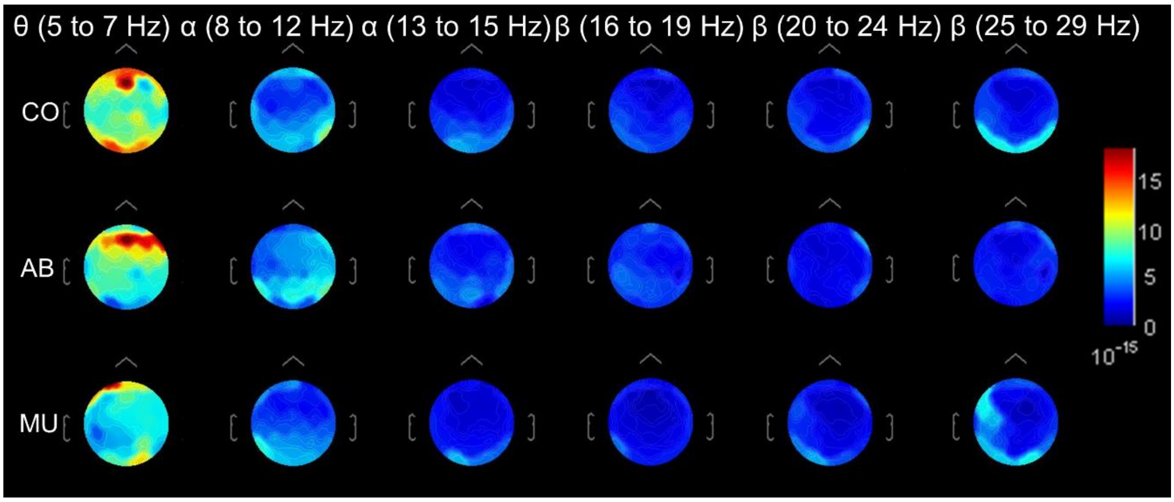
		Sphericity			RM ANOVA			
		W	*p*	ε	*F*	*df*	*p*	η_p^2
Theta	Frontal	.483	.003	.659	2.01	1.31, 22.41	.167	.106
	Frontal-Central	.616	.021	.722	1.23	1.44, 24.56	.304	.068
	Central	.973	.805	.974	1.43	2, 34	.252	.078
	Central-Parietal	.718	.071	.780	.57	2, 34	.567	.033
	Parietal	.822	.208	.849	.74	2, 34	.484	.042
Alpha	Frontal	.591	.015	.710	3.60	1.41, 24.12	.056	.175
	Frontal-Central	.442	.001	.642	2.65	1.28, 21.82	.111	.135
	Central	.733	.083	.789	3.83	2, 34	.032	.184
	Central-Parietal	.940	.608	.943	4.59	2, 34	.017	.213
	Parietal	.974	.810	.975	3.96	2, 34	.028	.189
SMR	Frontal	.994	.955	.994	4.56	2, 34	.018	.212
	Frontal-Central	.972	.794	.972	2.66	2, 34	.084	.135
	Central	.818	.200	.846	1.71	2, 34	.196	.091
	Central-Parietal	.724	.075	.784	1.26	2, 34	.296	.069
	Parietal	.889	.390	.900	1.37	2, 34	.266	.075
Low-Beta	Frontal	.944	.633	.947	3.03	2, 34	.650	.151
	Frontal-Central	.944	.629	.947	1.47	2, 34	.242	.080
	Central	.646	.030	.739	.85	1.47, 25.11	.435	.048
	Central-Parietal	.650	.032	.741	.810	1.48, 25.18	.422	.045
	Parietal	.819	.203	.847	1.44	2, 34	.250	.078
BCP	Frontal	.743	.093	.796	2.47	2, 34	.103	.125
	Frontal-Central	.754	.105	.803	1.70	2, 34	.198	.091
	Central	.544	.008	.687	.53	1.37, 23.35	.526	.031
	Central-Parietal	.742	.092	.795	.53	2, 34	.590	.031

Table 5.2 continues

Table 5.2 continued

	Parietal	.818	.200	.846	.91	2, 34	.411	.051
High-Beta	Frontal	.291	.001	.585	2.07	1.71, 19,89	.141	.109
	Frontal-Central	.295	.001	.586	1.86	1.12, 19.93	.187	.099
	Central	.183	.001	.550	.84	1.10, 18.71	.380	.047
	Central-Parietal	.303	.001	.589	.91	1.17, 20.03	.366	.051
	Parietal	.605	.018	.717	1.00	1.43, 24.36	.379	.056
TFC	Synchronisation	1.00	.924	1.00	4.48	2, 34	.020	.230
	Desynchronisation	.795	.159	.830	.375	2, 34	.690	.022
	Resynchronisation	.991	.927	.991	7.06	2, 34	.003	.294
RMS	Vastus Lateralis	.934	.685	.938	3.88	2, 34	.035	.244
MSC	Cz–FP1	.897	.421	.907	1.87	2, 34	.170	.099
	Cz–Fpz	.888	.386	.899	.85	2, 34	.919	.005
	Cz–FP2	.818	.201	.846	1.35	2, 34	.273	.074
	Cz–F7	.884	.374	.896	.459	2, 34	.636	.026
	Cz–F3	.860	.298	.877	.219	2, 34	.805	.013
	Cz–Fz	.717	.070	.779	3.34	2, 34	.047	.165
	Cz–F4	.897	.418	.906	1.52	2, 34	.232	.082
	Cz–F8	.771	.125	.814	1.43	2, 34	.252	.078
	Cz–FC5	.852	.277	.871	.139	2, 34	.870	.008
	Cz–FC1	.830	.225	.854	1.48	2, 34	.240	.081
	Cz–FC2	.952	.675	.954	2.84	2, 34	.072	.143
	Cz–FC6	.961	.727	.962	1.74	2, 34	.190	.093
	Cz–C3	.890	.385	.901	.654	2, 34	.526	.037
	Cz–C4	.950	.666	.953	8.12	2, 34	.001	.323
	Cz–CP5	.684	.048	.760	1.53	1.51, 25.83	.234	.083
	Cz–CP1	.722	.074	.782	.188	2, 34	.830	.011
	Cz–CP2	.932	.571	.937	.095	2, 34	.909	.006
	Cz–CP6	.873	.339	.888	.270	2, 34	.765	.016
	Cz–P7	.666	.039	.750	2.03	1.5, 25.49	.160	.107
	Cz–P3	.737	.087	.792	2.30	2, 34	.116	.119
	Cz–Pz	.801	.189	.834	.844	2, 34	.439	.050
	Cz–P4	.919	.509	.925	.774	2, 34	.469	.044
	Cz–P8	.622	.022	.725	1.64	1.45, 24.66	.208	.088
	Cz–POz	.730	.080	.787	2.33	2, 34	.113	.121

Note. SMR = Sensorimotor rhythm; BCP = Beta central portion; TFC = Time–frequency components; RMS = Root mean square of the electromyographic signal; MSC = Magnitude-squared coherence.


θ (5 to 7 Hz)
α (8 to 12 Hz)
α (13 to 15 Hz)
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CO
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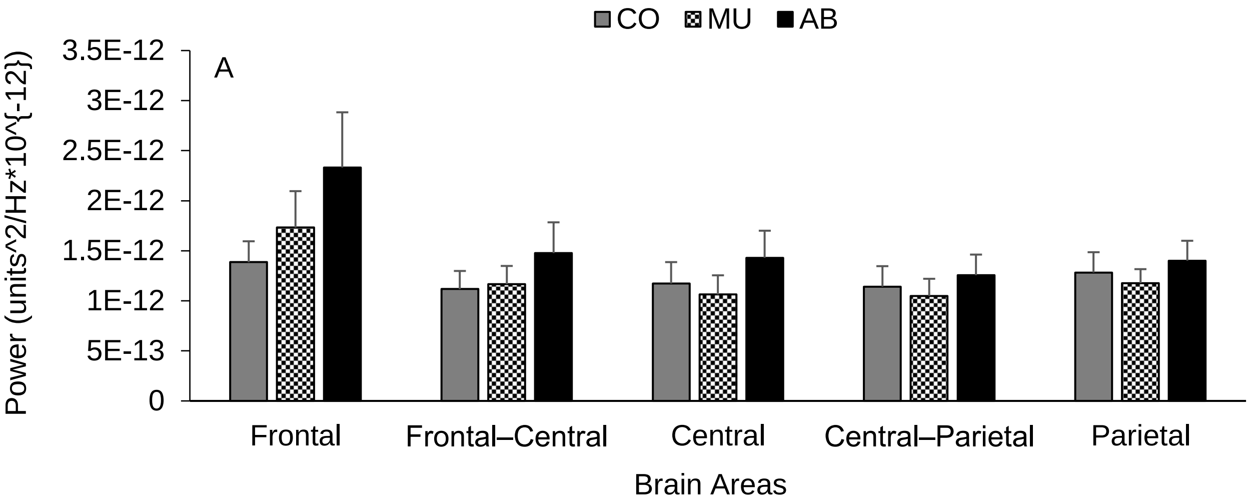
CO
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Frontal
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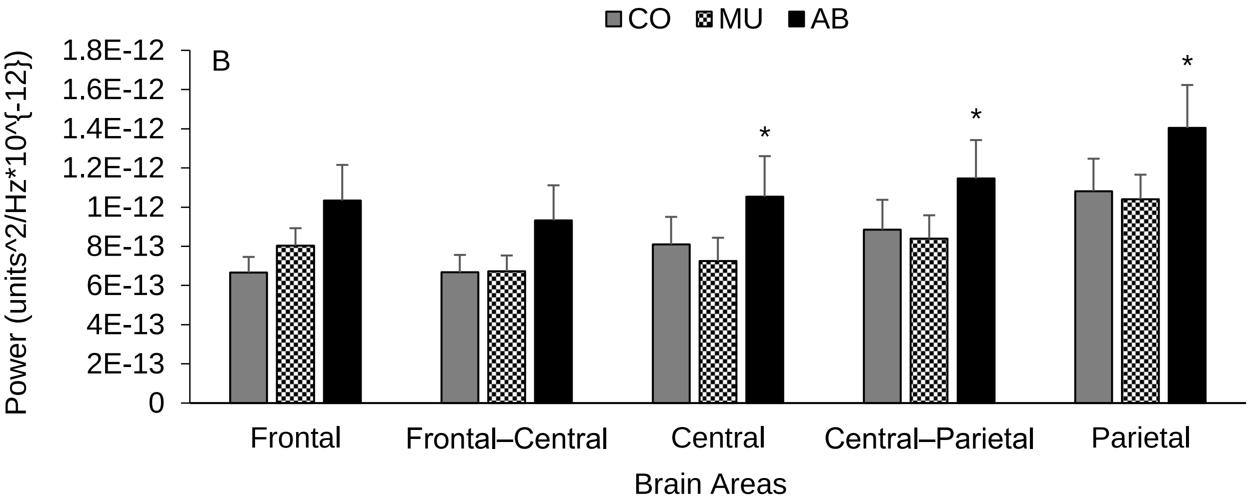
Central–Parietal
Parietal
Brain Areas


CO
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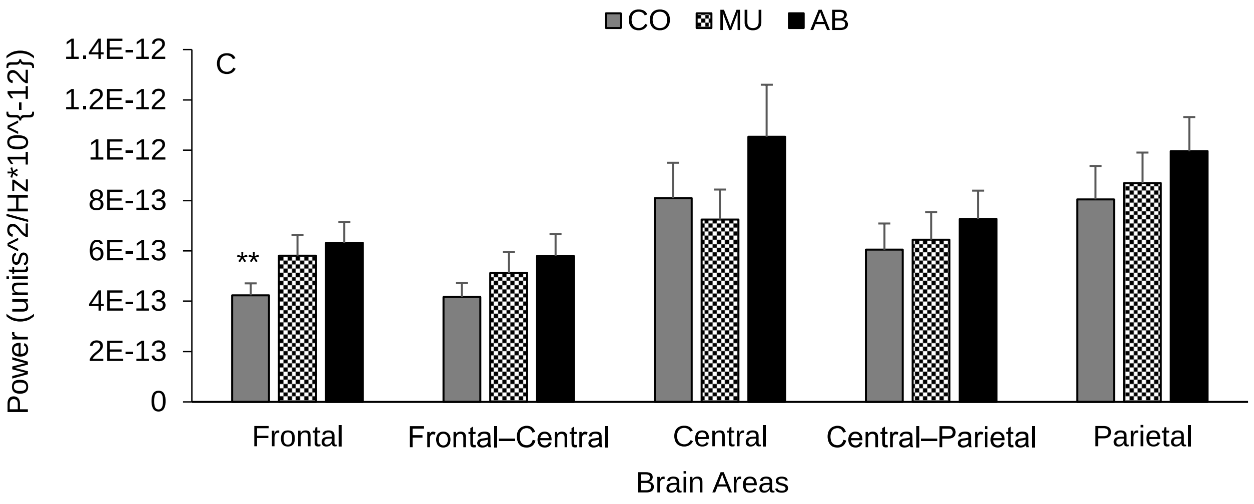
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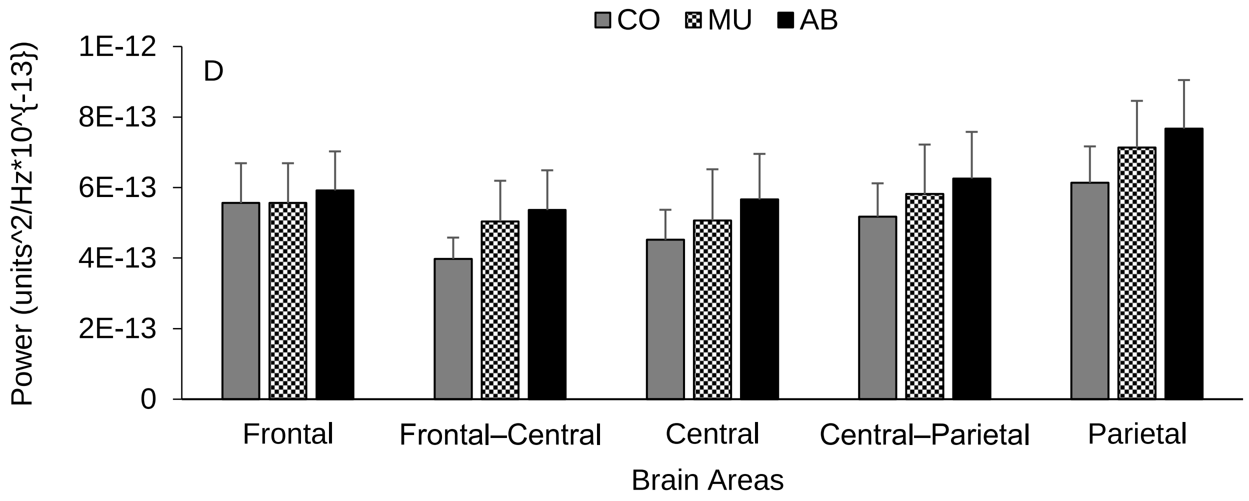
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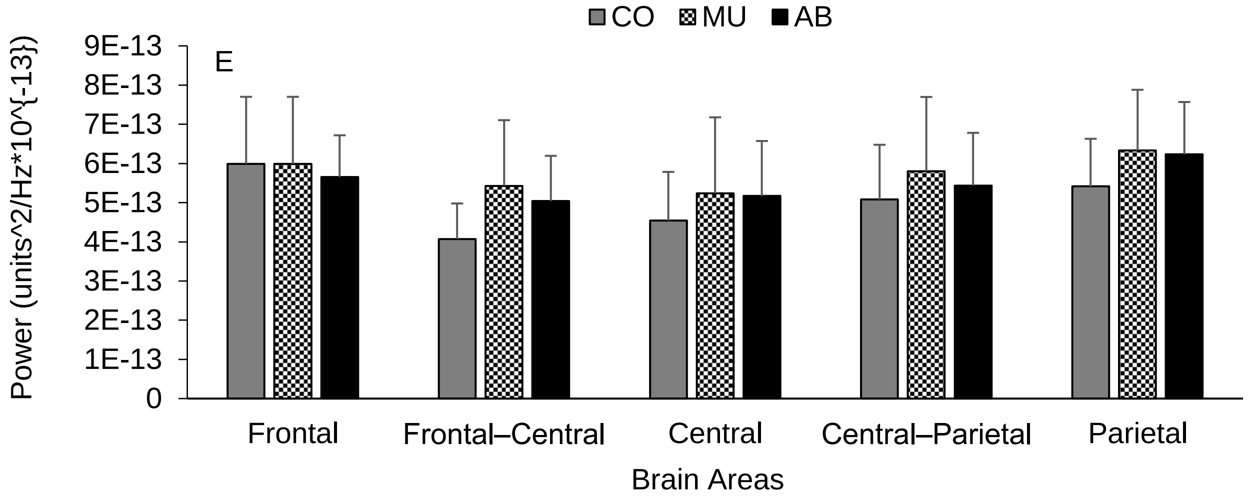
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Brain Areas

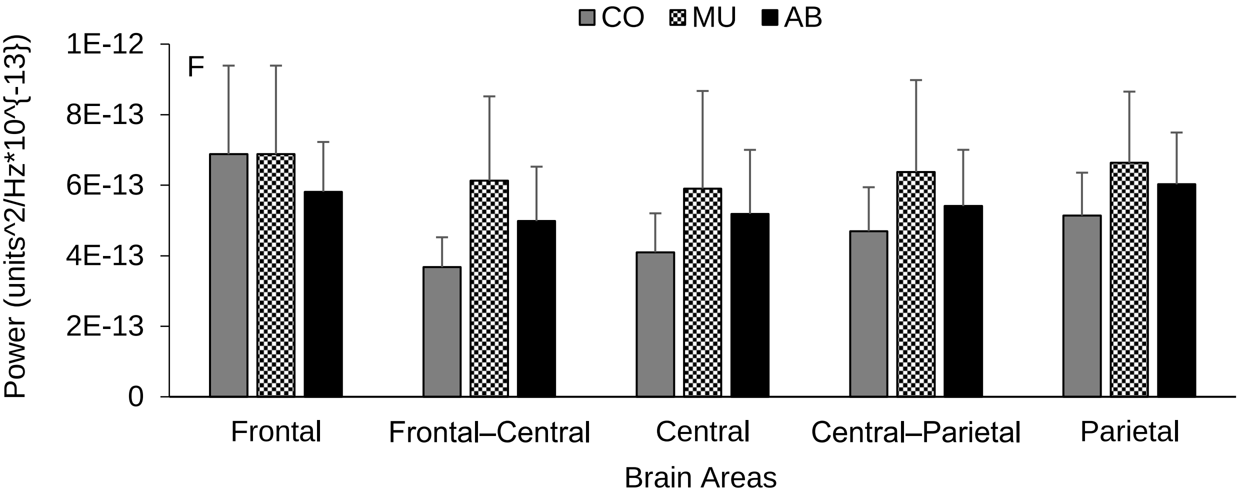


Figure 5.6. Group data time-averaged band frequencies for CO, AB, and MU. *Note.* The coloured scale indicates the power of the band frequencies (power [signal units^2/Hz*10^{-15}]); CO = Control condition; AB = Audiobook condition; MU = Music condition. A: Theta (5−7 Hz); B: Alpha (8−12 Hz); C: Sensorimotor Rhythm (SMR; 13−15 Hz); D: Low-Beta (16−19 Hz); E: Beta Central Portion (BCP; 20−24 Hz); F: High-Beta (25−29 Hz); * = AB was statistically different to both CO (*p* = .023) and MU (*p* = .011); ** = CO was statistically different to both AB (*p* = .034) and MU (*p* = .035).

5.5.5 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 colours represent higher-than-average EEG spectral power, while cool colours 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, changes in EEG activity were not limited to alpha, but similarly manifest from alpha through to BCP frequency bands (see Figure 5.7).

An oscillatory potential was identified during cycle exercise at 10% below VT. Synchronisation of low- and high-frequency components started at approximately .15 s prior to commencement of the muscle burst. In the CO condition, first synchronisation was followed by EEG desynchronisation and subsequent resynchronisation as previously observed by Jain et al. (2013) during cycle exercise. The same synchronisation–desynchronisation–resynchronisation pattern was identified when participants exercised in the presence of an audiobook stimulus (see Figure 5.7; AB condition). ANOVA indicates that synchronisation of the neural population underneath Cz differed significantly across conditions (see Table 5.2). Post hoc comparisons further indicated that MU up-regulated the amplitude of alpha frequencies at the beginning of the contraction to a greater degree than CO and AB. Conversely, the amplitude of the desynchronisation phase was not affected by the presence of auditory stimuli (AB and MU). The piece of music completely inhibited EEG resynchronisation throughout the time–frequency map in comparison with CO and AB.

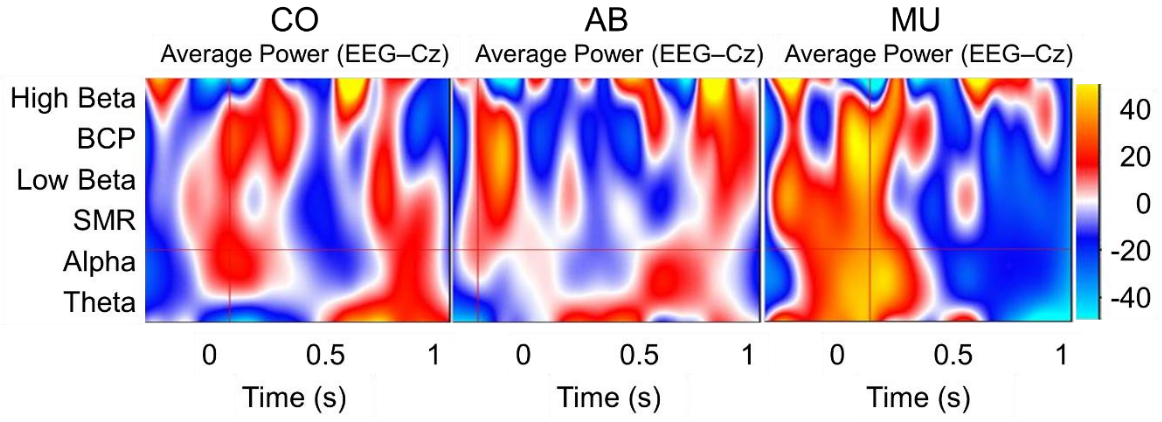


Figure 5.7. Group data averaged time–frequency maps (theta, alpha, sensorimotor rhythm, low-beta, beta central portion, and high-beta frequency components) in CO, AB, and MU. MU up-regulated alpha synchronisation to a greater extent when compared to CO and AB. Resynchronisation of low- and high-frequencies was fully inhibited when participants exercised in the presence of music. *Note.* CO = Control condition; AB = Audiobook condition; MU = Music condition.

5.5.6 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 = .51, SE = .05; AB: M = .53, SE = .06; MU: M = .37, SE = .07) coherence values were identified when participants exercised in the presence of MU when compared to CO and

AB (see Table 5.2 and Figure 5.8; $\eta_p^2 = .32$). MU also reduced the coherence values at Cz–Fz to a greater degree when compared to AB and MU (CO: *M* = .39, *SE* = .07; AB: *M* = .41, *SE* = .08; MU: *M* = .26, *SE* = .08; $\eta_p^2 = .16$).

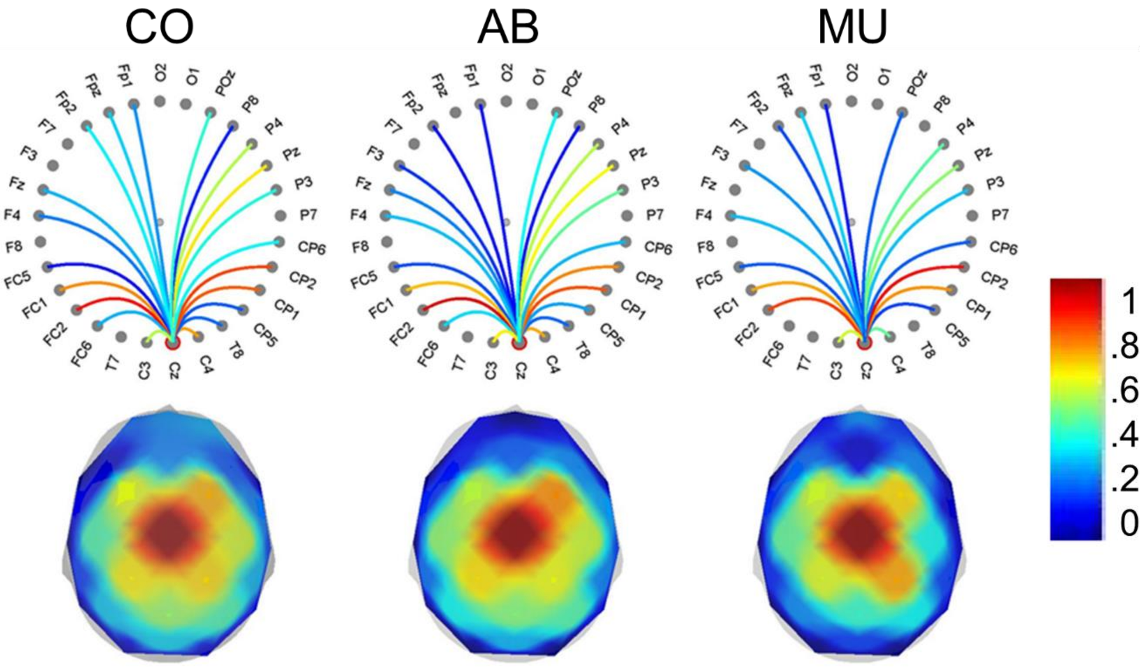


Figure 5.8. Group data alpha coherence values in CO, AB, and MU. Reduced spectral coherence is manifest across central and frontal electrodes sites in MU when compared to CO and AB. *Note.* CO = Control condition; AB = Audiobook condition; MU = Music condition.

5.5.7 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* = .30 µV; MU: $M_{RMS} = 4.77$, *SE* = .43 µV; AB: $M_{RMS} = 3.82$, *SE* = .22 µV; $\eta_p^2 = .24$; see Table 5.2 and Figure 5.9).

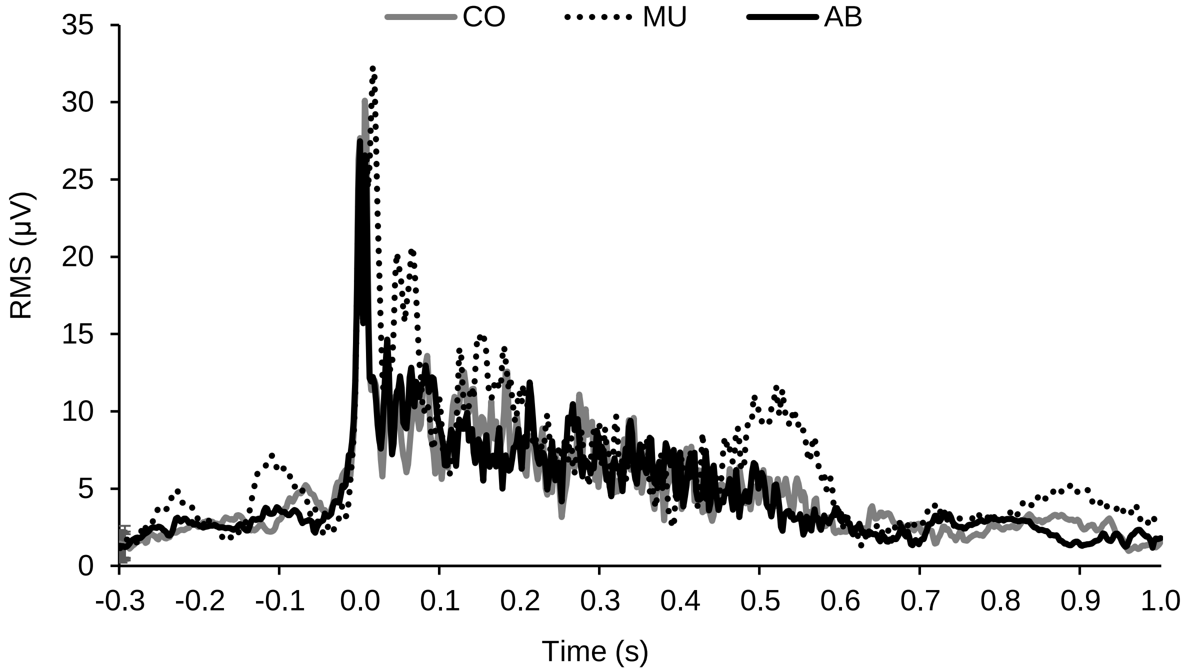


Figure 5.9. Group data-averaged RMS amplitude of the EMG signal collected from the vastus lateralis presented for CO, AB, and MU. *Note.* RMS = Root mean square; CO = Control condition; AB = Audiobook condition; MU = Music condition.

5.6 Discussion

The aim of Study 3 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 towards external stimuli and prompted the greatest use of dissociative thoughts (see Figure 5.3A). This dissociation mechanism served to reduce perceived exertion and induce a more positive affective state (Bigliassi, 2015a; Jones et al., 2014). 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 towards external cues and elicit psychophysiological responses during exercise. Nonetheless, up-regulation of alpha waves was evident in the central, central-parietal, and parietal regions of the brain when participants exercised in the AB condition.

Interestingly, up-regulation of alpha waves induced by AB was not associated with any perceptual, affective, or psychophysiological changes (see Figure 5.3, Figure 5.4, and Figure 5.5). It was hypothesised 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. Bartsch, Hamuni, Miskovic, Lang, & Keil, 2015), 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. It is hypothesised that music changed the EEG synchronisation 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 towards fatigue-related symptoms (Kiefer, 2012; Rejeski, 1985). The physiological mechanisms that underlie the frequency band and timing of neural synchronisation episodes might be associated with the effects of associative thoughts (e.g., focusing inwardly towards interoceptive sensory cues) as resynchronisation 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 hypothesised to resynchronise only at higher frequencies as a means by which to counteract the effects of fatigue and sustain the imposed exercise intensity (Bigliassi, et al., 2016a).

It could also be hypothesised 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 Figure 5.9) that might characterise 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 (Theurel, Crepin, Foissac, & Temprado, 2012) and lead, indirectly, to more positive affective responses. As RMS values were up-regulated in the vastus lateralis, EMG amplitudes could have been down-regulated 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 resynchronisation at the Cz electrode site, and facilitate the neural activation of working muscles.

5.6.1 Perceptual, Affective, and Psychophysiological Responses

The music prompted an increase in the use of dissociative thoughts (i.e., task-unrelated factors; see Figure 5.3). Conversely, AB was not sufficiently potent to direct attentional focus towards 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 ($M_{MU} = 6.72$, $SE = .28$; $M_{AB} = 4.50$, $SE = .50$; see 5.5 Results section).

The pattern of change observed in participants’ rating of perceived exertion followed a similar pattern to that of attentional focus (see Figure 5.3). It has been suggested that music-related interventions have the potential to assuage the effects of fatigue (Boutcher & Trenske, 1990; Hutchinson & Karageorghis, 2013). 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 (Karageorghis, 2017). Bigliassi et al. (2016b) demonstrated that a motivational piece of music down-regulated 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 Craig et al., 2012). Thus, the brain attempts to slow the body down by up-regulating theta waves and reducing the frequency of neural output that controls the working muscles. This is a conscious response (see Pageaux, 2014) based on the execution of what the brain considers as purposeless movements (see Marcora, 2016). In order to counteract the effects of fatigue and reassume the control of a given task, the brain has to up-regulate high-frequency waves in the central motor command (Bigliassi et al., 2016a).

The execution of cycling exercises performed at 10% below VT had a detrimental effect on participants' affective state (see Figure 5.4A). 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 (Marcora, 2016; Reddon et al., 2016). Cycling continuously in order to expend calories "that could be used in the future" might, therefore, be deemed to be a purposeless action (see Marcora, 2016). Interestingly, pleasant environmental stimuli have the potential to guide selective attention towards 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 (Karageorghis & Jones, 2014), which subsequently cause participants to report more positive affective responses.

Participants' perceived activation was not significantly affected by music (see Figure 5.4B). The piece of music used in Study 3 was selected by the author to only force attentional focus towards external dissociation. It has been hypothesised that one's felt arousal could be significantly influenced by motivational stimuli during the execution of high-intensity exercise (see Karageorghis & Priest, 2012a, 2012b for review). The selected track was task-unrelated and its psychoacoustic properties were not directed towards the up-regulation 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 stabilised after ~9 min of exercise (see Figure 5.5A and Figure 5.5B). 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 Study 3 confirm the nonlinear relationship between peripheral responses (e.g., heart rate) and one's perceived exertion (Marcora, 2008), 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; Study 1).

5.6.2 Neurophysiological Responses

An increase in EEG spectral power (low-to-high-frequency bands) has been consistently reported over the course of incremental exercise (Bailey et al., 2008; Enders et al., 2016). 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 behavioural experiments in which participants are tested at rest (e.g., Girges, Wright, Spencer, & O'Brien, 2014). Craig et al. (2012) suggested that up-regulations in low-frequency waves could be directly associated with fatigue. Therefore, the brain is hypothesised 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 (Chesler & Durfee, 1997; Petrofsky, 1979), as the median/mean frequency of the power spectrum tends to decrease as participants fatigue.

Time–frequency analysis was employed in Study 3 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 Figure 5.7). This valley waveform (i.e., characteristic synchronisation–desynchronisation–resynchronisation pattern) had been previously identified by other studies (e.g., Jain et al., 2013), and suggested to be associated with a synchronisation–resynchronisation pattern of response. Interestingly, neural resynchronisation was mostly inhibited when participants exercised with musical accompaniment. Inhibition of EEG resynchronisation 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 synchronisation occurred not only at alpha frequencies but also at high-frequency components of the power spectrum. It is important to highlight that the synchronisation–desynchronisation–resynchronisation 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, it was hypothesised that synchronisation–desynchronisation patterns could be associated with the neural control of working muscles (Cz electrode site; Jain et al., 2013).

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

Figure 5.8). 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 synchronisation (i.e., coordination of rhythmic movement with an external oscillating stimulus; Daly et al., 2014b). Similar neurophysiological responses have been identified when the median nerve was stimulated during the execution of finger movements (i.e., a gating mechanism; see Cebolla et al., 2009). Notably, the music selection was made with a view to actively discourage participants from synchronising their pedal rotations (45 rpm) with the tempo of the music (119 bpm). Auditory-motor synchronisation 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 synchronisation was inhibited through the choice of music.

5.6.3 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 theorised to increase one’s perceived effort (de Morree et al., 2014; de Morree et al., 2012). Accordingly, the recruitment of motor units is hypothesised 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 towards 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 Figure 5.9).

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 (Pageaux, 2016). Spectral coherence analysis indicated that the presence of music reduced the communication across frontal and central electrodes sites (see Figure 5.8). I hypothesise that reduced brain connectivity in the frontal and central regions of the brain could be associated with reduced exercise consciousness (see Figure 5.3; Cheron et al., 2016; Walker, Kozlowski, & Lawson, 2007) that is commonly induced by the presence of dissociative strategies such as pleasant music (Bigliassi et al., 2016b). Reallocation of attention towards environmental sensory cues rendered an autonomous and almost reflexive control of movements (i.e., reduced exercise consciousness; see Figure 5.3A). This neurophysiological mechanism is proposed to down-modulate neural resynchronisation and reduce connectivity across frontal and central regions of the cortex with corollary effects on participants’ perceived effort and affective state.

5.6.4 Limitations of Study 3

I 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; Juslin, 2013; North et al., 2004). 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., Stork et al., 2015). 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, I detected the very onset of muscle burst which is a reliable method with which to epoch the EEG data (see Figure 5.2). The EMG data were visually checked to ensure that Cz oscillatory potentials were precisely time-locked to muscle contractions.

In regard to pre-processing methods used to clean the raw data, I conducted traditional signal processing procedures to remove electrical artefacts generated by ocular and muscular interferences (see 5.4.7 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 stabilising muscles (e.g., trapezius and deltoid; Kline et al., 2015).

5.7 Conclusions

Study 3 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 towards 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 down-regulated 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 resynchronisation 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 optimise 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 resynchronisation 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 resynchronisation in the central motor command, and optimise gross motor control.

Chapter 6: *The Way You Make Me Feel*: Psychological and Cerebral Responses to Music During Real-Life Physical Activity

Study 4 was published in *Psychology of Sport and Exercise*

(see section Manuscripts Published in Peer-Reviewed Journals During the PhD Programme)

6.1 Introduction

Auditory stimuli such as music and podcasts have been widely used in the realm of exercise and sport (Karageorghis, 2016). Such use has proliferated over the last two decades through the advent of ergonomically-designed mp3 players and smartphones. Typically, auditory stimuli have been used at light-to-moderate work intensities (i.e., at intensities up to the ventilatory threshold) as a means by which to ameliorate the effects of fatigue, enhance exercise performance, and induce more positive affective responses than no-music control conditions (Study 3; Hutchinson & Karageorghis, 2013). It has been indicated that a shift in attentional focus caused by an increase in fatigue-related sensations (e.g., limb discomfort and breathlessness) would automatically increase the number of associative thoughts and partially suppress the influence of environmental sensory cues (Study 1; Hutchinson & Tenenbaum, 2007; Rejeski, 1985; Tenenbaum & Connolly, 2008). Owing to the limited number of available technologies, the mechanisms that underlie the influence of auditory stimuli on physical activity are presently under-examined (Karageorghis et al., 2017).

Notably, there is compelling evidence to suggest that pleasant stimuli have the potential not only to stimulate the sensory regions of the cortex, but also to deactivate areas affected by negative sensations (Hernández-Peón et al., 1961). In such instances, the effects of auditory stimuli are contingent upon the degree to which attention is reallocated from internal bodily cues towards external environmental cues (see Karageorghis et al., 2009). Put another way, music-related interventions have the potential to reallocate attentional focus towards external influences, facilitate the control of movements, enhance enjoyment, and induce positive affective memories (e.g., Jones et al., 2014; Stork et al., 2015). In the long term, pleasant sensory stimuli are hypothesised to increase adherence to physical activity programmes, which appears to be an effective strategy by which to reduce sedentariness and enhance well-being (Karageorghis & Priest, 2012a, 2012b; Priest & Karageorghis, 2008).

The brain mechanisms that underlie the effects of auditory stimuli during the execution of movements have only been recently investigated. Researchers have conducted laboratory-based experimental work to further understanding of the functional and cerebral mechanisms that underlie the effects of music during exercise (Bigliassi et al., 2016b), which has been found to be an effective form of auditory stimulation. In Study 1, participants were asked to execute a highly fatiguing isometric ankle-dorsiflexion type of contraction to the point of volitional exhaustion. The results indicated that the spectral power of low-frequency components (i.e., theta waves [4–7 Hz]) at the frontal, central, and parietal regions of the cortex were down-regulated when participants exercised in the presence of music. Interestingly, the same effect was not evident when participants listened to music at rest. Ostensibly, high-intensity exercise has the tendency to up-regulate theta waves, and music-related interventions appear to moderate this tendency.

It has been hypothesised that low-frequency components typically up-regulate as a means by which to induce a resting state (i.e., an index of neural fatigue; Craig et al., 2012). Thus, pleasant auditory stimuli appear to engender a prophylactic effect (e.g., Boutcher & Trenske, 1990) by re-arranging the brain’s electrical activity. Allied to this, music guides attention towards task-unrelated thoughts and reduces processing of internal sensory signals (e.g., muscle afferents). This psychophysiological mechanism can be characterised through reductions in the spectral power of theta waves (Study 1). Interestingly, individuals primarily execute whole-body movements at a light intensity during their daily physical activity routines (e.g., walking or cycling). In such instances, the effects of music-related interventions are primarily related to emotional experiences elicited by the stimuli (e.g., feeling happy; Koelsch, 2010; North et al., 2004). Despite the fact that music has the potential to ameliorate fatigue-related sensations when people exercise at a light-to-moderate intensity, they tend to use it primarily as a means by which to render the exercise experience more pleasurable (Clark, Baker, & Taylor, 2016; Hallett & Lamont, 2015).

The brain mechanisms that underlie the effects of auditory stimuli on psychophysiological responses during the execution of lifestyle physical activity (e.g., outdoor walking performed at light-intensity) have yet to be explored. Assessment of brain function has always proven to be a challenge in naturalistic settings given that cables and body movements tend to compromise the fidelity of the biological data. Fortunately, with recent technological advances, researchers are now able to investigate electrical activity in the brain during real-life situations such as walking and cycling. For instance, portable EEG devices have been developed to facilitate the acquisition of biological data during physical activity. Such devices incorporate an electrical system that protects the core components of cables with active shielding technology. Specifically, this functions as a portable Faraday cage that prevents extraneous factors (e.g., cable movements) from interfering with the electroencephalographic signal (i.e., zero-capacitance). Accordingly, portable devices designed to measure electrocortical activity during the execution of gross movements can provide a direct and objective measure of an individual's emotional state and shine new light on the mechanisms that underlie the effects of environmental sensory stimuli on perceptual and affective responses.

The objective of Study 4 was to investigate the effects of auditory stimuli on psychological responses and brain activity during self-paced physical activity performed in an ecologically valid setting. It was hypothesised that music would re-arrange the brain's electrical frequencies, increase the use of task-irrelevant thoughts (e.g., focusing outwardly towards external influences), induce more positive affective responses, and enhance enjoyment to a greater degree when compared to other auditory conditions that are devoid of musical components (i.e., a podcast).

6.2 Method

6.2.1. Participants

The required sample size for Study 4 was calculated by use of G*Power 3.1 (paired-samples *t* test; Faul et al., 2007) The effects of music on affective responses during exercise were used as group parameters to estimate the effect size (effect size $dz = 0.7$; Hutchinson & Karageorghis, 2013). It was indicated that 21 participants would be required ($\alpha = 0.05$; $1 - \beta = 0.85$). Volunteers were initially surveyed to enable collation of basic demographic information (e.g., age and gender). The inclusion criteria were that participants needed to be apparently healthy and not present visual- or hearing-related disorders. Participants with dreadlocks were excluded from the trials, given that this hairstyle tends to create a gap between the scalp and the electrodes, reducing conductance and thus compromising data fidelity. Three additional participants were recruited to account for likely experimental dropout and to facilitate a fully counterbalanced design. After obtaining institutional ethics committee approval and written informed consent, 24 healthy adults (11 women and 13 men; $M_{age} = 23.5$, $SD = 4.3$ years; $M_{height} = 173.4$, $SD = 9.1$ cm; $M_{weight} = 69.1$, $SD = 12.9$ kg) were recruited.

6.2.2 Experimental Procedures

To further understanding of the psychophysiological mechanisms that underlie the use of music on physical activity, the present experiment employed a portable EEG system with active shielding technology. Participants engaged in singular bouts of light-intensity physical activity (walking) performed at self-paced speeds (i.e., real-life physical activity) on a standard all-weather 400-m running track. An additional auditory stimulus – a podcast – was used to facilitate identification of the effects of auditory distractions that were devoid of musical elements such as melody and harmony. The apparatus used in the present experiment was non-invasive and developed for use during the execution of movements. In total, the experimental procedures took no longer than 80 min.

Pre-experimental phase. Prior to engaging in the main experimental phase, participants were asked to read a participant information sheet, provide written informed consent, and respond to the PAR-Q. The psychological measures to be used in the main phase were presented at this juncture as a means by which to improve participants' familiarity with them.

Main-experimental phase. A 32-channel EEG cap (EEGO Sports ANT Neuro) was placed on each participant's scalp, and conductive paste/gel (OneStep) was used to improve conductance between the biological signal and electrodes. The electronic devices were non-invasive and developed to be applied during movement (see Figure 6.1). Two experimental conditions (podcast [PO] and music [MU]) and a control (CO) were administered in a randomised and fully counterbalanced in order to identify the effects of auditory stimuli on electrical activity in the brain and psychological responses during exercise performed at light-intensities. A deterministic logarithm was used to randomise and counterbalance conditions; this was intended to prevent any influence of systematic order on the dependent variables. PO was used as a means by which to gauge the effects of auditory distractions that are devoid of musical elements. Participants were required to complete 400 m in lane 1 of an outdoor running track at self-paced speeds and respond to psychological instruments (see 6.2.4 Psychological Measures section) immediately after the exercise bouts. The electrical activity in the right anterior tibialis was used to measure how long each participant took to complete the self-paced task. White noise (static sound) was used in between conditions as a *filler* to negate any potential residual effects of previous experimental conditions (León-Carrión et al., 2007).

Figure 6.1. Experimental set-up with the portable EEG technology.

6.2.3 Auditory Stimuli Selection

Music (MU): A 6-min version of *Happy* (160 bpm; Pharrell Williams; *Despicable Me 2 soundtrack* album, 2013) was used as a means by which to guide the participant's attentional focus towards external influences and to enhance affective responses. Podcast (PO): *Building Better Cities* (TED Radio Hours) was selected as an auditory stimulus that is deemed to be task-irrelevant and neutral in terms of affective valence responses. PO was used in order to direct attention towards an auditory environmental cue that was devoid of musical properties during the exercise bout. The auditory stimuli were delivered via earphones (iPod compatible) and sound intensity was standardised at level 10, which is deemed relatively loud but entirely safe from an audiological perspective. A single-item auditory liking scale was used at the end of the experiment to gauge the degree to which participants liked the auditory stimuli (Karageorghis et al., 2008).

6.2.4 Psychological Measures

Four psychological measures were taken immediately after the exercise bouts. Attentional focus was assessed by use of a single-item attention scale (SIAS; Tammen, 1996). Affective valence was assessed by use of the Feeling Scale (FS; Hardy & Rejeski, 1989). Felt arousal was assessed by use of the Felt Arousal Scale (FAS; Svebak & Murgatroyd, 1985). Perceived exertion was assessed by use of Borg’s single-item CR10 scale; Borg, 1982). The aforementioned instruments were always administered in the same order (1st SIAS, 2nd CR10, 3rd FS, and 4th FAS). The Physical Activity Enjoyment Scale (PACES) was also administered at the end of each condition in order to assess the degree to which the participant enjoyed each exercise bout.

6.2.5 Electroencephalography

Electrical activity in the brain was assessed throughout each exercise bout by use of a portable EEG system (see Figure 6.1). The core components of the EEG cables were protected with active-shielding technology, which served to reduce the influence of extraneous factors (e.g., cable movements) and body movements on the electrical signal. This technology was recently developed through the application of one layer of active shield that is used to receive, reflect, and reduce the electrical interference of signals at the frequency range of 50–60 Hz, and facilitate data collection in situations where a participant is physically active. The compact EEG amplifier was placed in a compatible and ergonomically-designed backpack where the signal was digitised at 500 Hz and analysed online. Thirty-two Ag/AgCl electrodes were attached to the participant’s scalp in accord with the guidelines detailed in the 10-20 International System. The mastoid electrodes were used to digitally reference the electrical signal. Vertical eye movements were identified through the use of independent component analysis in order to remove the interference of eye blinks on frontal activity. The impedance level was kept below 10 kΩ and the signal was amplified at a gain of 1000 times. An online bandpass filter (0.1–100 Hz) was employed to reduce the influence of electrical artefacts on the acquired data.

The EEG signal was imported into the Brainstorm software (Tadel et al., 2011). Identification of bad electrodes and periods of electrical interference (bad segments) was the first procedure conducted to discard artefacts. A pair of EMG electrodes was placed on the participant’s right anterior tibialis in accord with the recommendations of the SENIAM project (Stegeman & Hermens, 1999). The EEG data were band-pass filtered offline (0.5–30 Hz), broken down into 1-s windows (asynchronous samples), and DC-offset corrected. One-second samples are representative of the time that most participants took to execute one step. Accordingly, changes in spectral power are more likely to represent the neural control of working muscles as well as the perceptual and affective changes associated with movement execution.

The EMG activity indicated the period of time when the participant started and finished the test. The number of samples acquired in Study 4 (*M* = 215.4, *SD* = 5.1 samples) varied in accord with how long participants took to complete the self-paced task. The initial and final 15 s of activity were removed in order to reduce the influence of fast neurological adaptations to the initiation and cessation of movement. Fast Fourier Transform was used to decompose the brain’s electrical activity into different brain frequencies. Lower-alpha (8–10 Hz), upper-alpha (10.5–12.5 Hz), SMR (13–15 Hz), and beta (15.5–29.5 Hz) waves were analysed to further understanding of the effects of auditory stimuli on the electrical activity in the brain during the execution of light-intensity bouts of physical activity (Bailey et al., 2008; Enders et al., 2016).

The FFT values were acquired by averaging the spectra across samples. This option reduces the potential influence of waveform averaging as EEG signals were not time-locked to the gait cycle (Bigliassi et al., 2016a). The power spectrum was subsequently 1/f corrected (Tadel et al., 2011) given that power decreases with frequency (i.e., spectral flattening; multiplies the power at 8 Hz by 8). The frequency data were exported to Excel (Microsoft) for each electrode site and band frequency. Two-dimensional topographical results were used to illustrate the influence of different conditions on the brain's electrical activity grouped into predetermined band waves. The power spectra of five brain regions (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 averaged and compared across conditions. Brainstorm (Tadel et al., 2011) was used to conduct the EEG procedures of Study 4.

6.2.6 Data Analysis

Checks for univariate outliers were performed by use of standardised (*z*) scores (i.e., > 3.29 or < -3.29) on SPSS Statistics 22.0. The Shapiro-Wilk test was used to identify patterns of data distribution that do not fit the Gaussian curve. Log10 and square root transformations were computed in the case of non-normal profiles. Those variables that did not present a normal distribution after data correction were compared by use of corresponding non-parametric tests. The liking scores were compared using a paired-samples *t* test. Task performance (i.e., time to complete the task), perceptual responses (i.e., attentional focus and perceived exertion), affective responses (i.e., affective state and perceived activation), perceived enjoyment, and the time-averaged power spectrum for each predetermined brain region were compared across conditions by use of one-way repeated-measures ANOVA. Bonferroni-adjusted pairwise comparisons were used to identify where differences lay. Friedman's analysis of variance by ranks was used for non-parametric data, followed up with the Wilcoxon rank tests to locate significant differences across conditions.

6.3 Results

No outliers were identified in the dataset but some variables did exhibit non-normal distribution. Accordingly, log10 transformations were used to normalise the distribution. Table 6.1 contains descriptive statistics for performance, perceptual, and affective variables.

The auditory stimuli (both CO and MU) used in Study 4 were considered to be moderately pleasant, and no significant differences were identified across conditions ($t(23) = 1.606$; $p = .122$). Additionally, task performance was not influenced by the presence of auditory stimuli ($W = .642$; $\varepsilon = .736$; $F(1.47, 33.86) = .54$; $p = .534$; $\eta_p^2 = .02$). Participants also reported similar exertional responses following execution of the task under the influence of PO and MU ($W = .884$; $F(2, 46) = 2.61$; $p = .084$; $\eta_p^2 = .10$). Nonetheless, attentional focus was significantly influenced by the presence/absence of auditory stimuli ($W = .996$; $\mathrm{F}(2, 46) = 3.46$; $p = .040$; $\eta_p^2 = .13$). MU elicited more dissociative thoughts when compared to CO ($p = .018$). No differences in attentional focus were identified between PO and MU ($p = .251$) or CO and PO ($p = .150$).

Participants' affective responses to exercise were also up-regulated during exercise in the presence of auditory stimuli ($W = .951$; $F(2, 46) = 9.93$; $p < .001$; $\eta_p^2 = .30$). The piece of music used in Study 4 induced more positive affective responses than CO ($p < .001$) and PO ($p = .029$). MU also up-regulated perceived activation to a greater degree when compared to CO and PO ($p < .001$). Furthermore, perceived enjoyment was positively influenced by the presence of auditory stimuli ($W = .764$; $F(2, 46) = 16.60$; $p < .001$; $\eta_p^2 = .42$) and this was associated with a large effect size. Bonferroni adjustments indicated that all conditions differed significantly from one another in terms of enjoyment (see Table 6.1).

Table 6.1

Descriptive Statistics for Liking, Performance, Perceptual, and Affective Variables

	CO		PO		MU	
	M	*SE*	*M*	*SE*	*M*	*SE*
Liking Scores	–	–	6.33	.46	7.33	.45
Task Performance (s)	269.75	5.08	269.9	4.67	267.33	5.43
Attentional Focus	74.58	4.54	81.45	3.65	86.87	3.30
Perceived Exertion	1.68	.16	1.58	.13	1.39	.10
Affective Valence	3.25	.25	3.58	.25	4.08	.18
Perceived Activation	3.01	.27	2.85	.22	3.91	.30
Enjoyment	76.20	4.61	86.66	3.92	98.51	2.59

Note. CO = Control condition; PO = Podcast condition; MU = Music condition; *M* = Mean; *SE* = Standard error.

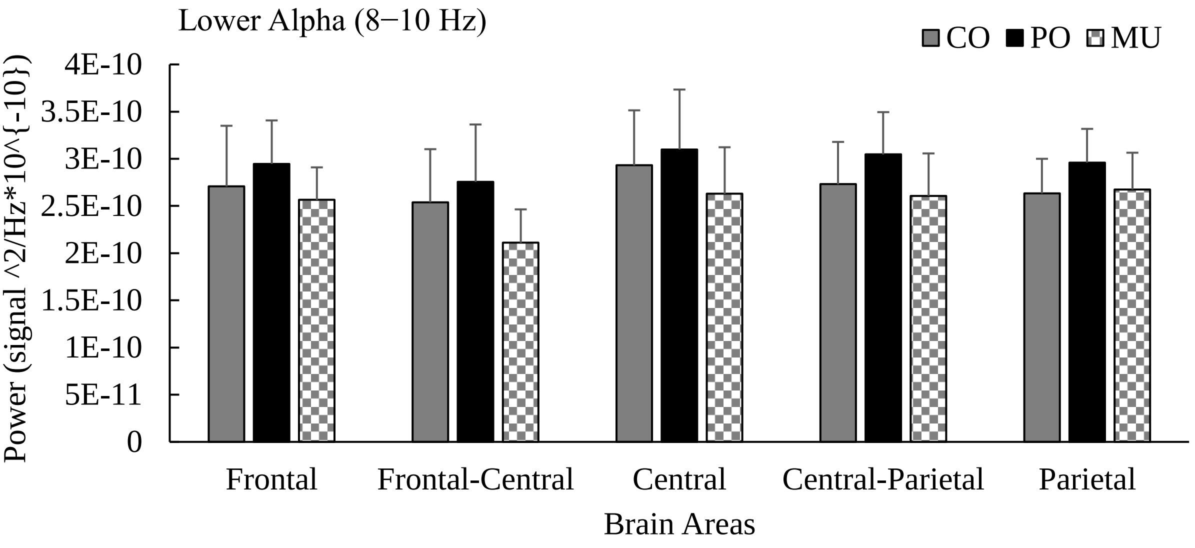
The results of Study 4 indicate that MU up-regulated high-frequency components of the power spectrum (i.e., beta waves) in the frontal (CO: *M* = 7.20, *SD* = 1.32; PO: *M* = 7.21, *SD*= 1.31; MU: *M* = 9.23, *SD* = 1.59 signal^2/Hz*10^{-10}) and frontal-central (CO: *M* = 6.24, *SD* = 1.07; PO: *M* = 6.06, *SD* = 1.23; MU: *M* = 7.29, *SD* = 1.12 signal^2/Hz*10^{-10}) regions of the brain to a greater extent when compared to CO and PO (see Table 6.2 and Figure 6.2).

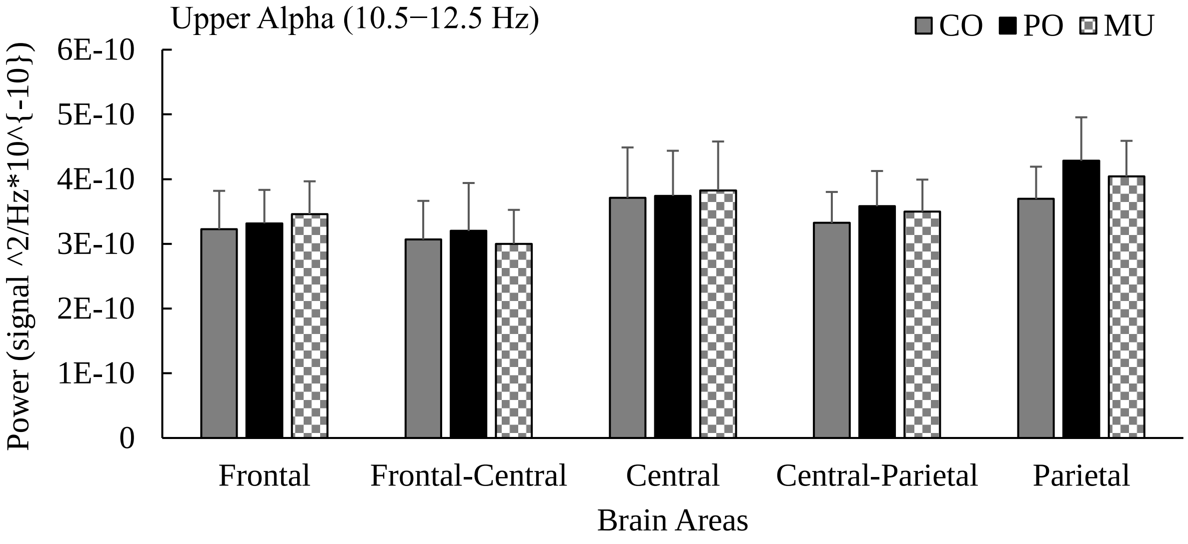
Table 6.2

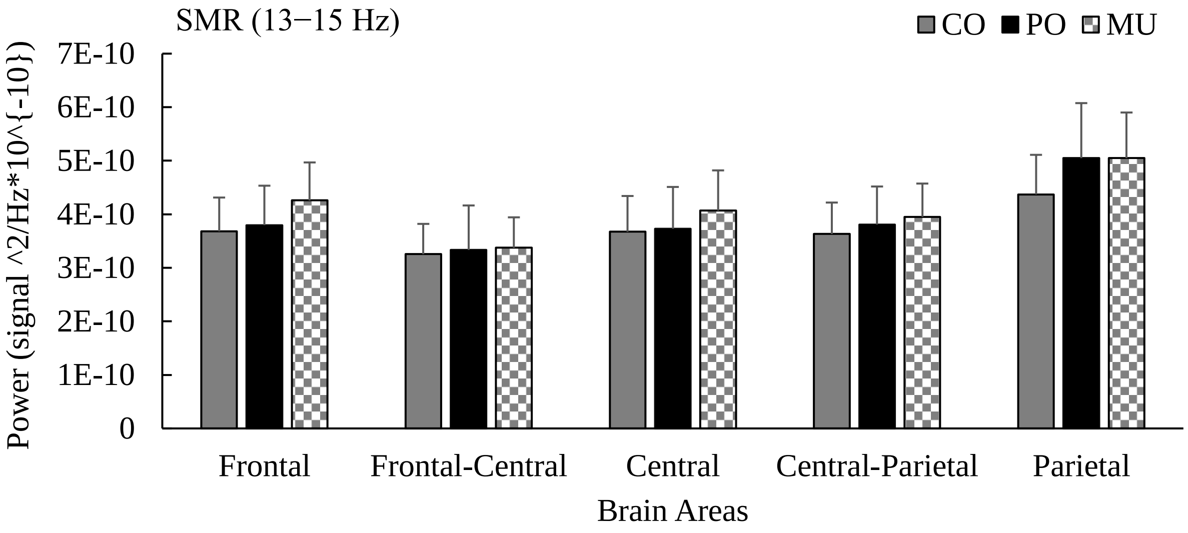
One-way Repeated-Measures (RM) ANOVA Results for Time-Averaged Band Frequencies

		Sphericity		RM ANOVA			
		W	ε	*F*	*df*	*p*	η_p^2
Lower Alpha	Frontal	.93	.93	.94	2, 46	.398	.04
	Frontal-Central	.73	.79	.77	1.58, 36.46	.442	.03
	Central	.77	.81	.96	2, 46	.374	.04
	Central-Parietal	.86	.88	1.73	2, 46	.189	.07
	Parietal	.63	.73	1.79	1.46, 33.66	.188	.07
Upper Alpha	Frontal	.90	.91	.47	2, 46	.626	.02
	Frontal-Central	.82	.85	.75	2, 46	.478	.03
	Central	.94	.95	.28	2, 46	.754	.01
	Central-Parietal	.97	.97	.58	2, 46	.561	.02
	Parietal	.77	.81	1.27	2, 46	.289	.05
SMR	Frontal	.76	.81	.88	2, 46	.419	.03
	Frontal-Central	.78	.82	.43	2, 46	.653	.01
	Central	.93	.93	.46	2, 46	.631	.02
	Central-Parietal	.94	.94	.72	2, 46	.488	.03
	Parietal	.88	.89	1.51	2, 46	.231	.06
Beta	Frontal	.76	.80	3.32	2, 46	.045	.12
	Frontal-Central	.85	.87	3.25	2, 46	.048	.12
	Central	.87	.88	2.94	2, 46	.062	.11
	Central-Parietal	.94	.94	2.96	2, 46	.061	.11
	Parietal	.90	.91	2.97	2, 46	.061	.11

Note. SMR = Sensorimotor rhythm.


Lower Alpha (8−10 Hz)
CO
PO
MU
Power (signal ^2/Hz*10^{-10})
4E-10
3.5E-10
3E-10
2.5E-10
2E-10
1.5E-10
1E-10
5E-11
0
Frontal
Frontal-Central
Central
Central-Parietal
Parietal
Brain Areas


Upper Alpha (10.5−12.5 Hz)
CO
PO
MU
Power (signal ^2/Hz*10^{-10})
6E-10
5E-10
4E-10
3E-10
2E-10
1E-10
0
Frontal
Frontal-Central
Central
Central-Parietal
Parietal
Brain Areas


SMR (13−15 Hz)
CO
PO
MU
Power (signal ^2/Hz*10^{-10})
7E-10
6E-10
5E-10
4E-10
3E-10
2E-10
1E-10
0
Frontal
Frontal-Central
Central
Central-Parietal
Parietal
Brain Areas

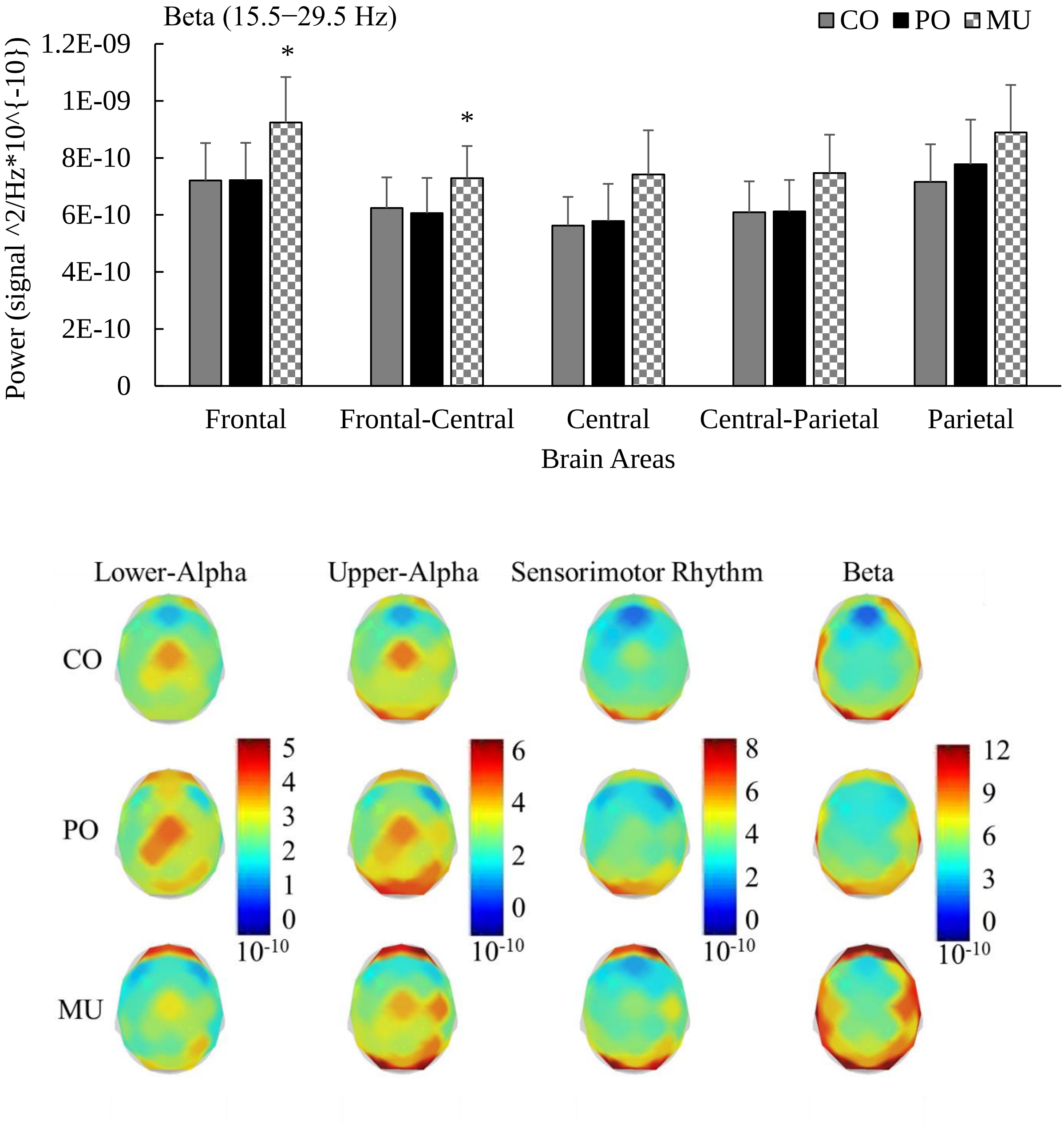


Figure 6.2. Group data time-averaged band frequencies for CO, PO, and MU. *Note.* SMR = Sensorimotor Rhythm. The coloured scale indicates the power of the band frequencies (signal^2/Hz*10^{-10}); CO = Control condition; PO = Podcast condition; MU = Music condition; * = MU was statistically different to both CO and PO ($p < .05$).

6.4 Discussion

The objective of Study 4 was to explore the cerebral mechanisms that underlie the effects of auditory stimuli in an ecologically valid setting and by use of portable EEG technology. The results indicate that music guided attention externally, induced more positive affective responses, up-regulated perceived activation, and enhanced perceived enjoyment to a greater degree when compared to CO and PO. Contrastingly, the podcast had no effect on perceptual and affective responses, but was sufficient to render perception of the task more pleasurable than CO (see Table 6.1). The brain mechanisms that underlie the effects of auditory stimuli on self-paced walking appear to be associated with the up-regulation of beta frequencies in the frontal and frontal-central regions of the cortex (see Figure 6.2).

The present experiment was designed to recreate a real-life scenario where participants could experience an everyday, outdoor physical activity; the EEG technology that was employed facilitated this. The exercise intensity was not expected to up-modulate exertional responses: I decided to use self-paced walking to facilitate the processing of auditory stimuli and leave scope for participants to experience more dissociative thoughts (Hutchinson & Tenenbaum, 2007; Rejeski, 1985). In such instances, light-intensity exercises performed for short periods (~4 min) would have no detrimental effects on affective responses and cognitive processes (cf. teleoanticipation mechanism; Wittekind, Micklewright, & Beneke, 2011). However, participants reported different psychological responses in accord with the presence/absence of auditory stimuli, despite no differences in the physiological load induced in terms of exercise intensity. The present results appear to concur with similar findings, which show that music can render a given activity more pleasurable than under normal circumstances (see Hutchinson & Karageorghis, 2013; Karageorghis, 2016).

6.4.1 Frequency of Cortical Rhythms

Up-regulation of high-frequency waves in the frontal and frontal-central areas could be associated with the psychological benefits that are commonly induced by music during activities of daily life such as walking (Daly et al., 2014a; Daly et al., 2014b). A previous experiment has indicated that environmental sensory cues have the potential not only to up-regulate high-frequency components of the power spectrum, but also to down-regulate theta waves in the frontal regions (Bigliassi et al., 2016a). Down-regulation of low-frequency components have been associated with amelioration of fatigue-related symptoms such as limb discomfort during the execution of high-intensity exercise performed to the point of volitional exhaustion (Study 1; Craig et al., 2012). On the other hand, high-frequency bands appear to change in response to one’s level of activation (Aspinall et al., 2015; Bigliassi et al., 2016a).

It was hypothesised that increases in beta wave activity could be induced primarily by the arousal potential of a stimulus (Berlyne, 1971; Sayorwan et al., 2013). Up-regulation of high-frequency waves in the brain could also have a protective effect against fatigue-related sensations during highly-demanding motor tasks. In such instances, beta waves might have the potential to partially inhibit the up-modulation of theta waves in the frontal cortex (i.e., an inhibitory mechanism; Sherman et al., 2016), leading to a subsequent amelioration of fatigue (Craig et al., 2012; Tanaka et al., 2012). It is noteworthy that participants reported the task to be more enjoyable with the podcast when compared to CO, indicating that a calming and task-unrelated stimulus could maintain or even down-regulate high-frequency waves and also render a given activity more pleasurable than under control conditions. Accordingly, future research is necessary to clarify the potential relationship between beta waves and psychological responses to exercise.

6.4.2 Strengths and Limitations

I selected auditory stimuli that would, in theory, elicit similar perceptual and affective responses across participants. Nonetheless, there is an idiosyncratic element to such responses (North et al., 2004). Despite the fact that both auditory stimuli were similar in terms of pleasantness, changes in how arousing the stimuli were perceived to be, could have induced changes in beta frequencies (Bigliassi et al., 2016a). Future research might employ the circumplex model of affect (Russell, 1980) and the associated Affect Grid (Russell, Weiss, & Mendelsohn, 1989) to further understanding of this potential confound prior to commencement of data collection. This is a means by which to standardise the emotional effects of the auditory stimuli (i.e., affective valence and arousal responses; North et al., 2004).

It is noteworthy that the differences in beta waves could have been induced by the sole effects of music regardless of the influence of exercise-related factors. Albeit previous research has indicated that such effects are not evident when participants listen to motivational pieces of music (see Bigliassi et al., 2016a), future studies might measure music-only effects on EEG activity as a means by which to further understanding of the combined effects of exercise and music on cerebral responses. Along similar lines, it is important to emphasise that one piece of music or even 10 pieces can never represent "music" as an artform in its entirety. Precisely the same principle applies to podcasts or audiobooks. The use of a wide range of musical selections/podcasts is not always viable in an experimental context given the high demands that this places upon participants. In this instance, the author was interested primarily in the simple acoustic distinction of music *vs*. podcast, and is not claiming that the approach described herein addresses the infinite complexity of such stimuli.

It is also important to emphasise that correlational analyses were not conducted in Study 4 given the differences in temporal resolution between EEG and the self-reported measures. For example, changes in beta waves can be swift and marked during light-intensity exercise, while changes in affective valence can up-/down-regulate in a slower, more subtle manner. Therefore, the present author can only speculate, based on previous findings (e.g., Bailey et al., 2008; Sayorwan et al., 2013), that re-arrangement of beta waves in the frontal and frontal-central regions serves to up-/down-regulate affective responses.

Finally, it is important to note that a very prudent approach was adopted to process the data, and primarily focused our analyses on central areas of the cortex (e.g., frontal-central and central), avoiding the influence of electrical interferences caused by the leg and neck muscles. The device used in this experiment was purposefully designed to prevent noises generated by body and cable movements. It should be highlighted that walking tasks could have generated waves of electrical interference as a result of the impact of the heels on the track. Notably, the portable EEG technology employed in this study acquired meaningful electroencephalographic signals during the execution of gross movements performed at light-intensity and generally protected the core components of the cable against such electrical artefacts. Despite this, O1 and O2 electrode sites were affected by the electrical activity of the trapezius; such noises are not easily removed by use of traditional filtering methods (e.g., band-pass filtering; Enders et al., 2016; Enders & Nigg, 2015; Kline, Huang, Snyder, & Ferris, 2015).

6.5 Conclusions

It is concluded that the psychological effects of music on low-intensity bouts of physical activity could be associated with the up-/down-regulation of high-frequency waves in the frontal and frontal-central regions of the brain. Re-arrangement of beta frequencies in the brain appears to elicit a more positive emotional state where participants are more likely to dissociate from internal sensory signals and focus on task-irrelevant factors. This positive psychophysiological state induced by musical stimuli can be capitalised upon during many forms of physical activity (e.g., functional mobility programmes or swimming) as a means by which to render a given activity more pleasurable.

It is also important to highlight that active shielding technology appears to function effectively as a portable Faraday cage that protects the core components of cables against external artefacts during the execution of walking tasks performed at self-paced speeds. Future researchers should attempt to use EMG electrodes to capture electrical activity in the working muscles (e.g., neck and leg muscles) and use independent component analysis

(Groppe et al., 2008) to remove muscle bursts from the brain’s electrical activity during offline procedures. Such technology with ergonomically-designed features will extend examination of cerebral mechanisms in a broad range of physical activity contexts.

Chapter 7: Cerebral Effects of Music During Isometric Exercise: An *f*MRI Study

Study 5 is accepted for publication in *International Journal of Psychophysiology*

(see section Manuscripts Published in Peer-Reviewed Journals During the PhD Programme)

7.1 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-/down-regulate 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., Study 1; 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.

7.1.1 Psychophysiological Mechanisms

The combined effects of peripheral feedback associated with interoceptive cues (e.g., group III and IV muscle afferents) are hypothesised 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 towards 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 towards task-irrelevant cues during exercise (Karageorghis & Jones, 2014). Therefore, exercise-related signals are hypothesised 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 towards interoceptive or exteroceptive signals is primarily defined by the stimulus relevance (Broadbent, 1958; Tenenbaum, 2001).

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 (Hutchinson & Karageorghis, 2013; Lim et al., 2014). Ameliorated fatigue enables exercisers to experience several positive outcomes, such as enhanced affective valence and situational motivation (Hutchinson & 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-/down-regulate 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 & 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. (Study 1) recently conducted an EEG experiment 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 hypothesised that low-frequency components of the EEG waveform are up-regulated by processing of interoceptive signals (Craig et al., 2012; Pires et al., 2018). As music redirects attention towards task-irrelevant cues, the detrimental effects of fatigue are partially suppressed. Thus, the central motor command (i.e., precentral and paracentral gyri; Voss, Ingram, Haggard, & Wolpert, 2006) is able to maintain the efferent control of working muscles for a longer period of time (de Morree et al., 2014).

7.1.2 Effects of Exercise and Music on Brain Activity

Brain assessment techniques are frequently used in the field of cognitive psychology and behavioural medicine as a means by which to explore the neurophysiological mechanisms that underlie the effects of music on attentional and emotional responses (Study 2; Juslin, 2013). The manifold effects of music on brain activity include increased activation in the temporal lobe, insular cortex, limbic system (amygdala, hippocampus, thalamus, hypothalamus, basal ganglia, and cingulate gyrus), 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 musical components (e.g., melody and harmony) and/or subsequent emotional responses that are elicited by music (Levitin, 2008).

Interestingly, the execution of movement yields 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 the incremental treadmill test increased the activity of the left frontal regions of the brain. The researchers postulated that such increase in brain activity was, perhaps, associated with emotional processing. Their postulate 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 (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, Herbst, Speck, & Zaitsev, 2013; Oakes et al., 2005). Furthermore, *f*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).

7.2 Aim of Study 5

Very few studies have examined the effects of music and isolated limb exercises using an *f*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, Martinez, & Parsons, 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.

7.3 Research Hypotheses

It was hypothesised that the presence of music would guide attentional focus externally, thus partially preventing afferent signals from entering focal awareness. The upshot would the amelioration of fatigue-related sensations (e.g., limb discomfort), up-regulation of affective arousal, and elicitation of a more positive affective state (Karageorghis, 2017). Attentional shifts induced by the presence of music were also hypothesised to influence the neural control of working muscles (i.e., decreasing the activity of the precentral gyrus; Bigliassi et al., 2017) and potentially decrease the activity of the right dorsolateral prefrontal cortex (see Karageorghis et al., 2017).

7.4 Method

7.4.1 Participants

The required sample size was calculated using G*Power 3.1 (Faul et al., 2007) for a paired-samples *t* test. 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. (Study 1) was used to estimate the effect size of asynchronous music on psychological responses during exercise (effect size d = .66). The software indicated that 18 participants would be required to detect an effect of this magnitude (α = .05; 1-β = .75). Two 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. 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 $\geq$ 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 (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; $M_{physical\ \mathrm{activity}}$ = 284.2, *SD* = 161.7 min) took part in the present study.

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 Study 5. 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 present visual- or hearing-related disorders. They were engaged in light-to-moderate-intensity motor tasks over short time periods (~20 min; see 7.4.2 Experimental Procedures section) and only non-invasive techniques were used. Study 5 was approved by the Institutional Research Ethics Committee at Brunel University London.

7.4.2 Experimental Procedures

Pre-experimental phase. Participants were asked to read the participant information sheet, provide written informed consent, and complete the 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 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 *f*MRI scanner and a handgrip dynamometer (Grip-D 5401, Takei) was used to determine their 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.

Main experimental phase. Participants were positioned in the *f*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 hour 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). 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 randomised 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.

7.4.3 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, Lutz, Schmidt, & Jäncke, 2006; Karageorghis & 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 *f*MRI-compatible earphones and sound intensity was maintained at ~75 dBA, which is deemed entirely safe from an audiological perspective (see Lindgren & Axelsson, 1988).

7.4.4 Psychological Measures

Five psychological measures were taken immediately after each exercise bout. At the end of each condition, the scales were presented on the *f*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 (SIAS) 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 participants' predominant focus of attention during the execution of motor tasks (e.g., Hutchinson & Karageorghis, 2013; Hutchinson et al., 2015).

Limb discomfort (CR10) 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 participants' 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, Fan, & Moe, 2002).

On the basis that we conceptualize affect as a dimensional domain, affective valence was assessed by use of the Feeling Scale (FS; Hardy & Rejeski, 1989), and affective arousal by use of the Felt Arousal Scale (FAS; Svebak & 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, Ekkekakis, Hall, & Petruzzello, 2000) that have been used extensively in field of exercise science to assess core affect (e.g., Study 3; Karageorghis et al., 2010). The psychological measures were administered in the same order for each exercise bout (1st SIAS, 2nd CR10, 3rd OE, 4th FS, and 5th FAS).

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, Jones, & Stuart, 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 & Jones, 2014).

7.4.5 Data Acquisition and Analysis

The brain was scanned continuously by use of a 3T 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). The BOLD response was subsequently identified using the software SPM12 (Friston, Ashburner, Kiebel, Nichols, & Penny, 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 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. 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 at an alpha level of $p < .0001$, uncorrected for the whole brain mass and a voxel extent threshold of 30 (cf. Dai, Liu, Saghal, Brown, & Yue, 2001). The Pickatlas toolbox (Maldjian, Laurienti, Kraft, & Burdette, 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 active regions of the brain and psychometric measures (see Poldrack, 2007). In such instances, the MarsBar toolbox (Brett, Anton, Valabregue, & Poline,

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.

7.4.6 Statistical Analysis

All statistical procedures were conducted by use of SPSS 22.0. Univariate outliers were identified through the use of standardised 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 $p < .05$.

7.5 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 & 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 ($M_{liking\ rate} = 7.10$, $SD = 1.88$ *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).

7.5.1 Perceptual and Affective Responses

No significant differences were identified between control and music for limb discomfort (CO: $M = 4.89$, $SE = .35$; MU: $M = 4.39$, $SE = .40$; $t_{18} = 1.264$; $p = .222$; $d = .29$), overall exertion (CO: $M = 3.15$, $SE = .31$; MU: $M = 2.89$, $SE = .28$; $t_{18} = .815$; $p = .426$; $d = .18$), and affective valence (CO: $M = 1.41$, $SE = .49$; MU: $M = 2.17$, $SE = .40$; $t_{16} = 1.879$; $p = .079$; $d = .43$). However, MU reallocated attention towards task-unrelated thoughts (CO: $M = 44.73$, $SE = 3.68$; MU: $M = 59.73$, $SE = 4.11$; $t_{18} = 2.286$; $p = .035$; $d = .52$; see Figure 7.1A) and up-regulated affective arousal (CO: $M = 2.39$, $SE = .18$; MU: $M = 2.94$, $SE = .15$; $t_{18} = 3.162$; $p = .005$; $d = .72$; see Figure 7.2B) when compared to CO.

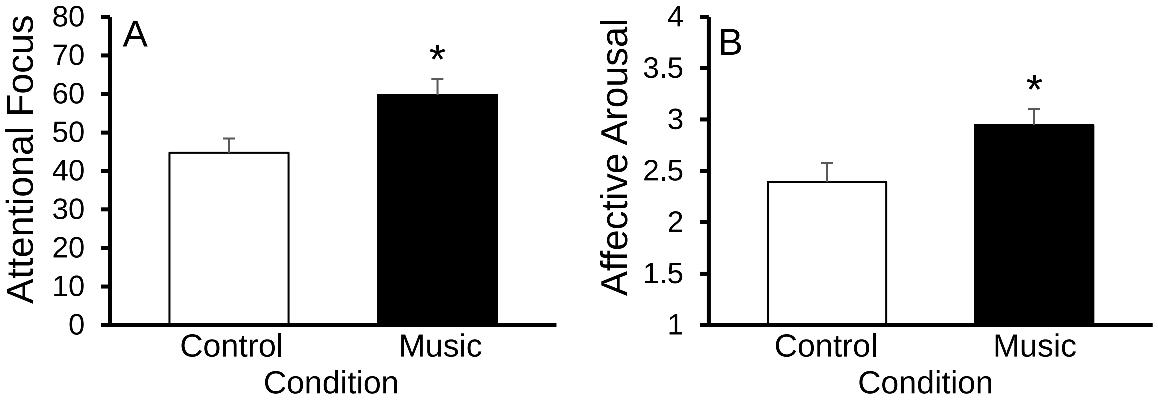


Figure 7.1. Comparison of psychological responses between CO and MU. *Note.* Means and standard errors are presented; A = attentional focus; B = affective arousal; $^{*} = p < .05$.

7.5.2 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 lingual gyrus (Brodmann area 18, MNI coordinates: $x = -8$, $y = -86$, $z = -20$; $t = 5.67$; $d = 1.30$; see Figure 7.2), 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 Figure 7.3). 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 Figure 7.4).

7.5.3 Correlational Analysis

We did not anticipate that the execution of isometric exercises performed in the presence of music would elicit increased activation of 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 centred on *x* = -18, *y* = 28, *z* = -8) and the psychological measures. A significant negative correlation was identified between the activity of the lIFG and exertional responses for MU (limb discomfort: *r* = -.54, *p* = .016; overall exertion: *r* = -.62, *p* = .005; see Figure 7.5) but not for CO (limb discomfort: *r* = -.25, *p* = .303; see Figure 7.5; overall exertion: *r* = -.25, *p* = .289). No significant correlations were identified with attentional focus (CO: *r* = .09, *p* = .696; MU: *r* = -.05, *p* = .827), affective valence (CO: *r* = .42, *p* = .073; MU: *r* = -.271, *p* = .262), and affective arousal (CO: *r* = .10, *p* = .672; MU: *r* = -.05, *p* = .845).

To avoid circular inference (i.e., double dipping; for details, see Kriegeskorte, Simmons, Bellgowan, & Baker, 2009), correlational analyses were conducted between psychological measures and activations in somatosensory regions of the brain (see 7.3 Research Hypotheses section). No significant correlations were identified between the activity of the left precentral gyrus (ROI: 5 mm sphere centred on x = -34, y = -22, z = 52) and any of the psychometric measures for both CO (attentional focus: *r* = -.35, *p* = .141; limb discomfort: *r* = -.06, *p* = .806; overall exertion: *r* = -.13, *p* = .578, affective valence: *r* = .28, *p* = .233; affective arousal: *r* = .34, *p* = .149) and MU (attentional focus: *r* = .10, *p* = .673; limb discomfort: *r* = .42, *p* = .864; overall exertion: *r* = -.13, *p* = .572, affective valence: *r* = .45, *p* = .053; affective arousal: *r* = .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 hypothesised by Karageorghis et al. (2017). In this case, a third 5 mm sphere was centred 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* = .25, *p* = .301; limb discomfort: *r* = -.24, *p* = .316; overall exertion: *r* = -.07, *p* = .773, affective valence: *r* = .25, *p* = .290; affective arousal: *r* = .14, *p* = .562) and music (attentional focus: *r* = .03, *p* = .894; limb discomfort: *r* = -.28, *p* = .234; overall exertion: *r* = -.38, *p* = .103, affective valence: *r* = -.09, *p* = .692; affective arousal: *r* = -.06, *p* = .812) conditions.

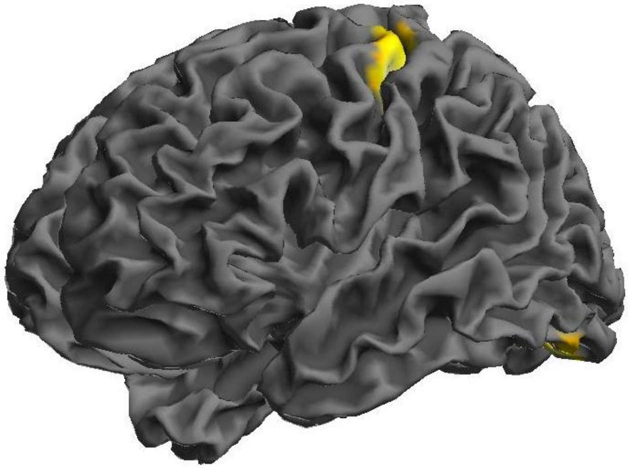


Figure 7.2. Significant group-level random-effects activation of left precentral gyrus and lingual gyrus during the execution of movements (contrast: exercise > rest).

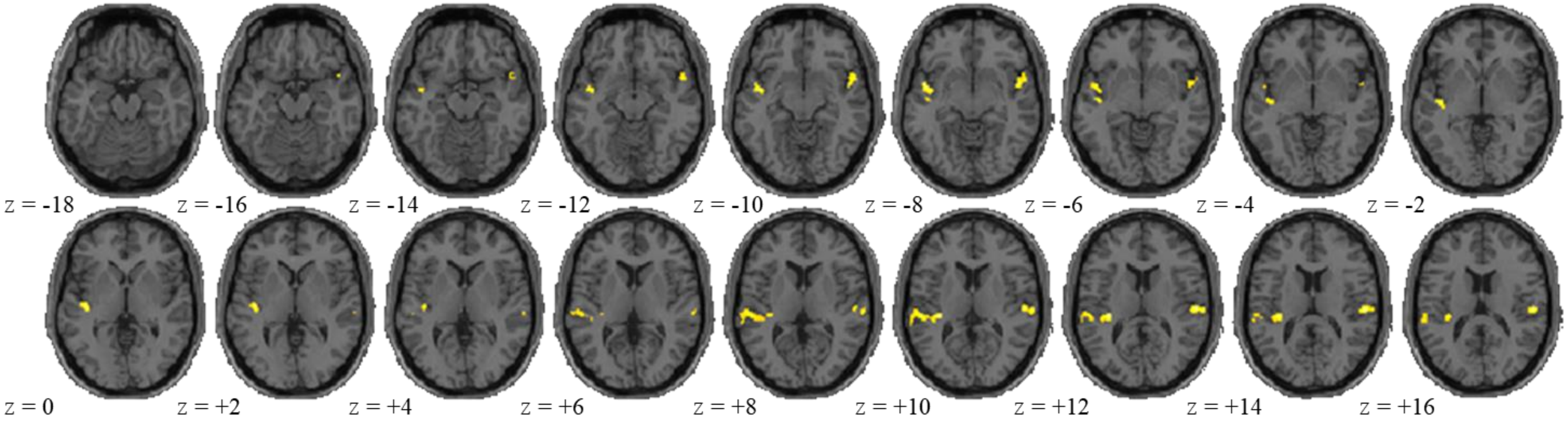


Figure 7.3. Significant group-level random-effects activation of superior temporal gyrus, transverse temporal gyrus, and insula during music listening (contrast: music > no-music).

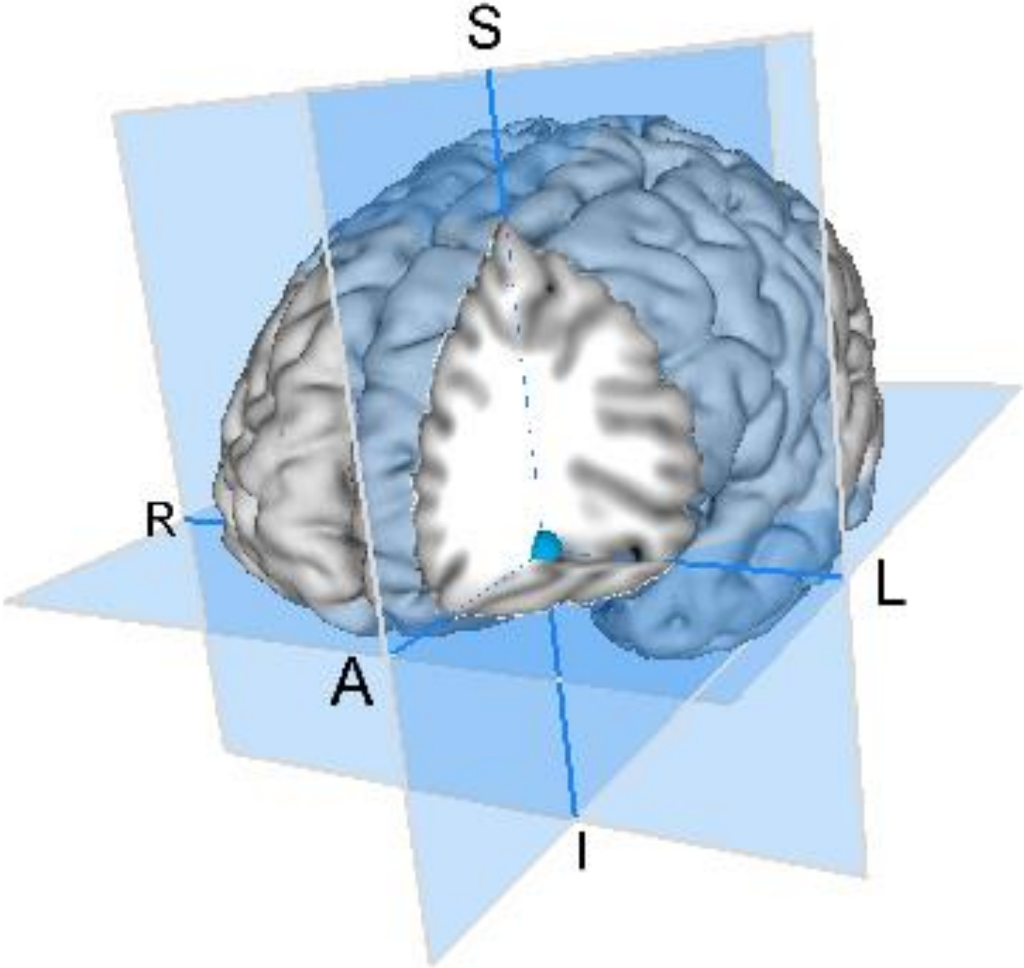


Figure 7.4. Significant group-level random-effects activation of left inferior frontal gyrus during exercise and music (contrast: exercise and music > exercise > music). *Note.* The blue blob represents the activity of the left inferior frontal gyrus; S = Superior; I = Inferior; R = Right; L = Left; A = Anterior.

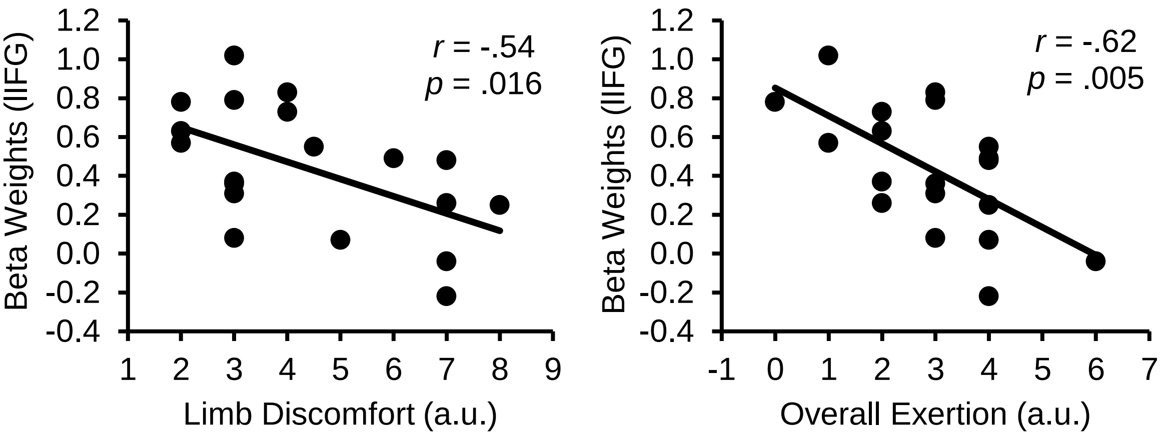


Figure 7.5. Significant correlation between the beta weights of the left inferior frontal gyrus and limb discomfort for the music condition (*n* = 19). *Note.* lIFG = left inferior frontal gyrus; a.u. = arbitrary units.

7.6 Discussion

The aim of Study 5 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 Study 5 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 Figure 7.4) and correlate negatively with exertional responses (limb discomfort: *r* = -.54; overall exertion: *r* = -.62; see Figure 7.5). 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 Study 5 was sufficiently potent to direct attentional focus towards task-unrelated thoughts (*d* = .52) and up-regulate affective arousal (*d* = .72) to a greater degree when compared to CO (see Figure 7.1). 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 Study 5 was relatively light (cf. Hutchinson & Karageorghis, 2013). 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).

7.6.1 Brain Activity

The execution of movements yielded greater activation in the precentral gyrus and lingual gyrus (see Figure 7.2). 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, Zubieta, & Liu, 2012) and could have been influenced by the visual stimulus used during the task (i.e., a bar timer). It is important to emphasise that the bar timer was also presented during the rest period, so participants were aware of the recovery period. However, this area may have activated to a greater degree in response to visual motion predictions (i.e., preparing for the period of contraction) that were absent 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 Figure 7.3). 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 Figure 7.4). Moreover, music has the potential to shift attention externally, up-regulate affective arousal, and increase activation of the lIFG during execution of an isometric muscle contraction. I 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 (Study 3). 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; see 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, Rüschemeyer, Hahne, & Fiebach, 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, Schandry, Auer, & Kaufmann, 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 Figure 7.4) and the negative relationship with exertional responses (see Figure 7.5).

7.6.2 Limitations

The piece of music used in Study 5 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 7.5 Results section). It is also important to emphasise that different auditory stimuli (e.g., self-selected music) could have imposed a threat to internal validity (Karageorghis & Priest, 2012). I decided to standardise 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 towards 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 (Study 2).

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 imposed 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.

7.7 Conclusions

Study 5 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 towards task-unrelated information and up-regulated 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. It has been hypothesised 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.

Chapter 8: General Discussion

The present research programme was undertaken with a view to further understanding of the cerebral mechanisms that underlie the effects of music on exercise. This body of work is comprised of an extensive review of literature and five original studies, each of which is now published in international peer-reviewed journals (Bigliassi et al., 2016b; Bigliassi et al., 2017; Bigliassi et al., 2018a; Bigliassi et al., 2018b; Bigliassi et al., 2018c). The author used a variety of contexts (e.g., laboratory and real-life), exercise modes (e.g., walking and cycling), intensities (e.g., maximal and submaximal), and research techniques (e.g., EEG and *f*MRI) to explore the main research question from different perspectives. The results indicate that music is a complex auditory stimulus that has the potential to influence psychophysical, psychological, physiological, and psychophysiological parameters during exercise. More importantly, music can be used as a *tool* to explore more complex neuropsychological phenomena such as attention and fatigue. This section summarises the main findings that emanated from chapters 3–7, discusses some of the commonalities across the studies, sets the programme of research in a broader context, and proposes future research directions.

8.1 Overview of Main Findings

Study 1 (Chapter 3): Cerebral mechanisms underlying the effects of music during a fatiguing isometric ankle-dorsiflexion task. Study 1 sought to explore the brain mechanisms that underlie the positive effects of music on task performance and fatigue-related sensations. The author decided to use EEG during a closed-kinetic chain exercise performed to the point of volitional exhaustion in order to reveal some of the neural networks that activate in response to exercise and music. The results indicate that music increased the use of dissociative thoughts, enhanced task performance, and down-regulated the power of low-frequency waves (i.e., theta) in the frontal, central, and parietal regions. These low-frequency waves are usually up-regulated when participants experience fatigue-related symptoms (Craig et al., 2012; Pires et al., 2018). In such instances, the author hypothesised that by forcing attention towards external influences, processing of internal sensory cues is reduced, which subsequently leads to a more autonomous control of working muscles and amelioration of exertional responses. The results of this study are also in line with another study published by the same group of researchers (Bigliassi et al., 2016a), which demonstrated that motivational audiovisual stimuli have the potential to re-arrange the brain's electrical frequency and enhance exercise performance to a greater degree when compared to a no-music condition.

Study 2 (Chapter 4): Effects of auditory distraction on voluntary movements: Exploring the underlying mechanisms associated with parallel processing. The second study of this thesis shared a similar experimental design to Study 1. However, Study 2 was undertaken to elucidate some of the neural networks that activate when individuals are distracted by music during the execution of highly-demanding cognitive motor tasks. In this case, participants were required to execute a part-body exercise task at 20% of MVC for short time periods and monitor the force produced and time of contraction. A short music excerpt was delivered randomly during the trials to reveal the brain mechanisms associated with selective attention.

The results indicated that the recruitment of motor units, measured indirectly through the use of EMG, was not affected by music and the amplitude of the ERPs was up-regulated at .368 ms after the stimulus onset. After reconstructing the sources of the electrical signal, the author identified that increased activity of the right parietal regions and reduced activity of the left frontal regions was evident in the presence of environmental distractors. The author hypothesised that a parallel processing mechanism takes place when individuals execute highly-demanding cognitive motor tasks in the presence of auditory distractions. This neurophysiological response could be associated with a decision-making strategy to reduce processing of external influences and thus prevent the disruption of task performance.

Study 3 (Chapter 5): Effects of auditory stimuli on electrical activity in the brain during cycle ergometry. Study 3 was conducted to clarify some of the brain mechanisms that underlie the use of music during a dynamic exercise mode (i.e., cycling) performed at light-to-moderate-intensities. This third study represents possibly the most comprehensive experiment in the field of exercise psychology to date that elucidated the neurophysiological mechanisms that underlie the effects of music during exercise. This is due to the fact that the author managed to employ a series of research techniques and processing methods to provide readers with a more complete picture of the brain mechanisms that are associated with the effects of music during exercise. The results indicated that music re-arranged the frequency of neural synchronisation at Cz electrode and increased the amplitude of the EMG signal in the vastus lateralis. This could be indicative of a more autonomous control of working muscles that is primarily mediated by changes in attention allocation (Bigliassi, 2015; Lim et al., 2014). This study also shed new light on the mechanisms that underlie the commonly reported effects of music on affective valence and perceived exertion. The author tested the corollary discharge model (Pageaux, 2016) and identified that music reduced the connectivity across somatosensory regions. This psychophysiological mechanism could be representative of a reduction in efferent copies that are emitted from the central motor command to adjacent areas such as the frontal cortex and postcentral gyrus.

Study 4 (Chapter 6): *The Way You Make Me Feel*: Psychological and cerebral responses to music during real-life physical activity. The experimental protocol of Study 4 was purposively designed to explore the effects of music on light-intensity bouts of physical activity. This study also represented one of the first scientific attempts to measure electrical activity in the brain during real-life situations by use of a state-of-the-art portable EEG technology (EEGO Sports ANT Neuro). The exercise task required participants to walk 400 m at self-paced speeds on an outdoor running track. The author used EEG to verify whether psychological responses that are commonly elicited by music were coupled with changes in the brain's electrical frequency. The main findings of this study were that music increased the use of dissociative thoughts, induced more positive affective responses, enhanced perceived enjoyment, and up-regulated high-frequency components of the power spectrum (i.e., beta waves) in the frontal and frontal-central regions to a greater degree than no-music conditions. The author hypothesised that increases in beta wave activity could be induced primarily by the arousal potential of a stimulus (Sayorwan et al., 2013). In such instances, high-frequency waves in the brain could have a prophylactic effect in regard to fatigue-related symptoms that are commonly reported during highly-demanding motor tasks (e.g., high-intensity exercises). Put another way, beta waves might have the potential to partially prevent the up-regulation of low-frequency brain waves (Sherman et al., 2016), leading to a subsequent amelioration of fatigue and enhancement of task performance when the exercise intensity becomes moderate to severe.

Study 5 (Chapter 7): Cerebral effects of music during isometric exercise: An *f*MRI Study. The final original contribution of this thesis was undertaken using *f*MRI to explore the brain regions that activate in response to exercise and music. Participants were required to execute a handgrip task performed at light-to-moderate-intensities for short periods of time. The author was responsible for constantly monitoring the BOLD response and measuring perceptual and affective responses after each condition (i.e., control and music). The results of Study 5 indicated that music forced attention towards exteroceptive sensory cues, and up-regulated arousal to a greater degree when compared to control. The combination of music and exercise (i.e., *f* contrast: music and exercise > exercise > music) also yielded increased activation in the lIFG. Correlational analysis indicated that a significant inverse relationship between the activity of this region and exertional responses was identified. In other words, music has the potential to guide attention externally and reduce processing of internal sensory cues; a neurophysiological mechanism responsible for the amelioration of fatigue-related symptoms and enhancement of affective responses (Karageorghis, 2017; Stork et al., 2015). Accordingly, increased activation in the lIFG appears to protect individuals against internal association and assuage negative bodily sensations during the execution of isometric exercises.

8.2 Common Themes

A series of commonalities was manifest in the studies that comprise the present research programme. In this section, the author provides a comprehensive framework that bridges the results of the five original studies. It became evident throughout the course of this programme that brain frequencies and amplitudes are not isolated responses. On the contrary, the power of each frequency, the amplitude of ERPs, and the activity of brain regions are highly interactive in nature. For example, up-regulation of theta waves will certainly impact upon the power of high-frequency bands such as beta waves. Similarly, increased activity in the parietal cortex can lead to subsequent effects on frontal areas of the brain. Accordingly, changes in brain activity will almost certainly affect psychophysical, affective, and psychophysiological responses. In such instances, self-reported measures should not be interpreted in a simplistic and reductionist manner (cf. Ring, Kavussanu, & Willoughby, 2016). In actuality, some of the questionnaires and scales used in this body of work provide a vista of complex neural mechanisms.

Psychophysiological mechanisms. In order to describe how brain activity is re-organised during exercise, the author used a series of exteroceptive (e.g., ambient music) and interoceptive (e.g., movement execution) sensory signals. Such signals are valuable tools that can be used to explore complex psychophysiological phenomena. Music, podcasts, and audiobooks have the potential to force attention externally and initiate a cascade of reactions that lead to the commonly observed psychological responses such as enhanced affect and reduced perceived exertion (Study 3; Karageorghis, 2017). However, music has been consistently more potent than the other forms of auditory stimuli used in this research programme. This is probably due to the fact that participants tend to have a more positive aesthetic response to music when compared to other forms of auditory stimuli during exercise (Study 3 and Study 4).

It is evident in Study 4 (Chapter 6) that music reallocates attentional focus towards environmental sensory cues, elicits more positive emotional responses, and up-regulates the power of beta waves in the frontal and frontal-central regions during exercise tasks performed at self-paced speeds (i.e., light-intensity). Interestingly, beta waves show a negative correlation with low-frequency waves such as theta (Sherman et al., 2016), which commonly up-regulate when participants experience fatigue-related sensations (Craig et al., 2012; Pires et al., 2018). It is also evident that the power of theta waves was partially suppressed when participants exercised to the point of volitional exhaustion (Study 1; see Chapter 3). The question that remains is why the author could not identify up-modulations in beta frequencies when participants executed the motor task until the point of voluntary exhaustion? It is hypothesised that exertional responses are much more potent (in terms of brain processing) than environmental sensory stimuli (Rejeski, 1985). In such instances, it is only a matter of time until fatigue-related sensations suppress processing of external influences and inhibit high-frequency waves throughout the brain.

According to the heuristic psychophysiological model of exercise proposed herein (see Figure 8.1), up-regulation of theta waves initiates a conscious mechanism where individuals *evaluate* the purpose of their actions and are forced to make decisions as to whether they should continue the exercise. Music-related interventions have the potential to distract and prevent associative thoughts from compromising the neural control of working muscles (Study 1 and Study 3). By guiding attention externally, music can delay the point at which the execution of movements becomes a conscious process (i.e., it usually occurs at VT), and reduce processing of muscle afferents (Hutchinson & Karageorghis, 2013). This psychological response has also been coupled with increases in beta wave power (see Figure 6.2). Beta waves are also up-regulated when individuals are exposed to highly motivational stimuli and are generally inversely correlated with low-frequency waves. Therefore, music may serve to counteract the detrimental effects of fatigue and facilitate voluntary control (Bigliassi et al., 2016a). From a practical point of view, a clutch of studies has used the same mechanism serendipitously in order to enhance affective responses and ameliorate perceived exertion in clinical populations, for example people with diabetes, COPD, and cystic fibrosis (see e.g., Brooks et al., 2003; Calik-Kutukcu et al., 2016; Hutchinson, Karageorghis, & Black, 2017). It is important to emphasise that the model presented in this thesis is an instrument that can be used to provide further evidence regarding the up-/down-modulations in psychophysiological responses that occur during exercise, and potentially reveal a mechanistic explanation of fatigue. This is based, in part, on Williams James's epistemological notion of pragmatism: "theories thus become instruments, not answers to enigmas in which we can rest" (Olin, 1992, p. 42).

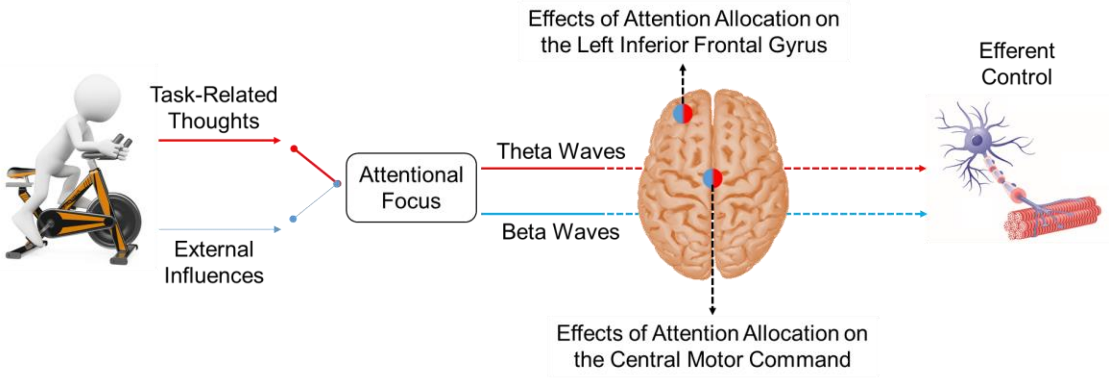


Figure 8.1. A heuristic psychophysiological model of exercise. *Note*. Blue arrows/semi-circle are representative of a positive influence and red arrows/semi-circle are representative of a negative influence.

It is important to emphasise that changes in spectral power (i.e., average) were not manifest in Study 3 (Chapter 5). The present author hypothesises that the exercise intensity employed was sufficient to increase perceived exertion to the degree to which the amplitude of beta waves was partially suppressed but fatigue-related sensations were not sufficiently potent to up-regulate low-frequency waves such as theta. Accordingly, the author employed more complex processing methods and identified that the frequency of the synchronisation–desynchronisation–resynchronisation cycle was affected by the presence of music. Study 3 served to clarify that the presence of music can alter the neural control of working muscles and influence the recruitment of motor units. In order to further explore the mechanisms that underlie the psychological responses associated with the use of music, the author also calculated the level of communication across somatosensory regions. A reduction in brain connectivity was revealed and the author hypothesised that changes in the synchronisation–desynchronisation–resynchronisation cycle could also have an impact upon the frequency of electrical signals that reach other regions of the brain concerned with exercise consciousness and focal awareness (e.g., middle frontal and postcentral gyri; de Morree et al., 2014).

The author still felt the need to investigate the brain region(s) that activate in response to exercise and music through the use of high-spatial resolution techniques. The fifth study (Chapter 7) indicated that a very specific region (i.e., the lIFG) appears to activate and is negatively correlated with exertional responses. Interestingly, results from Study 2 (Chapter 4) revealed through the use of source reconstruction analysis that auditory stimuli are usually suppressed/parallel processed at .368 ms following the stimulus onset and the left frontal regions of the brain are not so active in such instances. It is hypothesised that the left frontal regions of the cortex represent a hub of sensory integration responsible for processing signals from internal and external sources. The execution of highly-demanding cognitive motor tasks has the potential to prevent this region from becoming active. It appears that the right parietal regions assume an inhibitory effect with the ultimate goal of preventing performance disruption. Conversely, when individuals execute low-demanding motor tasks performed at light-intensity, the left frontal regions of the cortex activate in the presence of music and reduce processing of interoceptive signals; a neurophysiological mechanism that might serve to facilitate voluntary control and assuage exertional responses (cf. Pollatos et al., 2007; Shigihara et al., 2013).

Practical concerns. Although music-related interventions have been used extensively in the field of sport and exercise sciences as a form of distraction to guide attention externally and ameliorate negative bodily sensations (see Karageorghis, 2017), the author made use of music and other auditory stimuli as *tools* to study complex neuropsychological phenomena such as attention and fatigue. It could be argued that based on the results of the five original studies presented in this thesis, music-related interventions should be implemented by exercise professionals and healthcare providers as an effective means through which to facilitate the control of movements and elicit a more positive affective state (e.g., Clark et al., 2016). However, the neurophysiological measures employed in the present body of work indicated that, perhaps, music is an even more potent stimulus than previously thought. Accordingly, music-related interventions can also lead to detrimental effects that were not fully appreciated by the scientific community.

The recurrent use of music and other forms of stimulation in gymnasia and health centres might also lead to the phenomenon of stimulus dependence, where individuals feel unable to exercise in the absence of environmental distractions. This could be primarily due to the fact that many exercisers have learnt how to distract themselves from the negative sensations elicited by moderate-to-high- and high-intensity exercise (cf. Hallet & Lamont, 2015). However, there has been a noticeable dearth of interventions aiming to imbue exercisers with a sense of appreciation for the joys of physical activity conducted in the absence of sensory distractions. Therefore, the present author suggests that music-related interventions and other forms of both auditory and visual stimulation should be implemented with due care during exercise/training sessions, in accord with guidelines for best practice (see e.g., Karageorghis, 2017). Finally, it is also important to emphasise that individuals should learn how to cope with the negative bodily sensations that are commonly experienced during exercise or training performed above the ventilatory threshold (see Blanchfield et al., 2014). A suitable coping strategy has the potential to facilitate the execution of movements during challenging physical tasks when music and other forms of stimulation might be unavailable or even contraindicated (e.g., during road cycling; Karageorghis et al., 2012).

8.3 Conclusions and Recommendations

The present research programme sought to further understanding of the neural networks that activate in response to exercise and music. The results of the five original studies presented herein support the use of music as an auditory stimulus that has the potential to guide attention externally, assuage negative bodily sensations, and enhance affective responses during exercise. The cerebral mechanisms that underlie the psychophysical, psychological, and psychophysiological effects of music on exercise appear to be associated with the re-arrangement of the brain electrical frequency and increased activation of the left frontal cortex. Reallocation of attentional focus towards exteroceptive sensory cues prevents internal signals from entering focus awareness; a phenomenon that may initiate a series of domino psychophysiological reactions (e.g., changes in heart rate variability). Up-regulation of low-frequency waves that is commonly observed during the execution of movements are primarily associated with fatigue-related symptoms (Craig et al., 2012). It has been hypothesised that low-frequency waves increase as a means by which to slow the body down and force individuals to interrupt the execution of movements performed at high-intensities (Pires et al., 2018).

The results of the present body of work indicate that music can also be used as a tool to explore some of the most recent models to study fatigue (e.g., the corollary discharge model; see Pageaux, 2016). Music can alleviate negative bodily sensations during exercise, meaning that a parallel processing mechanism takes place when individuals exercise in the presence of pleasant environmental stimuli (Karageorghis et al., 2017; Rejeski, 1985). In such instances, brain connectivity analysis can be used as an indirect measure to further understanding of how different regions communicate and then explore the effects of auditory distractions on efferent control and corollary signals (Study 3). Similarly, by investigating the brain region(s) that activate in response to exercise and music researchers are able to study interoceptive and exteroceptive awareness from a unique perspective. It has also been proposed that brain stimulation techniques can be employed as a counterproof method to modulate the activity of the left frontal cortex and clarify whether the lIFG is actually involved in processing of exertional responses.

Taken holistically, the present body of work demonstrates a vibrant and reflexive matrix of attentional, emotional, physiological, and psychophysiological responses to music during various exercise modes and intensities. The five original studies presented in this thesis also provide evidence of the role that music-related interventions can play in increasing the use of dissociative thoughts, assuaging negative bodily sensations, and eliciting a more positive affective state during exercise performed at a variety of intensities. Albeit the late, great Bob Marley was clearly mindful of the analgesic properties of music with the utterance, “When music hits you, you feel no pain”, the neurophysiological mechanisms that underlie such effects were largely unexplored; until now, that is. All emergent hypotheses and the heuristic conceptual model proposed by the author (see Figure 8.1) can be used to frame future research efforts.

References

Abbiss, C. R., Karagounis, L. G., Laursen, P. B., Peiffer, J. J., Martin, D. T., Hawley, J. A., … Martin, J. C. (2011). Single-leg cycle training is superior to double-leg cycling in improving the oxidative potential and metabolic profile of trained skeletal muscle. *Journal of Applied Physiology, 110,* 1248–1255. doi:10.1152/japplphysiol.01247.2010

Abbiss, C. R., Peiffer, J. J., Meeusen, R., & Skorski, S. (2015). Role of ratings of perceived exertion during self-paced exercise: What are we actually measuring? *Sports Medicine, 45,* 1235–1243. doi:10.1007/s40279-015-0344-5

Abbott, A. (2002). Music, maestro, please! *Nature, 416,* 412–416. doi:10.1038/416012a

Abdulhay, E., Oweis, R., Alhaddad, A., Sublaban, F., Radwan, M., & Almasaeed, H. (2014). Non-invasive fetal heart rate monitoring techniques. *Biomedical Science and Engineering, 2,* 53–67. doi:10.12691/bse-2-3-2

Aftanas, L. I., & Golocheikine, S. A. (2001). Human anterior and frontal midline theta and lower alpha reflect emotionally positive state and internalized attention: High-resolution EEG investigation of meditation. *Neuroscience Letters, 310,* 57–60. doi:10.1016/S0304-3940(01)02094-8

Allen, D. P., & MacKinnon, C. D. (2010). Time-frequency analysis of movement-related spectral power in EEG during repetitive movements: A comparison of methods. *Journal of Neuroscience Methods, 186,* 107–115. doi:10.1016/j.jneumeth.2009.10.022

Allman, P. (1988). Crying and laughing after brain damage: A confused nomenclature. *Journal of the Neurological Sciences, 52,* 1439–1440.

Altimari, L. R., Dantas, J. L., Bigliassi, M., Kanthack, T. F. D., Moraes, A. C., & Abrão, T. (2012). Influence of different strategies of treatment muscle contraction and relaxation phases on EMG signal processing and analysis during cyclic exercise. In G. R. Naik (Eds.), *Computational intelligence in electromyography analysis – a perspective on current applications and future challenges* (pp. 97–116). Rijeka, Croatia: Intech. doi:10.5772/50599

Amann, M., & Secher, N. H. (2010). Last word on point: Counterpoint: Afferent feedback from fatigued locomotor muscles is an important determinant of endurance exercise performance. *Journal of Applied Physiology, 108,* 469–469. doi:10.1152/japplphysiol.01386.2009

Amann, M., Sidhu, S. K., Weavil, J. C., Mangum, T. S., & Venturelli, M. (2015). Autonomic responses to exercise: Group III/IV muscle afferents and fatigue. *Autonomic Neuroscience, 188,* 19–23. doi:10.1016/j.autneu.2014.10.018

Amann, M., Venturelli, M., Ives, S. J., McDaniel, J., Layec, G., Rossman, M. J., & Richardson, R. S. (2013). Peripheral fatigue limits endurance exercise via a sensory feedback-mediated reduction in spinal motoneuronal output. *Journal of Applied Physiology, 115,* 355–364. doi:10.1152/japplphysiol.00049.2013

Amaro, E., & Barker, G. J. (2006). Study design in *f*MRI: Basic principles. *Brain and Cognition, 60,* 220–232. doi:10.1016/j.bandc.2005.11.009

Arendt-Nielsen, L., & Mills, K. R. (1988). Muscle fibre conduction velocity, mean power frequency, mean EMG voltage and force during submaximal fatiguing contractions of human quadriceps. *European Journal of Applied Physiology and Occupational Physiology, 58,* 20–25. doi:10.1007/BF00636598

Arida, R. M., de Almeida, A.-C. G., Cavalheiro, E. A., & Scorza, F. A. (2013). Experimental and clinical findings from physical exercise as complementary therapy for epilepsy. *Epilepsy & Behavior, 26,* 273–278. doi:10.1016/j.yebeh.2012.07.025

Aspinall, P., Mavros, P., Coyne, R., & Roe, J. (2015). The urban brain: Analysing outdoor physical activity with mobile EEG. *British Journal of Sports Medicine, 49,* 272–276. doi:10.1136/bjsports-2012-091877

Asutay, E., & Västfjäll, D. (2012). Perception of loudness is influenced by emotion. *PLoS ONE, 7,* 2–6. doi:10.1371/journal.pone.0038660

Aue, T., Lavelle, L. A., & Cacioppo, J. T. (2009). Great expectations: What can *f*MRI research tell us about psychological phenomena? *International Journal of Psychophysiology, 73,* 10–16. doi:10.1016/j.ijpsycho.2008.12.017

Averill, J., Chon, K., & Hahn, D. (2001). Emotions and creativity, East and West. *Asian Journal of Social Psychology, 4,* 165–183.

Avitan, L., Teicher, M., & Abeles, M. (2009). EEG generator—A model of potentials in a volume conductor. *Journal of Neurophysiology, 102,* 3046–3059. doi:10.1152/jn.91143.2008

Ayres, L. (1911). The influence of music on speed in the six-day bicycle race. *American Physical Education Review, 16,* 321–324. doi:10.1080/23267224.1911.10651270

Baccalá, L. A., & Sameshima, K. (2001). Partial directed coherence: a new concept in neural structure determination. *Biological Cybernetics, 84,* 463–474. doi:10.1007/PL00007990

Bacon, C. J., Myers, T. R., & Karageorghis, C. I. (2012). Effect of music-movement synchrony on exercise oxygen consumption. *The Journal of Sports Medicine and Physical Fitness, 52,* 359–365.

Baghurst, T., Thierry, G., & Holder, T. (2004). Evidence for a relationship between attentional styles and effective cognitive strategies during performance. *Athletic Insight, 6,* 36–51.

Bailey, S. P., Hall, E. E., Folger, S. E., & Miller, P. C. (2008). Changes in EEG during graded exercise on a recumbent cycle ergometer. *Journal of Sports Science and Medicine, 7,* 505–511. doi:10.1016/j.neuroscience.2012.10.037.

Ball, P. (2008). Science & Music: Facing the music. *Nature, 453,* 160–162. doi:10.1038/453160a

Baniweicz, N. (1961). A new external reflex in cases of severe cerebral damage. *British Medical Journal, 23,* 1675–1678.

Banks, S. J., Eddy, K. T., Angstadt, M., Nathan, P. J., & Phan, K. L. (2007). Amygdala-frontal connectivity during emotion regulation. *Social Cognitive and Affective Neuroscience, 2,* 303–312. doi:10.1093/scan/nsm029

Barreto-Silva, V., Bigliassi, M., Chierotti, P., & Altimari, L. R. (2018). Psychophysiological effects of audiovisual stimuli during cycle exercise. *European Journal of Sport Science, 18,* 560–568. doi:10.1080/17461391.2018.1439534

Barrett, K., Barman, S., Boitano, S., & Brooks, H. (2009). *Ganong's review of medical physiology* (23rd ed.). New York, NY: McGraw-Hill Medical.

Barstow, T. J., Buchthal, S., Zanconato, S., & Cooper, D. M. (1994). Muscle energetics and pulmonary oxygen uptake kinetics during moderate exercise. *Journal of Applied Physiology, 77,* 1742–1749.

Bartsch, F., Hamuni, G., Miskovic, V., Lang, P. J., & Keil, A. (2015). Oscillatory brain activity in the alpha range is modulated by the content of word-prompted mental imagery. *Psychophysiology, 52,* 727–735. doi:10.1111/psyp.12405

Bassett, D., & Gazzaniga, M. (2011). Understanding complexity in the human brain. *Trends in Cognitive Sciences, 15,* 200–209. doi:10.1016/j.tics.2011.03.006.

Baumeister, R. F., Bratslavsky, E., Finkenauer, C., & Vohs, K. D. (2001). Bad is stronger than good. *Review of General Psychology, 5,* 323–370. doi:10.1037//1089-2680.5.4.323

Baumgartner, T., Lutz, K., Schmidt, C. F., & Jäncke, L. (2006). The emotional power of music: How music enhances the feeling of affective pictures. *Brain Research, 1075,* 151–164. doi:10.1016/j.brainres.2005.12.065

Beaulac, J., Carlson, A., & Boyd, R. J. (2011). Counseling on physical activity to promote mental health. *Canadian Family Physician, 57,* 399–401.

Beedie, C., Terry, P., & Lane, A. (2005). Distinctions between emotion and mood. *Cognition & Emotion, 19,* 847–878. doi:10.1080/02699930541000057

Bellini, L. M., Blaime, M., & Shea, J. (2002). Variation of mood and empathy during internship. *Jama, 287,* 3143–3146. doi:10.1001/jama.287.23.3143

Bensimon, M., Amir, D., & Wolf, Y. (2008). Drumming through trauma: Music therapy with post-traumatic soldiers. *The Arts in Psychotherapy, 35,* 34–48. doi:10.1016/j.aip.2007.09.002

Berlyne, D. E. (1971). *Aesthetics and psychobiology*. New York, NY: Appleton-Century-Crofts.

Bernier, M., Codron, R., Thienot, E., & Fournier, J. F. (2011). The attentional focus of expert golfers in training and competition: A naturalistic investigation. *Journal of Applied Sport Psychology, 23,* 326–341. doi:10.1080/10413200.2011.561518

Bernstein, J. J., & Bernstein, J. (2015). Texting at the light and other forms of device distraction behind the wheel. *BMC Public Health, 15,* 968. doi:10.1186/s12889-015-2343-8

Berridge, K., & Kringelbach, M. (2013). Neuroscience of affect: Brain mechanisms of pleasure and displeasure. *Current Opinion in Neurobiology*, *23*, 294–303. doi:10.1016/j.conb.2013.01.017.

Berti, S., & Schröger, E. (2003). Working memory controls involuntary attention switching: Evidence from an auditory distraction paradigm. *European Journal of Neuroscience, 17,* 1119–1122. doi:10.1046/j.1460-9568.2003.02527.x

Bigliassi, M. (2015). Corollary discharges and fatigue-related symptoms: The role of attentional focus. *Frontiers in Psychology, 6,* e1002. doi:10.3389/fpsyg.2015.01002

Bigliassi, M., Barreto-Silva, V., Altimari, L. R., Vandoni, M., Codrons, E., & Buzzachera, C. F. (2015b). How motivational and calm music may affect the prefrontal cortex area and emotional responses: A functional near-infrared spectroscopy (*f*NIRS) study. *Perceptual & Motor Skills, 120,* 202–218. doi:10.2466/27.24.PMS.120v12x5

Bigliassi, M., Karageorghis, C. I., Nowicky, A. V., Wright, M. J., & Orgs, G. (2018a). Effects of auditory distraction on voluntary movements: exploring the underlying mechanisms associated with parallel processing. *Psychological Research*. Advance online publication. doi:10.1007/s00426-017-0859-5

Bigliassi, M., Karageorghis, C. I., Bishop, D. T., Nowicky, A. V., & Wright, M. J. (2018c). Cerebral effects of music during isometric exercise: An *f*MRI study. *International Journal of Psychophysiology*. Accepted for publication.

Bigliassi, M., Karageorghis, C. I., Hoy, G. K., & Layne, G. S. (2018b). *The Way You Make Me Feel*: Psychological and cerebral responses to music during real-life physical activity. *Psychology of Sport and Exercise*. Advance online publication. doi:10.1016/j.psychsport.2018.01.010

Bigliassi, M., Karageorghis, C. I., Nowicky, A. V., Orgs, G., & Wright, M. J. (2016b). Cerebral mechanisms underlying the effects of music during a fatiguing isometric ankle-dorsiflexion task. *Psychophysiology, 53,* 1472–1483. doi:10.1111/psyp.12693

Bigliassi, M., Karageorghis, C. I., Wright, M. J., Orgs, G., & Nowicky, A. V. (2017). Effects of auditory stimuli on electrical activity in the brain during cycle ergometry. *Physiology & Behavior, 177,* 135–147. doi:10.1016/j.physbeh.2017.04.023

Bigliassi, M., León-Domínguez, U., Buzzachera, C. F., Barreto-Silva, V., & Altimari, L. R. (2015a). How does music aid 5 km of running? *Journal of Strength & Conditioning Research, 29,* 305–314. doi:10.1519/JSC.0000000000000627

Bigliassi, M., Scalassara, P., Kanthack, T., Abrão, T., Moraes, A., & Altimari, L. (2014). Fourier and Wavelet spectral analysis of EMG signals in 1-km cycling time-trial. *Applied Mathematics, 5,* 1878–1886.

Bigliassi, M., Silva, V. B., Karageorghis, C. I., Bird, J. M., Santos, P. C., & Altimari, L. R. (2016a). Brain mechanisms that underlie the effects of motivational audiovisual stimuli on psychophysiological responses during exercise. *Physiology & Behavior, 158,* 128–136. doi:10.1016/j.physbeh.2016.03.001

Billman, G. E. (2011). Heart rate variability – a historical perspective. *Frontiers in Physiology, 2,* e86. doi:10.3389/fphys.2011.00086

Bishop, D. J. (2012). Fatigue during intermittent-sprint exercise. *Clinical and Experimental Pharmacology and Physiology, 39,* 836–841. doi:10.1111/j.1440-1681.2012.05735.x

Bishop, D. T., Karageorghis, C. I., & Loizou, G. (2007). A grounded theory of young tennis players use of music to manipulate emotional state. *Journal of Sport & Exercise Psychology, 29,* 584–607.

Bishop, D. T., Wright, M. J., & Karageorghis, C. I. (2014). Tempo and intensity of pre-task music modulate neural activity during reactive task performance. *Psychology of Music, 42,* 714–727. doi:10.1177/0305735613490595

Bisley, J. W., & Goldberg, M. E. (2010). Attention, intention, and priority in the parietal lobe. *Annual Review of Neuroscience, 33,* 1–21. doi:10.1146/annurev-neuro-060909-152823.

Bispham, J. (2006). Rhythm in music: What is it? who has it? and why? *Music Perception, 24,* 125–134. doi:MP.2006.24.2.125

Blanchfield, A. W., Hardy, J., De Morree, H. M., Staiano, W., & Marcora, S. M. (2014). Talking yourself out of exhaustion: The effects of self-talk on endurance performance. *Medicine & Science in Sports & Exercise, 46,* 998–1007. doi:10.1249/MSS.0000000000000184

Bland, J. M., & Altman, D. G. (1996). Transformations, means, and confidence intervals. *British Medical Journal, 312,* 1079. doi:10.1136/bmj.312.7038.1079

Blood, A., Zatorre, R., Bermudez, P., & Evans, A. (1999). Emotional responses to pleasant and unpleasant music correlate with activity in paralimbic brain regions. *Nature Neuroscience, 2,* 382–387.

Bood, R. J., Nijssen, M., van der Kamp, J., & Roerdink, M. (2013). The power of auditory-motor synchronization in sports: Enhancing running performance by coupling cadence with the right beats. *PLoS ONE, 8,* e70758. doi:10.1371/journal.pone.0070758

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Champaign, IL: Human Kinetics.

Borg, G. A. V. (1982). Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise, 14,* 377–381.

Boudreaux, B. D., Hebert, E. P., Hollander, D. B., Williams, B. M., Cormier, C. L., Naquin, M. R., … Kraemer, R. R. (2018). Validity of wearable activity monitors during cycling and resistance exercise. *Medicine & Science in Sports & Exercise, 50,* 624–633. doi:10.1249/MSS.0000000000001471

Boullosa, D., & Nakamura, F. (2013). The evolutionary significance of fatigue. *Frontiers in Physiology, 4,* e309. doi:10.3389/fphys.2013.00309

Boutcher, S., & Trenske, M. (1990). The effects of sensory deprivation and music on perceived exertion and affect during exercise. *Journal of Sport & Exercise Psychology, 12,* 167–176.

Bowler, D. E., Buyung-Ali, L. M., Knight, T. M., & Pullin, A. S. (2010). A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health, 10,* 456. doi:10.1186/1471-2458-10-456

Bradt, J., Dileo, C., & Shim, M. (2013). Music interventions for preoperative anxiety. *Cochrane Database of Systematic Reviews, 6,* 1–81. doi:10.1002/14651858.CD006908.pub2

Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences of the United States of America, 105,* 14325–14329. doi:10.1073/pnas.0803390105

Braith, R. W., Wood, C. E., Limacher, M. C., Pollock, M. L., Lowenthal, D. T., Phillips, M. I., & Staples, E. D. (1992). Abnormal neuroendocrine responses during exercise in heart transplant recipients. *Circulation, 86,* 1453–1463. doi:10.1161/01.CIR.86.5.1453

Brett, M., Anton, J.-L. L., Valabregue, R., & Poline, J.-B. (2002). Region of interest analysis using an SPM toolbox. In *8th International Conferance on Functional Mapping of the Human Brain* (Vol. 16, p. 497). doi:10.1016/S1053-8119(02)90010-8

Brewer, B., Van Raalte, J., & Linder, D. (1996). Attentional focus and endurance performance. *Applied Research in Coaching and Athletics Annual, 11,* 1–14.

Broadbent, D. E. (1958). *Perception and communication*. Elmsford, NY: Pergamon Press. doi:10.1037/10037-000

Brooks, D., Graydon, J., & Mcbride, S. (2003). Evaluating the effects of music on dyspnea during exercise in individuals with chronic obstructive pulmonary disease: A pilot study. *Rehabilitation Nursing, 28,* 192–196.

Brotons, M., Koger, S. M., & Pickett-Cooper, P. (1997). Music and dementias: A review of literature. *Journal of Music Therapy, 34,* 204–245. doi:10.1093/jmt/34.4.204

Brown, S., Martinez, M. J., & Parsons, L. M. (2004). Passive music listening spontaneously engages limbic and paralimbic systems. *NeuroReport, 15,* 2033–2037. doi:10.1097/00001756-200409150-00008

Brown, S., Martinez, M. J., & Parsons, L. M. (2006). The neural basis of human dance. *Cerebral Cortex, 16,* 1157–1167. doi:10.1093/cercor/bhj057

Brunetti, M., Della Penna, S., Ferretti, A., Del Gratta, C., Cianflone, F., Belardinelli, P., … Romani, G. L. (2008). A frontoparietal network for spatial attention reorienting in the auditory domain: A human *f*MRI/MEG study of functional and temporal dynamics. *Cerebral Cortex, 18,* 1139–1147. doi:10.1093/cercor/bhm145

Buckthorpe, M., Pain, M. T. G., & Folland, J. P. (2014). Central fatigue contributes to the greater reductions in explosive than maximal strength with high-intensity fatigue. *Experimental Physiology, 99,* 964–973. doi:10.1113/expphysiol.2013.075614

Bullock, T., & Giesbrecht, B. (2014). Acute exercise and aerobic fitness influence selective attention during visual search. *Frontiers in Psychology, 5, e*1290. doi:10.3389/fpsyg.2014.01290

Burnley, M., & Jones, A. M. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sport Science, 7,* 63–79. doi:10.1080/17461390701456148

Buschman, T., & Miller, E. (2007). Top-down versus bottom-up control of attention in the prefrontal and posterior parietal cortices. *Science, 315,* 1860–1862. doi:10.1126/science.1138071

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends in Cognitive Sciences, 4,* 215–222. doi:10.1016/S1364-6613(00)01483-2

Cacioppo, J., Tassinary, L. G., & Berntson, G. G. (2007). *The Handbook of Psychophysiology*. *Dreaming* (3rd ed., Vol. 44). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511546396

Calbet, J. A. L., Gonzalez-Alonso, J., Helge, J. W., Søndergaard, H., Munch-Andersen, T., Boushel, R., & Saltin, B. (2007). Cardiac output and leg and arm blood flow during incremental exercise to exhaustion on the cycle ergometer. *Journal of Applied Physiology, 103,* 969–978. doi:10.1152/japplphysiol.01281.2006

Calik-Kutukcu, E., Saglam, M., Vardar-Yagli, N., Cakmak, A., Inal-Ince, D., Bozdemir-Ozel, C., … Karakaya, J. (2016). Listening to motivational music while walking elicits more positive affective response in patients with cystic fibrosis. *Complementary Therapies in Clinical Practice, 23,* 52–58. doi:10.1016/j.ctcp.2016.03.002

Cao, T., Wan, F., Wong, C., da Cruz, J., & Hu, Y. (2014). Objective evaluation of fatigue by EEG spectral analysis in steady-state visual evoked potential-based brain-computer interfaces. *BioMedical Engineering OnLine, 13,* e28. doi:10.1186/1475-925X-13-28

Caputo, G., & Guerra, S. (1998). Attentional selection by distractor suppression. *Vision Research, 38,* 669–689. doi:10.1016/S0042-6989(97)00189-2

Carroll, L. (1865). *Alice's adventures in wonderland*. London, UK: Macmillan.

Caspari, R. (2012). The evolution of grandparents. *Scientific American, 22,* 38–43. doi:10.1038/scientificamericanhuman1112-38

Castellanos, N. P., & Makarov, V. A. (2006). Recovering EEG brain signals: Artifact suppression with wavelet enhanced independent component analysis. *Journal of Neuroscience Methods, 158,* 300–312. doi:10.1016/j.jneumeth.2006.05.033

Catani, M., Dell'acqua, F., & Thiebaut de Schotten, M. (2013). A revised limbic system model for memory, emotion and behaviour. *Neuroscience and Biobehavioral Reviews, 37,* 1724–1737. doi:10.1016/j.neubiorev.2013.07.001

Cebolla, A. M., De Saedeleer, C., Bengoetxea, A., Leurs, F., Balestra, C., D'Alcantara, P., … Cheron, G. (2009). Movement gating of beta/gamma oscillations involved in the N30 somatosensory evoked potential. *Human Brain Mapping, 30,* 1568–1579. doi:10.1002/hbm.20624

Chadick, J. Z., & Gazzaley, A. (2011). Differential coupling of visual cortex with default or frontal-parietal network based on goals. *Nature Neuroscience, 14,* 830–832. doi:10.1038/nn.2823

Chen, M. J., Fan, X., & Moe, S. T. (2002). Criterion-related validity of the Borg ratings of perceived exertion scale in healthy individuals: A meta-analysis. *Journal of Sports Sciences, 20,* 873–899. doi:10.1080/026404102320761787

Cheong, D., Zubieta, J.-K., & Liu, J. (2012). Neural correlates of visual motion prediction. *PLoS ONE, 7,* e39854. doi:10.1371/journal.pone.0039854

Cheron, G., Petit, G., Cheron, J., Leroy, A., Cebolla, A. M., Cevallos, C., … Dan, B. (2016). Brain oscillations in sport: Toward EEG biomakers of performance. *Frontiers in Psychology, 7,* e246. doi:10.3389/fpsyg.2016.00246

Chesler, N. C., & Durfee, W. K. (1997). Surface EMG as a fatigue indicator during FES-induced isometric muscle contractions. *Journal of Electromyography and Kinesiology, 7,* 27–37. doi:10.1016/S1050-6411(96)00016-8

Chiel, H. J., Ting, L. H., Ekeberg, O., & Hartmann, M. J. Z. (2009). The brain in its body: Motor control and sensing in a biomechanical context. *The Journal of Neuroscience, 29,* 12807–12814. doi:10.1523/JNEUROSCI.3338-09.2009

Chong, T. T. J., Williams, M. A., Cunnington, R., & Mattingley, J. B. (2008). Selective attention modulates inferior frontal gyrus activity during action observation. *NeuroImage, 40,* 298–307. doi:10.1016/j.neuroimage.2007.11.030

Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., & Schooler, J. W. (2009). Experience sampling during *f*MRI reveals default network and executive system contributions to mind wandering. *Proceedings of the National Academy of Sciences of the United States of America, 106,* 8719–8724. doi:10.1073/pnas.0900234106

ChuDuc, H., NguyenPhan, K., & NguyenViet, D. (2013). A review of heart rate variability and its applications. *The 3rd International Conference on Biomedical Engineering and Technology, 7,* 80–85. doi:10.1016/j.apcbee.2013.08.016

Chun, M. M., & Turk-Browne, N. B. (2007). Interactions between attention and memory. *Current Opinion in Neurobiology, 17,* 177–184. doi:10.1016/j.conb.2007.03.005

Cifrek, M., Medved, V., Tonković, S., & Ostojić, S. (2009). Surface EMG-based muscle fatigue evaluation in biomechanics. *Clinical Biomechanics, 24,* 327–340. doi:10.1016/j.clinbiomech.2009.01.010

Clark, I. N., Baker, F. A., & Taylor, N. F. (2016). The modulating effects of music listening on health-related exercise and physical activity in adults: A systematic review and narrative synthesis. *Nordic Journal of Music Therapy, 25,* 76–104. doi:10.1080/08098131.2015.1008558

Coch, D., Sanders, L. D., & Neville, H. J. (2005). An event-related potential study of selective auditory attention in children and adults. *Journal of Cognitive Neuroscience, 17,* 605–622. doi:10.1162/0898929053467631

Cohen, J. (1994). The earth is round (p < .05). *American Psychologist, 49,* 168–173.

Collura, T. (1993). History and evolution of electroencephalographic instruments and techniques. *Journal of Clinical Neurophysiology, 10,* 476–504.

Conard, N. J., Malina, M., & Münzel, S. C. (2009). New flutes document the earliest musical tradition in southwestern Germany. *Nature, 460,* 737–740. doi:10.1038/nature08169

Conrad, C., Niess, H., Jauch, K.-W., Bruns, C. J., Hartl, W. H., & Welker, L. (2007). Overture for growth hormone: Requiem for interleukin-6? *Critical Care Medicine, 35,* 2709–2713. doi:10.1097/01.CCM.0000291648.99043.B9

Conway, M. A., & Pleydell-Pearce, C. W. (2000). The construction of autobiographical memories in the self-memory system. *Psychological Review, 107,* 261–288. doi:10.1037//0033-295X.107.2.261

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience, 3,* 201–215. doi:10.1038/nrn755

Cottin, F., Médigue, C., Lopes, P., Leprêtre, P. M., Heubert, R., & Billat, V. (2007). Ventilatory thresholds assessment from heart rate variability during an incremental exhaustive running test. *International Journal of Sports Medicine, 28,* 287–294. doi:10.1055/s-2006-924355

Craig, A., Tran, Y., Wijesuriya, N., & Nguyen, H. (2012). Regional brain wave activity changes associated with fatigue. *Psychophysiology, 49,* 574–582. doi:10.1111/j.1469-8986.2011.01329.x

Craig, M. C., Catani, M., Deeley, Q., Latham, R., Daly, E., Kanaan, R., … Murphy, D. G. M. (2009). Altered connections on the road to psychopathy. *Molecular Psychiatry, 14,* 946–953. doi:10.1038/mp.2009.40

Creem, S., & Proffitt, D. (2001). Defining the cortical visual systems:“what”,“where”, and “how.” *Acta Psychologica, 107,* 43–68.

Crust, L. (2008). Perceived importance of components of asynchronous music during circuit training. *Journal of Sports Sciences, 26,* 1547–1555. doi:10.1080/02640410802315427

Cutsuridis, V. (2013). Cognitive models of the perception-action cycle: A view from the brain. In *Proceedings of the International Joint Conference on Neural Networks*. doi:10.1109/IJCNN.2013.6706713

Dai, T. H., Liu, J. Z., Saghal, V., Brown, R. W., & Yue, G. H. (2001). Relationship between muscle output and functional MRI-measured brain activation. *Experimental Brain Research, 140,* 290–300. doi:10.1007/s002210100815

Dalgleish, T. (2004). The emotional brain. *Nature Reviews Neuroscience, 5,* 252–256. doi:10.1038/nrn1432

Daly, I., Hallowell, J., Hwang, F., Kirke, A., Malik, A., Roesch, E., … Nasuto, S. J. (2014b). Changes in music tempo entrain movement related brain activity. In *Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (Vol. 2014, pp. 4595–4598). doi:10.1109/EMBC.2014.6944647

Daly, I., Malik, A., Hwang, F., Roesch, E., Weaver, J., Kirke, A., … Nasuto, S. J. (2014a). Neural correlates of emotional responses to music: An EEG study. *Neuroscience Letters, 573,* 52–57. doi:10.1016/j.neulet.2014.05.003

Danner, D. D., Snowdon, D. A., & Friesen, W. V. (2001). Positive emotions in early life and longevity: Findings from the nun study. *Journal of Personality and Social Psychology, 80,* 804–813. doi:10.1037//0022-3514.80.5.804

Darrow, C. W. (1964). Psychophysiology, yesterday, today, and tomorrow. *Psychophysiology, 1,* 4–7. doi:10.1111/j.1469-8986.1964.tb02615.x

Darwin, C. (1859). *On the origin of species*. London, UK: John Murray.

Dasilva, S. G., Guidetti, L., Buzzachera, C. F., Elsangedy, H. M., Krinski, K., De Campos, W., … Baldari, C. (2011). Psychophysiological responses to self-paced treadmill and overground exercise. *Medicine & Science in Sports & Exercise, 43,* 1114–1124. doi:10.1249/MSS.0b013e318205874c

Davidson, R. (2004). What does the prefrontal corte do in affect: Perspectives on frontal EEF asymmetry research. *Biological Psychology, 67,* 219–233. doi:0.1016/j.biopsycho.2004.03.008

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics, 13,* 135–163. doi: 10.1123/jab.13.2.135

De Luca, C. J., Sabbahi, M. A., & Roy, S. H. (1986). Median frequency of the myoelectric signal: Effects of hand dominance. *European Journal of Applied Physiology, 55,* 457–464.

De Meersman, R. E., Zion, A. S., Weir, J. P., Lieberman, J. S., & Downey, J. A. (1998). Mechanoreceptors and autonomic responses to movement in humans. *Clinical Autonomic Research, 8,* 201–205. doi:10.1007/BF02267782

de Morree, H. M., Klein, C., & Marcora, S. M. (2012). Perception of effort reflects central motor command during movement execution. *Psychophysiology, 49,* 1242–1253. doi:10.1111/j.1469-8986.2012.01399.x

de Morree, H. M., Klein, C., & Marcora, S. M. (2014). Cortical substrates of the effects of caffeine and time-on-task on perception of effort. *Journal of Applied Physiology, 117,* 1514–1523. doi:10.1152/japplphysiol.00898.2013 de Morree, H. M., & Marcora, S. M. (2013). Effects of isolated locomotor muscle fatigue on pacing and time trial performance. *European Journal of Applied Physiology, 113,* 2371–2380. doi:10.1007/s00421-013-2673-0

Deforche, B., & De Bourdeaudhuij, I. (2015). Attentional distraction during exercise in overweight and normal-weight boys. *International Journal of Environmental Research and Public Health, 12,* 3077–3090. doi:10.3390/ijerph120303077

Delfabbro, P., King, D. L., & Griffiths, M. (2012). Behavioural profiling of problem gamblers: A summary and review. *International Gambling Studies, 12,* 349–366. doi:10.1080/14459795.2012.678274

Delorme, A., & Makeig, S. (2004). EEGLAB: an open sorce toolbox for analysis of single-trail EEG dynamics including independent component anlaysis. *Journal of Neuroscience Methods, 134,* 9–21. doi:10.1016/j.jneumeth.2003.10.009

Delorme, A., Sejnowski, T., & Makeig, S. (2007). Enhanced detection of artifacts in EEG data using higher-order statistics and independent component analysis. *NeuroImage, 34,* 1443–1449. doi:10.1016/j.neuroimage.2006.11.004

Demaree, H. A., Everhart, D. E., Youngstrom, E. A., & Harrison, D. W. (2005). Brain lateralization of emotional processing: Historical roots and a future incorporating "dominance." *Behavioral and Cognitive Neuroscience Reviews, 4,* 3–20. doi:10.1177/1534582305276837

Desbordes, G., Negi, L. T., Pace, T. W. W., Wallace, B. A., Raison, C. L., & Schwartz, E. L. (2012). Effects of mindful-attention and compassion meditation training on amygdala response to emotional stimuli in an ordinary, non-meditative state. *Frontiers in Human Neuroscience, 6,* e292. doi:10.3389/fnhum.2012.00292

Desimone, R. (1996). Neural mechanisms for visual memory and their role in attention. *Proceedings of the National Academy of Sciences of the United States of America, 93,* 13494–13499. doi:10.1073/pnas.93.24.13494

Dickter, C. L., & Kieffaber, P. D. (2013). *EEG methods for the psychological sciences*. Thousand Oaks, CA: Sage.

Dodds, W. J. (1878). On the localisation of the functions of the brain: Being an historical and critical analysis of the question. *Journal of Anatomy and Physiology, 12,* 454–494.

Donina, Z. A. (2011). Intersystem relationship between respiration and blood circulation. *Human Physiology, 37,* 229–239. doi:10.1134/S0362119711020034

Douglas, C. (1911). A method for determining the total respiratory exchange in man. *Journal of Physiology, 42,* 17–18.

Driver, J. (2001). A selective review of selective attention research from the past century. *British Journal of Psychology, 92,* 53–78. doi:10.1348/000712601162103

Dudai, Y. (2004). The neurobiology of consolidations, or, how stable is the engram? *Annual Review of Psychology, 55,* 51–86. doi:10.1146/annurev.psych.55.090902.142050

Dunckley, P., Aziz, Q., Wise, R. G., Brooks, J., Tracey, I., & Chang, L. (2007). Attentional modulation of visceral and somatic pain. *Neurogastroenterology and Motility, 19,* 569–577. doi:10.1111/j.1365-2982.2007.00908.x

Duvinage, M., Castermans, T., Petieau, M., Hoellinger, T., Cheron, G., & Dutoit, T. (2013). Performance of the Emotiv Epoc headset for P300-based applications. *Biomedical Engineering Online, 12,* 56. doi:10.1186/1475-925X-12-56

Ekkekakis, P. (2003). Pleasure and displeasure from the body: Perspectives from exercise. *Cognition & Emotion, 17,* 213–239. doi:10.1080/02699930302292

Ekkekakis, P. (2009). Illuminating the black box: Investigating prefrontal cortical hemodynamics during exercise with near-infrared spectroscopy. *Journal of Sport & Exercise Psychology, 31,* 505–553.

Ekkekakis, P. (2012). Affect, mood, and emotion. In G. Tenenbaum, R. Eklund, & A. Kamata (Eds.), *Measurement in sport and exercise psychology*. New York, NY: Cambridge University Press.

Ekkekakis, P. (2013). *The measurement of affect, mood, and emotion: A guide for health-behavioral research*. Cambridge, UK: Cambridge University Press.

Ekkekakis, P., Parfitt, G., & Petruzzello, S. J. (2011). The pleasure and displeasure people feel when they exercise at different intensities: decennial update and progress towards a tripartite rationale for exercise intensity prescription. *Sports Medicine, 41,* 641–671. doi:10.2165/11590680-000000000-00000

Elliott, K. J., Cable, N. T., & Reilly, T. (2005). Does oral contraceptive use affect maximum force production in women? *British Journal of Sports Medicine, 39,* 15–19. doi:10.1136/bjsm.2003.009886

Enders, H., Cortese, F., Maurer, C., Baltich, J., Protzner, A. B., & Nigg, B. M. (2016). Changes in cortical activity measured with EEG during a high-intensity cycling exercise. *Journal of Neurophysiology, 115,* 379–388. doi:10.1152/jn.00497.2015

Enders, H., & Nigg, B. M. (2015). Measuring human locomotor control using EMG and EEG: Current knowledge, limitations and future considerations. *European Journal of Sport Science, 16,* 416–426. doi:10.1080/17461391.2015.1068869

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage, 26,* 471–479. doi:10.1016/j.neuroimage.2005.02.004

Farfán, F. D., Politti, J. C., & Felice, C. J. (2010). Evaluation of EMG processing techniques using Information Theory. *Biomedical Engineering Online, 9,* 72. doi:10.1186/1475-925X-9-72

Farina, D., Fosci, M., & Merletti, R. (2002). Motor unit recruitment strategies investigated by surface EMG variables. *Journal of Applied Physiology, 92,* 235–247. doi:11744666

Faul, F., Erdfelder, E., Lang, A., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39,* 175–191.

Fehr, B., & Russell, J. A. (1984). Concept of emotion viewed from a prototype perspective. *Journal of Experimental Psychology, 113,* 464–486. doi:10.1037/0096-3445.113.3.464

Fernandes, A., Galbo, H., Kjaer, M., Mitchell, J., Secher, N., & Thomas, S. (1990). Cardiovascular and ventilatory responses to dynamic exercise during epidural anaesthesia in man. *The Journal of Physiology, 420,* 281–293.

Fletcher, H., & Munson, W. (1993). Loudness, its definition, measurement and calculation. *Bell System Technical Journal, 12,* 377–430. doi:10.1002/j.1538-7305.1933.tb00403.x

Fontes, E. B., Okano, A. H., De Guio, F., Schabort, E. J., Min, L. L., Basset, F. A., … Noakes, T. D. (2015). Brain activity and perceived exertion during cycling exercise: an *f*MRI study. *British Journal of Sports Medicine, 49,* 556–560. doi:10.1136/bjsports-2012-091924

Foxe, J. J., & Snyder, A. C. (2011). The role of alpha-band brain oscillations as a sensory suppression mechanism during selective attention. *Frontiers in Psychology, 2,* e154. doi:10.3389/fpsyg.2011.00154

Friederici, A. D., Rüschemeyer, S.-A., Hahne, A., & Fiebach, C. J. (2003). The role of left inferior frontal and superior temporal cortex in sentence comprehension: localizing syntactic and semantic processes. *Cerebral Cortex, 13,* 170–177. doi:10.1093/cercor/13.2.170

Friedkin, W. (1973). *The exorcist*. United States of America: Warner Bros.

Friston, J. K., Ashburner, T. J., Kiebel, J. S., Nichols, E. T., & Penny, D. W. (2007). *Statistical parametric mapping: The analysis of functional brain images*. Elsevier.

Friston, K. J. (2011). Functional and effective connectivity: A review. *Brain Connectivity, 1,* 13–36. doi:10.1089/brain.2011.0008

Fritz, T. H., Hardikar, S., Demoucron, M., Niessen, M., Demey, M., Giot, O., … Leman, M. (2013). Musical agency reduces perceived exertion during strenuous physical performance. *Proceedings of the National Academy of Sciences of the United States of America, 110,* 17784–17789. doi:10.1073/pnas.1217252110

Fukuta, H., & Little, W. (2008). The cardiac cycle and the physiologic basis of left ventricular contraction, ejection, relaxation, and filling. *Heart Failure Clinics, 4,* 1–11. doi:10.1016/j.hfc.2007.10.004.

Fumoto, M., Oshima, T., Kamiya, K., Kikuchi, H., Seki, Y., Nakatani, Y., … Arita, H. (2010). Ventral prefrontal cortex and serotonergic system activation during pedaling exercise induces negative mood improvement and increased alpha band in EEG. *Behavioural Brain Research, 213,* 1–9. doi:10.1016/j.bbr.2010.04.017

Gabana, N. T., Van Raalte, J. L., Hutchinson, J. C., Brewer, B. W., & Petitpas, A. J. (2015). The effects of music and a coxswain on attentional focus, perceived exertion, motivation, and performance during a 1,000 m ergometer rowing sprint. *Journal of Applied Sport Psychology, 27,* 288–300. doi:10.1080/10413200.2014.993775

Gage, G., Parikh, H., & Marzullo, T. (2008). The cingulate cortex does everything. *Annals of Improbable Research, 14,* 12–15.

Gamelin, F., Brethoin, S., & Bosquet, L. (2006). Validity of the polar S810 heart rate monitor to measure RR intervals at rest. *Medicine & Science in Sports & Exercise, 38,* 887–893. doi:10.1249/01.mss.0000218135.79476.9c

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews, 81,* 1725–1789.

Garrison, T. M., & Williams, C. C. (2013). Impact of relevance and distraction on driving performance and visual attention in a simulated driving environment. *Applied Cognitive Psychology, 27,* 396–405. doi:10.1002/acp.2917

Gazendam, M. G. J., & Hof, A. L. (2007). Averaged EMG profiles in jogging and running at different speeds. *Gait and Posture, 25,* 604–614. doi:10.1016/j.gaitpost.2006.06.013

Geng, J. J. (2014). Attentional mechanisms of distractor suppression. *Current Directions in Psychological Science, 23,* 147–153. doi:10.1177/0963721414525780

Gennaro, F., & de Bruin, E. D. (2018). Assessing brain–muscle connectivity in human locomotion through mobile brain/body imaging: Opportunities, pitfalls, and future directions. *Frontiers in Public Health, 6,* e39. doi:10.3389/fpubh.2018.00039

Giles, D., Draper, N., & Neil, W. (2016). Validity of the Polar V800 heart rate monitor to measure RR intervals at rest. *European Journal of Applied Physiology, 116,* 563–571. doi:10.1007/s00421-015-3303-9

Girges, C., Wright, M. J., Spencer, J. V, & O’Brien, J. M. D. (2014). Event-related alpha suppression in response to facial motion. *PloS ONE, 9,* e89382. doi:10.1371/journal.pone.0089382

Gladwell, V. F., Brown, D. K., Wood, C., Sandercock, G. R., & Barton, J. L. (2013). The great outdoors: how a green exercise environment can benefit all. *Extreme Physiology & Medicine, 2,* e3. doi:10.1186/2046-7648-2-3

Gleim, G., Coplan, N., & Nicholas, J. (1986). Acute cardiovascular response to exercise. *Bulletin of the New York Academy of Medicine, 62,* 211–218.

Goldman-Rakic, P. (1988). Topography of cognition: Parallel distributed networks in primate association cortex. *Annual Review of Neuroscience, 11,* 137–156. doi:10.1146/annurev.ne.11.030188.001033

Goode, K., & Roth, D. (1993). Factor analysis of cognitions during running: Association with mood change. *Journal of Sport & Exercise Psychology, 15,* 375–389.

Gramfort, A., Papadopoulo, T., Olivi, E., & Clerc, M. (2010). OpenMEEG: opensource software for quasistatic bioelectromagnetics. *Biomedical Engineering Online, 9,* e45. doi:10.1186/1475-925X-9-45

Grech, R., Cassar, T., Muscat, J., Camilleri, K. P., Fabri, S. G., Zervakis, M., … Vanrumste, B. (2008). Review on solving the inverse problem in EEG source analysis. *Journal of NeuroEngineering and Rehabilitation, 5, e*25. doi:10.1186/1743-0003-5-25

Gregoire, J., Tuck, S., Hughson, R. L., & Yamamoto, Y. (1996). Heart rate variability at rest and exercise: Influence of age, gender, and physical Training. *Canadian Journal of Applied Physiology, 21,* 455–470. doi:10.1139/h96-040

Griffiths, T., & Warren, J. (2004). “When the feeling’s gone”: A selective loss of musical emotion. *Journal of Neurology, Neurosurgery, and Psychiatry, 75,* 344–345. doi:10.1136/jnnp.2003.015586

Groppe, D., Makeig, S., & Kutas, M. (2008). Independent component analysis of event-related potentials. *Cognitive Science Online, 6,* 1–44.

Gross, C. (1995). Aristotle on the brain. *The Neuroscientist, 1,* 245–250.

Guinote, A. (2007). Power affects basic cognition: Increased attentional inhibition and flexibility. *Journal of Experimental Social Psychology, 43,* 685–697. doi:10.1016/j.jesp.2006.06.008

Haga, S., Sano, A., Sekine, Y., Sato, H., Yamaguchi, S., & Masuda, K. (2015). Effects of using a smart phone on pedestrians' attention and walking. *Procedia Manufacturing, 3,* 2574–2580. doi:10.1016/j.promfg.2015.07.564

Hallett, R., & Lamont, A. (2015). How do gym members engage with music during exercise? *Qualitative Research in Sport, Exercise and Health, 7,* 411–427. doi:10.1080/2159676X.2014.949835

Hameroff, S., & Penrose, R. (2014). Consciousness in the universe: a review of the "Orch OR" theory. *Physics of Life Reviews, 11,* 39–78. doi:10.1016/j.plrev.2013.08.002

Hardy, C. J., & Rejeski, W. J. (1989). Not what, but how one feels: The measurement of affect during exercise. *Journal of Sport & Exercise Psychology, 11,* 304–317.

Harlow, J. (1868). Recovery from the passage of an iron bar through the head. *Publications of the Massachusetts Medical Society, 2,* 327–347.

Harrison, N. A., Gray, M. A., Gianaros, P. J., & Critchley, H. D. (2010). The embodiment of emotional feelings in the brain. *The Journal of Neuroscience, 30,* 12878–12884. doi:10.1523/JNEUROSCI.1725-10.2010

Hartwigsen, G., Saur, D., Price, C. J., Ulmer, S., Baumgaertner, A., & Siebner, H. R. (2013). Perturbation of the left inferior frontal gyrus triggers adaptive plasticity in the right homologous area during speech production. *Proceedings of the National Academy of Sciences of the United States of America, 110,* 16402–16407. doi:10.1073/pnas.1310190110

Hasson, U., Landesman, O., Knappmeyer, B., Vallines, I., Rubin, N., & Heeger, D. J. (2008). Neurocinematics: The Neuroscience of Film. *Projections, 2,* 1–26. doi:10.3167/proj.2008.020102

Hasson, U., Nir, Y., Levy, I., Fuhrmann, G., & Malach, R. (2004). Intersubject synchronization of cortical activity during natural vision. *Science, 303,* 1634–1640. doi:10.1126/science.1089506

Hatfield, B., & Landers, D. (1987). Psychophysiology in exercise and sport research: An overview. *Exercise & Sport Sciences Reviews, 15,* 351–388.

Haufe, S., Nikulin, V., & Nolte, G. (2011). Identifying brain effective connectivity patterns from EEG: performance of Granger Causality, DTF, PDC and PSI on simulated data. *BMC Neuroscience, 12,* P141. doi:10.1186/1471-2202-12-S1-P141

He, Y. (2010). Missing data analysis using multiple imputation: Getting to the heart of the matter. *Circulation: Cardiovascular Quality and Outcomes, 3,* 98–105. doi:10.1161/CIRCOUTCOMES.109.875658

Hebb, D. (1949). *The organization of behavior: A neuropsychological theory*. New York, NY: John Wiley & Sons.

Hegde, S. (2014). Music-based cognitive remediation therapy for patients with traumatic brain injury. *Frontiers in Neurology, 5,* 34. doi:10.3389/fneur.2014.00034

Henderson, R. G. (1983). Nuclear magnetic resonance imaging: A review. *Journal of the Royal Society of Medicine, 76,* 206–212.

Hendrix, C. R., Housh, T. J., Johnson, G. O., Mielke, M., Camic, C. L., Zuniga, J. M., & Schmidt, R. J. (2009). Comparison of critical force to emg fatigue thresholds during isometric leg extension. *Medicine & Science in Sports & Exercise, 41,* 956–964. doi:10.1249/MSS.0b013e318190bdf7

Hernández-Peón, R., Brust-Carmona, H., Peñaloza-Rojas, J., & Bach-Y-Rita, G. (1961). The efferent control of afferent signals entering the central nervous system. *Annals of the New York Academy of Sciences, 89,* 866–882.

Hinsey, J. (1934). The innervation of skeletal muscle. *Physiological Reviews, 14,* 514–585.

Ho, C. S., & Giaschi, D. E. (2009). Low- and high-level first-order random-dot kinematograms: Evidence from *f*MRI. *Vision Research, 49,* 1814–1824. doi:10.1016/j.visres.2009.04.018

Holden, C. (2001). "Behavioral" addictions: Do they exist? *Science, 294,* 980–982.

Hommel, B. (2010). Grounding attention in action control: The intentional control of selection. In B. Bruya (Ed.), *Effortless attention: A new perspective in the cognitive science of attention and action* (pp. 121–140). London, UK: MIT Press.

Horváth, J., Sussman, E., Winkler, I., & Schröger, E. (2011). Preventing distraction: Assessing stimulus-specific and general effects of the predictive cueing of deviant auditory events. *Biological Psychology, 87,* 35–48. doi:10.1016/j.biopsycho.2011.01.011

Hötting, K., & Röder, B. (2013). Beneficial effects of physical exercise on neuroplasticity and cognition. *Neuroscience and Biobehavioral Reviews, 37,* 2243–2257. doi:10.1016/j.neubiorev.2013.04.005

Hug, F., & Dorel, S. (2009). Electromyographic analysis of pedaling: A review. *Journal of Electromyography and Kinesiology, 19,* 182–198. doi:10.1016/j.jelekin.2007.10.010

Hug, F., Faucher, M., Kipson, N., & Jammes, Y. (2003). EMG signs of neuromuscular fatigue related to the ventilatory threshold during cycling exercise. *Clinical Physiology and Functional Imaging, 23,* 208–214. doi:10.1046/j.1475-097X.2003.00497.x

Hughes, J. R., & Hendrix, D. E. (1968). Telemetered EEG from a football player in action. *Electroencephalography and Clinical Neurophysiology, 24,* 183–186.

Huijbers, M. J., Bergmann, H. C., Olde Rikkert, M. G. M., & Kessels, R. P. C. (2011). Memory for emotional pictures in patients with Alzheimer's dementia: comparing picture-location binding and subsequent recognition. *Journal of Aging Research, 2011,* 409364. doi:10.4061/2011/409364

Hunter, A. M., St Clair Gibson, A., Lambert, M. I., Nobbs, L., & Noakes, T. D. (2003). Effects of supramaximal exercise on the electromyographic signal. *British Journal of Sports Medicine, 37,* 296–299. doi:10.1136/bjsm.37.4.296

Hutchinson, J. C., Jones, L., Vitti, S. N., Moore, A., Dalton, P. C., & O'Neil, B. J. (2018). The influence of self-selected music on affect-regulated exercise intensity and remembered pleasure during treadmill running. *Sport, Exercise, and Performance Psychology, 7,* 80–92. doi:10.1037/spy0000115

Hutchinson, J. C., & Karageorghis, C. I. (2013). Moderating influence of dominant attentional style and exercise intensity on responses to asynchronous music. *Journal of Sport & Exercise Psychology, 35,* 625–643.

Hutchinson, J. C., Karageorghis, C. I., & Black, J. D. (2017). The diabeates project: Perceptual, affective and psychophysiological effects of music and music-video in a clinical exercise setting. *Canadian Journal of Diabetes, 41,* 90–96. doi:10.1016/j.jcjd.2016.07.009

Hutchinson, J. C., Karageorghis, C. I., & Jones, L. (2015). See hear: Psychological effects of music and music-video during treadmill running. *Annals of Behavioral Medicine, 49,* 199–211. doi:10.1007/s12160-014-9647-2

Hutchinson, J. C., & Tenenbaum, G. (2007). Attention focus during physical effort: The mediating role of task intensity. *Psychology of Sport and Exercise, 8,* 233–245. doi:10.1016/j.psychsport.2006.03.006

Ille, A., Selin, I., Do, M., & Thon, B. (2013). Attentional focus effects on sprint start performance as a function of skill level. *Journal of Sports Sciences, 31,* 1705–1712. doi:10.1080/02640414.2013.797097

Irisawa, H., Brown, H., & Giles, W. (1993). Cardiac pacemaking in the sinoatrial node. *Physiological Reviews, 73,* 197–227.

Jain, S., Gourab, K., Schindler-Ivens, S., & Schmit, B. D. (2013). EEG during pedaling: Evidence for cortical control of locomotor tasks. *Clinical Neurophysiology, 124,* 379–390. doi:10.1016/j.clinph.2012.08.021

Jäncke, L. (2008). Music, memory and emotion. *Journal of Biology, 7,* 21. doi:10.1186/jbiol82

Jefferys, J. G. R. (2010). Advances in understanding basic mechanisms of epilepsy and seizures. *Seizure, 19,* 638–646. doi:10.1016/j.seizure.2010.10.026

Jensen, M. P., Adachi, T., Tomé-Pires, C., Lee, J., Osman, Z. J., & Miró, J. (2015). Mechanisms of hypnosis: toward the development of a biopsychosocial model. *The International Journal of Clinical and Experimental Hypnosis, 63,* 34–75. doi:10.1080/00207144.2014.961875

Johanson, D., & Taieb, M. (1976). Plio-pleistocene hominid discoveries in Hadar, Ethiopia. *Nature, 260,* 293–297.

Jones, L., Karageorghis, C. I., & Ekkekakis, P. (2014). Can high-intensity exercise be more pleasant? Attentional dissociation using music and video. *Journal of Sport & Exercise Psychology, 36,* 528–541. doi:10.1123/jsep.2014-0251

Jovanović, A., Perović, A., & Borovčanin, M. (2013). Brain connectivity measures: Computation and comparison. *EPJ Nonlinear Biomedical Physics, 1,* e2. doi:10.1186/epjnbp2

Juslin, P. N. (2013). What does music express? Basic emotions and beyond. *Frontiers in Psychology, 4,* e596. doi:10.3389/fpsyg.2013.00596

Juslin, P. N., & Västfjäll, D. (2008). Emotional responses to music: The need to consider underlying mechanisms. *The Behavioral and Brain Sciences, 31,* 559–621. doi:10.1017/S0140525X08005293

Kaelen, M., Barrett, F. S., Roseman, L., Lorenz, R., Family, N., Bolstridge, M., … Carhart-Harris, R. L. (2015). LSD enhances the emotional response to music. *Psychopharmacology, 232,* 3607–3614. doi:10.1007/s00213-015-4014-y

Kal, E. C., van der Kamp, J., & Houdijk, H. (2013). External attentional focus enhances movement automatization: a comprehensive test of the constrained action hypothesis. *Human Movement Science, 32,* 527–539. doi:10.1016/j.humov.2013.04.001

Kamarajan, C., Pandey, A. K., Chorlian, D. B., Porjesz, B., & Begleiter, H. (2016). The use of current source density as electrophysiological correlates in neuropsychiatric disorders: a review of human studies. *International Journal of Psychophysiology, 97,* 310–322. doi:10.1016/j.ijpsycho.2014.10.013

Kamiński, M. J., & Blinowska, K. J. (1991). A new method of the description of the information flow in the brain structures. *Biological Cybernetics, 65,* 203–210. doi:10.1007/BF00198091

Karageorghis, C. I., Ekkekakis, P., Bird, J. M., & Bigliassi, M. (2017). Music in the exercise and sport domain: Conceptual approaches and underlying mechanisms. In M. Lesaffre, P.-J. Maes, & M. Leman (Eds.), *Routledge companion to embodied music interaction* (pp. 284–293). London, UK: Routledge.

Karageorghis, C. I. (2016). The scientific application of music in sport and exercise: Towards a new theoretical model. In A. Lane (Ed.), *Sport and exercise psychology* (2nd ed., pp. 277–322). London, UK: Routledge.

Karageorghis, C. I. (2017). *Applying music in exercise and sport*. Champaign, IL: Human Kinetics.

Karageorghis, C. I., Bigliassi, M., Tayara, K., Priest, D.-L., & Bird, J. M. (2018b). A grounded theory of music use in the psychological preparation of academy soccer players. *Sport, Exercise, and Performance Psychology, 7,* 109–127. doi:10.1037/spy0000110

Karageorghis, C. I., Bruce, A. C., Pottratz, S. T., Stevens, R. C., Bigliassi, M., & Hamer, M. (2018c). Psychological and psychophysiological effects of recuperative music postexercise. *Medicine & Science in Sports & Exercise, 50,* 739–746. doi:10.1249/MSS.0000000000001497

Karageorghis, C. I., Hutchinson, J. C., Jones, L., Farmer, H. L., Ayhan, M. S., Wilson, R. C., … Bailey, S. G. (2013). Psychological, psychophysical, and ergogenic effects of music in swimming. *Psychology of Sport and Exercise, 14,* 560–568. doi:10.1016/j.psychsport.2013.01.009

Karageorghis, C. I., Cheek, P., Simpson, S. D. D., & Bigliassi, M. (2018a). Interactive effects of music tempi and intensities on grip strength and subjective affect. *Scandinavian Journal of Medicine & Science in Sports, 28,* 1166–1175. doi:10.1111/sms.12979

Karageorghis, C. I., & Jones, L. (2014). On the stability and relevance of the exercise heart rate–music-tempo preference relationship. *Psychology of Sport and Exercise, 15,* 299–310. doi:10.1016/j.psychsport.2013.08.004

Karageorghis, C. I., & Priest, D.-L. (2012a). Music in the exercise domain: a review and synthesis (Part I). *International Review of Sport and Exercise Psychology, 5,* 44–66. doi:10.1080/1750984X.2011.631026

Karageorghis, C. I., & Priest, D.-L. (2012b). Music in the exercise domain: a review and synthesis (Part II). *International Review of Sport and Exercise Psychology, 5,* 67–84. doi:10.1080/1750984X.2011.631027

Karageorghis, C. I., Priest, D.-L., Terry, P., Chatzisarantis, N., & Lane, A. (2006). Redesign and initial validation of an instrument to assess the motivational qualities of music in exercise: The Brunel Music Rating Inventory-2. *Journal of Sports Sciences, 24,* 899–909. doi:10.1080/02640410500298107

Karageorghis, C. I., Priest, D. L., Williams, L. S., Hirani, R. M., Lannon, K. M., & Bates, B. J. (2010). Ergogenic and psychological effects of synchronous music during circuit-type exercise. *Psychology of Sport and Exercise, 11,* 551–559. doi:10.1016/j.psychsport.2010.06.004

Karageorghis, C. I., & Terry, P. (2008). The psychological, psychophysical and ergogenic effects of music in sport: a review and synthesis. In A. Bateman & J. Bale (Eds.), *Sporting sounds: Relationship between sport and music* (pp. 13–36). London, UK: Routeledge. doi:10.4324/9780203887974

Karageorghis, C. I., & Terry, P. (2011). *Inside sport psychology*. Champaign, IL: Human Kinetics.

Karageorghis, C. I., & Terry, P. C. (1997). The psychophysical effects of music in sport and exercise: A review. *Journal of Sport Behavior, 20,* 54–68.

Karageorghis, C. I., Terry, P. C., & Lane, A. M. (1999). Development and initial validation of an instrument to assess the motivational qualities of music in exercise and sport: The Brunel Music Rating Inventory. *Journal of Sports Sciences, 17,* 713–724. doi:10.1080/026404199365579

Karageorghis, C. I., Terry, P. C., Lane, A. M., Bishop, D. T., & Priest, D. (2012). The BASES Expert Statement on use of music in exercise. *Journal of Sports Sciences, 30,* 953–956. doi:10.1080/02640414.2012.676665

Karageorghis, C. I., Jones, L., & Stuart, D. P. (2008). Psychological effects of music tempi during exercise. *International Journal of Sports Medicine, 29,* 613–619. doi:10.1055/s-2007-989266

Karageorghis, C. I., Mouzourides, D., Priest, D., Sasso, T., Morrish, D., & Walley, C. (2009). Psychophysical and ergogenic effects of synchronous music during treadmill walking. *Journal of Sport & Exercise Psychology, 31,* 18–36.

Karapetian, G. K., Engels, H. J., & Gretebeck, R. J. (2008). Use of heart rate variability to estimate LT and VT. *International Journal of Sports Medicine, 29,* 652–657. doi:10.1055/s-2007-989423

Katsuki, F., & Constantinidis, C. (2014). Bottom-up and top-down attention: Different processes and overlapping neural systems. *The Neuroscientist, 20,* 509–521. doi:10.1177/1073858413514136

Keil, A., Debener, S., Gratton, G., Junghöfer, M., Kappenman, E. S., Luck, S. J., … Yee, C. M. (2014). Committee report: Publication guidelines and recommendations for studies using electroencephalography and magnetoencephalography. *Psychophysiology, 51,* 1–21. doi:10.1111/psyp.12147'

Kiefer, M. (2012). Executive control over unconscious cognition: attentional sensitization of unconscious information processing. *Frontiers in Human Neuroscience, 6,* e61. doi:10.3389/fnhum.2012.00061

Kim, D., Koo, H., Lee, W., & Kim, M. (2014). Application and limitation of frequency domain, LF/HF component in heart rate variability as an acute stress index. *Proceedings of the International Conference on Biomedical Engineering and Systems, 14,* 1–4.

Klapuri, A., Eronen, A., & Astola, J. (2006). Analysis of the meter of acoustic musical signals. *Audio, Speech, and Language Processing, IEEE Transactions, 14*, 342–355. doi:10.1109/TSA.2005.854090

Klein, A., & Hirsch, J. (2005). Mindboggle: A scatterbrained approach to automate brain labeling. *NeuroImage, 24,* 261–280. doi:10.1016/j.neuroimage.2004.09.016

Kline, J. E., Huang, H. J., Snyder, K. L., & Ferris, D. P. (2015). Isolating gait-related movement artifacts in electroencephalography during human walking. *Journal of Neural Engineering, 12,* 46022. doi:10.1088/1741-2560/12/4/046022

Kocovic, D., Harada, T., Shea, J., Soroff, D., & Friedman, P. (1993). Alterations of heart rate and of heart rate variability after radiofrequency catheter ablation of supraventricular tachycardia. Delineation of parasympathetic pathways in the human heart. *Circulation, 88,* 1671–1681.

Koelsch, S. (2010). Towards a neural basis of music-evoked emotions. *Trends in Cognitive Sciences, 14,* 131–137. doi:10.1016/j.tics.2010.01.002

Koelsch, S. (2011). Toward a neural basis of music perception – a review and updated model. *Frontiers in Psychology, 2,* e110. doi:10.3389/fpsyg.2011.00110

Koelsch, S. (2014). Brain correlates of music-evoked emotions. *Nature Reviews Neuroscience, 15,* 170–180. doi:10.1038/nrn3666

Koessler, L., Cecchin, T., Colnat-Coulbois, S., Vignal, J. P., Jonas, J., Vespignani, H., … Maillard, L. G. (2014). Catching the invisible: Mesial temporal source contribution to simultaneous EEG and SEEG recordings. *Brain Topography, 28,* 5–20. doi:10.1007/s10548-014-0417-z

Kokoras, P. (2007). Towards a holophonic musical texture. *The Journal of Music and Meaning, 4,* 1–7.

Kravitz, D. J., Saleem, K. S., Baker, C. I., & Mishkin, M. (2011). A new neural framework for visuospatial processing. *Nature Reviews Neuroscience, 12,* 217–230. doi:10.1038/nrn3008

Kriegeskorte, N., Simmons, W. K., Bellgowan, P. S., & Baker, C. I. (2009). Circular analysis in neuroscience: The dangers of double dipping. *Nature Neuroscience, 12,* 535–540. doi:10.1038/nn.2303

Krigolson, O. E., Williams, C. C., Norton, A., Hassall, C. D., & Colino, F. L. (2017). Choosing MUSE: Validation of a low-cost, portable EEG system for ERP research. *Frontiers in Neuroscience, 11,* e109. doi:10.3389/fnins.2017.00109

Kringelbach, M. L., & Berridge, K. C. (2009). Towards a functional neuroanatomy of pleasure and happiness. *Trends in Cognitive Sciences, 13,* 479–487. doi:10.1016/j.tics.2009.08.006

Kucyi, A., & Davis, K. D. (2014). Dynamic functional connectivity of the default mode network tracks daydreaming. *NeuroImage, 100,* 471–480. doi:10.1016/j.neuroimage.2014.06.044

Künecke, J., Hildebrandt, A., Recio, G., Sommer, W., & Wilhelm, O. (2014). Facial EMG responses to emotional expressions are related to emotion perception ability. *PLoS ONE, 9,* e84053. doi:10.1371/journal.pone.0084053

Kuo, F. E., & Faber Taylor, A. (2004). A potential natural treatment for attention-deficit/hyperactivity disorder: Evidence from a national study. *American Journal of Public Health, 94,* 1580–1586. doi:10.2105/AJPH.94.9.1580

LaCaille, R. A., Masters, K. S., & Heath, E. M. (2004). Effects of cognitive strategy and exercise setting on running performance, perceived exertion, affect, and satisfaction. *Psychology of Sport and Exercise, 5,* 461–476. doi:10.1016/S1469-0292(03)00039-6

Lamprecht, R., & LeDoux, J. (2004). Structural plasticity and memory. *Nature Reviews Neuroscience, 5,* 45–54. doi:10.1038/nrn1301

Lancaster, J. L., Cykowski, M. D., McKay, D. R., Kochunov, P. V., Fox, P. T., Rogers, W., … Mazziotta, J. (2010). Anatomical global spatial normalization. *Neuroinformatics, 8,* 171–182. doi:10.1007/s12021-010-9074-x

Landa, L., Krpoun, Z., Kolarova, M., & Kasparek, T. (2014). Event-related potentials and their application. *Journal of Neurocognitive Research, 56,* 17–23.

Lane, A. M., Davis, P. A., & Devonport, T. J. (2011). Effects of music interventions on emotional states and running performance. *Journal of Sports Science & Medicine, 10,* 400–407.

Lane, R., McRae, K., Reiman, E., Chen, K., Ahern, G., & Thayer, J. (2009). Neural correlates of heart rate variability during emotion. *NeuroImage, 44,* 213–222. doi:10.1016/j.neuroimage.2008.07.056

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (1998). Emotion, motivation, and anxiety: brain mechanisms and psychophysiology. *Biological Psychiatry, 44,* 1248–1263. doi:10.1016/S0006-3223(98)00275-3

Laukka, P., & Quick, L. (2011). Emotional and motivational uses of music in sports and exercise: A questionnaire study among athletes. *Psychology of Music, 41,* 198–215. doi:10.1177/0305735611422507

Lautenschlager, N. T., Cox, K., & Cyarto, E. V. (2012). The influence of exercise on brain aging and dementia. *Biochimica et Biophysica Acta, 1822,* 474–481. doi:10.1016/j.bbadis.2011.07.010

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences, 9,* 75–82. doi:10.1016/j.tics.2004.12.004

Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General, 133,* 339–354. doi:10.1037/0096-3445.133.3.339

LeDoux, J. (2000). Emotion circuits in the brain. *Annual Review of Neuroscience, 23,* 155–184. doi:10.1146/annurev.neuro.23.1.155

LeDoux, J. (2012). Rethinking the emotional brain. *Neuron, 73,* 653–676. doi:10.1016/j.neuron.2012.02.004

Lee, A. K. C., Rajaram, S., Xia, J., Bharadwaj, H., Larson, E., Hämäläinen, M. S., & Shinn-Cunningham, B. G. (2013). Auditory selective attention reveals preparatory activity in different cortical regions for selection based on source location and source pitch. *Frontiers in Neuroscience, 6,* e190. doi:10.3389/fnins.2012.00190

Lee, Y.-Y., & Hsieh, S. (2014). Classifying different emotional states by means of EEG-based functional connectivity patterns. *PloS ONE, 9,* e95415. doi:10.1371/journal.pone.0095415

León-Carrión, J., Martín-Rodríguez, J., Damas-López, J., Pourrezai, K., Izzetoglu, K., Barroso y Martin, J., & Domínguez-Morales, M. (2007). A lasting post-stimulus activation on dorsolateral prefrontal cortex is produced when processing valence and arousal in visual affective stimuli. *Neuroscience Letters, 422,* 147–152. doi:10.1016/j.neulet.2007.04.087

Leone, S. (1966). *The Good, the Bad and the Ugly*. Italy: PEA.

Levitin, D. J. (2008). *This is your brain on music: Understanding a human obsession*. London, UK: Atlantic Books.

Liégeois-Chauvel, C., Peretz, I., Babaï, M., Laguitton, V., & Chauvel, P. (1998). Contribution of different cortical areas in the temporal lobes to music processing. *Brain, 121,* 1853–1867. doi:10.1093/brain/121.10.1853

Light, G., Williams, L., Minow, F., Sprock, J., Rissling, A., Sharp, R., … Braff, D. (2010). Electroencephalography (EEG) and event-related potentials (ERPs) with human participants. *Current Protocols in Neuroscience, 6,* 1–24. doi:10.1002/0471142301.ns0625s52

Lim, C. L., Byrne, C., & Lee, J. K. W. (2008). Human thermoregulation and measurement of body temperature in exercise and clinical settings. *Annals of the Academy of Medicine, Singapore, 37,* 347–353.

Lim, H. B. T., Karageorghis, C. I., Romer, L. M., & Bishop, D. T. (2014). Psychophysiological effects of synchronous versus asynchronous music during cycling. *Medicine & Science in Sports & Exercise, 46,* 407–413. doi:10.1249/MSS.0b013e3182a6378c

Lima-Silva, A. E., Silva-Cavalcante, M. D., Pires, F. O., Bertuzzi, R., Oliveira, R. S. F., & Bishop, D. (2012). Listening to music in the first, but not the last 1.5 km of a 5 km running trial alters pacing strategy and improves performance. *International Journal of Sports Medicine, 33,* 813–818.

Linden, D. E. J. (2005). The P300: Where in the brain is it produced and what does it tell us? *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry, 11,* 563–576. doi:10.1177/1073858405280524

Lindgren, F., & Axelsson, A. (1988). The influence of physical exercise on susceptibility to noise-induced temporary threshold shift. *Scandinavian Audiology, 17,* 11–17.

Lindquist, K. A, Wager, T. D., Kober, H., Bliss-Moreau, E., & Barrett, L. F. (2012). The brain basis of emotion: A meta-analytic review. *The Behavioral and Brain Sciences, 35,* 121–143. doi:10.1017/S0140525X11000446

Liu, Z., Ding, L., & He, B. (2006). Integration of EEG/MEG with MRI and fMRI. *IEEE Engineering in Medicine and Biology Magazine, 25,* 46–53. doi:10.1109/MEMB.2006.1657787

Logothetis, N. K. (2002). The neural basis of the blood-oxygen-level-dependent functional magnetic resonance imaging signal. *Philosophical Transactions of the Royal Society of London, 357,* 1003–1037. doi:10.1098/rstb.2002.1114

Lohse, K. R., & Sherwood, D. E. (2011). Defining the focus of attention: Effects of attention on perceived exertion and fatigue. *Frontiers in Psychology, 2,* e332. doi:10.3389/fpsyg.2011.00332

Lohse, K. R., & Sherwood, D. E. (2012). Thinking about muscles: The neuromuscular effects of attentional focus on accuracy and fatigue. *Acta Psychologica, 140,* 236–245. doi:10.1016/j.actpsy.2012.05.009

Lohse, K. R., Sherwood, D. E., & Healy, A. F. (2010). How changing the focus of attention affects performance, kinematics, and electromyography in dart throwing. *Human Movement Science, 29,* 542–555. doi:10.1016/j.humov.2010.05.001

Lohse, K. R., Sherwood, D. E., & Healy, A. F. (2011). Neuromuscular effects of shifting the focus of attention in a simple force production task. *Journal of Motor Behavior, 43,* 173–184. doi:10.1080/00222895.2011.555436

Loiperdinger, M., & Elzer, B. (2004). Lumiere’s arrival of the train: Cinema’s founding myth. *The Moving Image, 4,* 89–118. doi:10.1353/mov.2004.0014

Loizou, G., & Karageorghis, C. I. (2015). Effects of psychological priming, video, and music on anaerobic exercise performance. *Scandinavian Journal of Medicine & Science in Sports, 25,* 909–920. doi:10.1111/sms.12391

Loizou, G., Karageorghis, C. I., & Bishop, D. T. (2014). Interactive effects of video, priming, and music on emotions and the needs underlying intrinsic motivation. *Psychology of Sport and Exercise, 15,* 611–619. doi:10.1016/j.psychsport.2014.06.009

Londeree, B. (1997). Effect of training on lactate/ventilatory tresholds: A meta-analysis. *Medicine & Science in Sports & Exercise, 29,* 837–843.

Loomis, A. L., Harvey, E. N., & Hobart, G. (1936). Electrical potentials of the human brain. *Journal of Experimental Psychology, 19,* 249–279.

Lopes-Silva, J. P., Lima-Silva, A. E., Bertuzzi, R., & Silva-Cavalcante, M. D. (2015). Influence of music on performance and psychophysiological responses during moderate-intensity exercise preceded by fatigue. *Physiology & Behavior, 139,* 274–280. doi:10.1016/j.physbeh.2014.11.048

Lopez-Gordo, M. A., Sanchez Morillo, D., & Pelayo Valle, F. (2014). Dry EEG electrodes. *Sensors, 14,* 12847–12870. doi:10.3390/s140712847

López-Sintas, J., Cebollada, À., Filimon, N., & Gharhaman, A. (2014). Music access patterns: A social interpretation. *Poetics, 46,* 56–74. doi:10.1016/j.poetic.2014.09.003

Losonczi, L., Márton, L. F., Brassai, T. S., & Farkas, L. (2014). Embedded EEG signal acquisition systems. *Procedia Technology, 12,* 141–147. doi:10.1016/j.protcy.2013.12.467

Lovejoy, L. P., & Krauzlis, R. J. (2010). Inactivation of primate superior colliculus impairs covert selection of signals for perceptual judgments. *Nature Neuroscience, 13,* 261–266. doi:10.1038/nn.2470

Luck, S. J. (2014). *An introduction to the event-related potential technique* (2nd ed.). Cambridge, MA: MIT Press.

Luck, S. J., Woodman, G. F., & Vogel, E. K. (2000). Event-related potential studies of attention. *Trends in Cognitive Sciences, 4,* 432–440.

Lynn, B. (1975). Somatosensory receptors and their CNS connections. *Annual Review of Physiology, 37,* 105–127.

Mackay, W. A. (2005). Wheels of motion: Oscillatory potentials in the motor cortex. In A. Riehle & E. Vaadia (Eds.), *Motor cortex in voluntary movements: A distributed system for distributed functions* (pp. 181–211). Boca Raton, FL: CRC Press.

Maclaren, J., Herbst, M., Speck, O., & Zaitsev, M. (2013). Prospective motion correction in brain imaging: A review. *Magnetic Resonance in Medicine, 69,* 621–636. doi:10.1002/mrm.24314

Maguire, M. J. (2012). Music and epilepsy: A critical review. *Epilepsia, 53,* 947–961. doi:10.1111/j.1528-1167.2012.03523.x

Makeig, S. (1993). Auditory event-related dynamics of the EEG spectrum and effects of exposure to tones. *Electroencephalography and Clinical Neurophysiology, 86,* 283–293. doi:10.1016/0013-4694(93)90110-H

Maldjian, J. A., Laurienti, P. J., Kraft, R. A., & Burdette, J. H. (2003). An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of *f*MRI data sets. *NeuroImage, 19,* 1233–1239. doi:10.1016/S1053-8119(03)00169-1

Marban, E., & Gariepy, T. (1978). A thematic approach to the history of physiology. *The Yale Journal of Biology and Medicine, 51*, 565–570.

Marcora, S. (2009). Perception of effort during exercise is independent of afferent feedback from skeletal muscles, heart, and lungs. *Journal of Applied Physiology, 106,* 2060–2062. doi:10.1152/japplphysiol.90378.2008

Marcora, S. (2016). Can doping be a good thing? Using psychoactive drugs to facilitate physical activity behaviour. *Sports Medicine, 46,* 1–5. doi:10.1007/s40279-015-0412-x

Marcora, S. M. (2008). Do we really need a central governor to explain brain regulation of exercise performance? *European Journal of Applied Physiology, 104*, 929–935. doi:10.1007/s00421-008-0818-3

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *Journal of Applied Physiology, 106,* 857–864. doi:10.1152/japplphysiol.91324.2008

Mason, N. P. (2000). The physiology of high altitude: An introduction to the cardio-respiratory changes occurring on ascent to altitude. *Current Anaesthesia & Critical Care, 11,* 34–41. doi:10.1054/cacc.2000.0242

Maughan, R., & Nimmo, M. (1984). The influence of variations in muscle fibre composition on muscle strength and cross-sectional area in untrained males. *The Journal of Physiology, 351,* 299–311.

Mauss, I. B., & Robinson, M. D. (2009). Measures of emotion: A review. *Cognition & Emotion, 23,* 209–237. doi:10.1080/02699930802204677

Mcauley, J. D. (2010). Tempo and rhythm. In M. Riess Jones, R. R. Fay, & A. N. Popper (Eds.), *Music Perception* (Vol. 36, pp. 165–199). New York, NY: Springer New York. doi:10.1007/978-1-4419-6114-3

McCormick, A., Meijen, C., & Marcora, S. (2015). Psychological determinants of whole-body endurance performance. *Sports Medicine, 45,* 997–1015. doi:10.1007/s40279-015-0319-6

McNevin, N. H., Shea, C. H., & Wulf, G. (2003). Increasing the distance of an external focus of attention enhances learning. *Psychological Research, 67,* 22–29. doi:10.1519/JSC.0b013e31823f275c

Mello, R. G. T., Oliveira, L. F., & Nadal, J. (2006). Detection of the anaerobic threshold by surface electromyography. *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings, 2000,* 6189–6192. doi:10.1109/IEMBS.2006.260619

Michiels, C. (2004). Physiological and pathological responses to hypoxia. *The American Journal of Pathology, 164,* 1875–1882. doi:10.1016/S0002-9440(10)63747-9

Mierau, A., Pester, B., Hülsdünker, T., Schiecke, K., Strüder, H. K., & Witte, H. (2017). Cortical correlates of human balance control. *Brain Topography, 30,* 434–446. doi:10.1007/s10548-017-0567-x

Mihajlovic, V., Grundlehner, B., Vullers, R., & Penders, J. (2015). Wearable, wireless EEG solutions in daily life applications: What are we missing? *IEEE Journal of Biomedical and Health Informatics, 19,* 6–21. doi:10.1109/JBHI.2014.2328317

Minoshima, S., Giordani, B., Berent, S., Frey, K., Foster, N., & Kuhl, D. (1997). Metabolic reduction in the posterior cingulate cortex in very early Alzheimer’s disease. *Annals of Neurology, 42,* 85–94.

Mishkin, M., Ungerleider, L., & Macko, K. (1983). Object vision and spatial vision: two cortical pathways. *Trends in Neurosciences, 6,* 414–417. doi:10.1016/0166-2236(83)90190-X

Monte, O. D., Krueger, F., Solomon, J. M., Schintu, S., Knutson, K. M., Strenziok, M., … Grafman, J. (2013). A voxel-based lesion study on facial emotion recognition after penetrating brain injury. *Social Cognitive and Affective Neuroscience, 8,* 632–639. doi:10.1093/scan/nss041

Moran, A. (1996). *The psychology of concentration in sport performers: A cognitive analysis*. London, UK: Psychology Press.

Morgane, P. J., Galler, J. R., & Mokler, D. J. (2005). A review of systems and networks of the limbic forebrain/limbic midbrain. *Progress in Neurobiology, 75,* 143–160. doi:10.1016/j.pneurobio.2005.01.001

Müller-Putz, G. R., Zimmermann, D., Graimann, B., Nestinger, K., Korisek, G., & Pfurtscheller, G. (2007). Event-related beta EEG-changes during passive and attempted foot movements in paraplegic patients. *Brain Research, 1137,* 84–91. doi:10.1016/j.brainres.2006.12.052

Mundy-Castle, A. C., & McKiever, B. L. (1953). The psychophysiological significance of the galvanic skin response. *Journal of Experimental Psychology, 46,* 15–24.

Mysore, S., & Knudsen, E. (2013). A shared inhibitory circuit for both exogenous and endogenous control of stimulus selection. *Nature Neuroscience, 16,* 473–478. doi:10.1038/nn.3352.A

Nash, K., Schiller, B., Gianotti, L. R. R., Baumgartner, T., & Knoch, D. (2013). Electrophysiological indices of response inhibition in a Go/NoGo task predict self-control in a social context. *PLoS ONE, 8,* e79462. doi:10.1371/journal.pone.0079462

Newman, T., Heyworth, S., & Oldfield, M. (1973). *Tubular Bells*. Oxfordshire: The Manor Studio.

Nicolay, C. W., Kenney, J. L., & Lucki, N. C. (2007). Grip strength and endurance throughout the menstrual cycle in eumenorrheic and women using oral contraceptives. *International Journal of Industrial Ergonomics, 37,* 291–301. doi:10.1016/j.ergon.2006.11.004

Nieuwenhuis, S., Aston-Jones, G., & Cohen, J. D. (2005). Decision making, the P3, and the locus coeruleus--norepinephrine system. *Psychological Bulletin, 131,* 510–532. doi:10.1037/0033-2909.131.4.510

Nilsson, U. (2008). The anxiety-and pain-reducing effects of music interventions: A systematic review. *AORN Journal, 87,* 780–807. doi:10.1016/j.aorn.2007.09.013

Noakes, T. (2000). Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. *Scandinavian Journal of Medicine & Science in Sports, 10,* 123–145.

Noakes, T. D. (2011). Time to move beyond a brainless exercise physiology: The evidence for complex regulation of human exercise performance. *Applied Physiology, Nutrition, and Metabolism, 36,* 23–35. doi:10.1139/H10-082

Noakes, T. D. (2012). Fatigue is a brain-derived emotion that regulates the exercise behavior to ensure the protection of whole body homeostasis. *Frontiers in Physiology, 3,* e82. doi:10.3389/fphys.2012.00082

Noakes, T. D., St Clair Gibson, A., & Lambert, E. V. (2005). From catastrophe to complexity: A novel model of integrative central neural regulation of effort and fatigue during exercise in humans: Summary and conclusions. *British Journal of Sports Medicine, 39,* 120–124. doi:10.1136/bjsm.2003.010330

North, A. C., Hargreaves, D. J., & Hargreaves, J. J. (2004). Uses of music in everyday life. *Music Perception, 22,* 41–77. doi:10.1525/mp.2004.22.1.41

Novacheck, T. F. (1998). The biomechanics of running. *Gait & Posture, 7,* 77–95. doi:10.1016/S0966-6362(97)00038-6

O’Craven, K. M., Rosen, B. R., Kwong, K. K., Treisman, a, & Savoy, R. L. (1997). Voluntary attention modulates *f*MRI activity in human MT-MST. *Neuron, 18,* 591–598. doi:10.1016/S0896-6273(00)80300-1

Oakes, T. R., Johnstone, T., Ores Walsh, K. S., Greischar, L. L., Alexander, A. L., Fox, A. S., & Davidson, R. J. (2005). Comparison of *f*MRI motion correction software tools. *NeuroImage, 28,* 529–543. doi:10.1016/j.neuroimage.2005.05.058

Olejniczak, P. (2006). Neurophysiologic basis of EEG. *Journal of Clinical Neurophysiology, 23,* 186–189. doi:10.1097/01.wnp.0000220079.61973.6c

Olin, D. (1992). *William James: Pragmatism in focus*. London, UK: Routledge.

Oxenham, A. J. (2012). Pitch perception. *The Journal of Neuroscience, 32,* 13335–13338. doi:10.1523/JNEUROSCI.3815-12.2012

Pageaux, B. (2014). The psychobiological model of endurance performance: An effort-based decision-making theory to explain self-paced endurance performance. *Sports Medicine, 44,* 1319–1320. doi:10.1007/s40279-014-0198-2

Pageaux, B. (2016). Perception of effort in exercise science: Definition, measurement and perspectives. *European Journal of Sport Science, 16,* 885–894. doi:10.1080/17461391.2016.1188992

Pageaux, B., & Lepers, R. (2016). Fatigue induced by physical and mental exertion increases perception of effort and impairs subsequent endurance performance. *Frontiers in Physiology, 7,* e587. doi:10.3389/fphys.2016.00587

Pageaux, B., Marcora, S. M., Rozand, V., & Lepers, R. (2015). Mental fatigue induced by prolonged self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise. *Frontiers in Human Neuroscience, 9,* e67. doi:10.3389/fnhum.2015.00067

Park, J. L., Fairweather, M. M., & Donaldson, D. I. (2015). Making the case for mobile cognition: EEG and sports performance. *Neuroscience & Biobehavioral Reviews, 52,* 117–130. doi:10.1016/j.neubiorev.2015.02.014

Parry, D., Chinnasamy, C., Papadopoulou, E., Noakes, T., & Micklewright, D. (2011). Cognition and performance: Anxiety, mood and perceived exertion among Ironman triathletes. *British Journal of Sports Medicine, 45,* 1088–1094. doi:10.1136/bjsm.2010.072637

Pascual-Marqui, R. D. (2002). Standardized low-resolution brain electromagnetic tomography (sLORETA): technical details. *Methods and Findings in Experimental and Clinical Pharmacology, 24,* 5–12.

Pashler, H., Johnston, J., & Ruthruff, E. (2001). Attention and performance. *Annual Review of Psychology, 52,* 629–651.

Penfield, W. (1954). Mechanisms of voluntary movement. *Brain: A Journal of Neurology, 77,* 1–17.

Peretz, I., Gagnon, L., & Bouchard, B. (1998). Music and emotion: perceptual determinants, immediacy, and isolation after brain damage. *Cognition, 68,* 111–141. doi:10.1016/S0010-0277(98)00043-2

Périard, J. D., Racinais, S., Knez, W. L., Herrera, C. P., Christian, R. J., & Girard, O. (2014). Thermal, physiological and perceptual strain mediate alterations in match-play tennis under heat stress. *British Journal of Sports Medicine, 48,* 32–38. doi:10.1136/bjsports-2013-093063

Péronnet, F., Thibault, G., Rhodes, E. C., & McKenzie, D. C. (1987). Correlation between ventilatory threshold and endurance capability in marathon runners. *Medicine & Science in Sports & Exercise, 19,* 610–615.

Perrey, S. (2010). Predominance of central motor command in the regulation of exercise. *Journal of Applied Physiology, 108,* 458. doi:10.1152/japplphysiol.01388.2009

Peters, C. H. L., Vullings, R., Rooijakkers, M. J., Bergmans, J. W. M., Oei, S. G., & Wijn, P. F. F. (2011). A continuous wavelet transform-based method for time-frequency analysis of artefact-corrected heart rate variability data. *Physiological Measurement, 32,* 1517–1527. doi:10.1088/0967-3334/32/10/001

Petersen, S., & Posner, M. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience, 35,* 73–89. doi:10.1146/annurev-neuro-062111-150525

Petersen, T. H., Willerslev-Olsen, M., Conway, B. a, & Nielsen, J. B. (2012). The motor cortex drives the muscles during walking in human subjects. *The Journal of Physiology, 590,* 2443–2452. doi:10.1113/jphysiol.2012.227397

Petrofsky, J. S. (1979). Frequency and amplitude analysis of the EMG during exercise on the bicycle ergometer. *European Journal of Applied Physiology, 41,* 1–15.

Pfurtscheller, G., & Lopes Da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: Basic principles. *Clinical Neurophysiology, 110,* 1842–1857. doi:10.1016/S1388-2457(99)00141-8

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., … Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology, 37,* 127–152. doi:10.1111/1469-8986.3720127

Pinto, B., & Silva, C. Q. (2007). A simple method for calculating the depth of EEG sources using minimum norm estimates (MNE). *Medical and Biological Engineering and Computing, 45,* 643–652. doi:10.1007/s11517-007-0204-z

Pires, F. O., Silva-Júnior, F. L. e, Brietzke, C., Franco-Alvarenga, P. E., Pinheiro, F. A., França, N., … Santos, T. M. (2018). Mental fatigue alters cortical activation and psychological responses, impairing performance in a distance-based cycling trial. *Frontiers in Physiology, 9,* e227. doi:10.3389/fphys.2018.00227

Poldrack, R. A. (2007). Region of interest analysis for *f*MRI. *Social Cognitive and Affective Neuroscience, 2,* 67–70. doi:10.1093/scan/nsm006

Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology, 118,* 2128–2148. doi:10.1016/j.clinph.2007.04.019

Pollak, K. A., Swenson, J. D., Vanhaitsma, T. A., Hughen, R. W., Jo, D., Light, K. C., … Light, A. R. (2014). Exogenously applied muscle metabolites synergistically evoke sensations of muscle fatigue and pain in human subjects. *Experimental Physiology, 99,* 358–366. doi:10.1113/expphysiol.2013.075812

Pollatos, O., Schandry, R., Auer, D. P., & Kaufmann, C. (2007). Brain structures mediating cardiovascular arousal and interoceptive awareness. *Brain Research, 1141,* 178–187. doi:10.1016/j.brainres.2007.01.026

Popovich, C., & Staines, W. R. (2015). Acute aerobic exercise enhances attentional modulation of somatosensory event-related potentials during a tactile discrimination task. *Behavioural Brain Research, 281,* 267–275. doi:10.1016/j.bbr.2014.12.045

Posner, M. I., Rothbart, M. K., Sheese, B. E., & Voelker, P. (2014). Developing attention: Behavioral and brain mechanisms. *Advances in Neuroscience, 2014,* 405094. doi:10.1155/2014/405094

Pourtois, G., Schettino, A., & Vuilleumier, P. (2013). Brain mechanisms for emotional influences on perception and attention: What is magic and what is not. *Biological Psychology, 92,* 492–512. doi:10.1016/j.biopsycho.2012.02.007

Power, G. A., Handrigan, G. A., & Basset, F. A. (2012). Ventilatory response during an incremental exercise test: A mode of testing effect. *European Journal of Sport Science, 12,* 491–498. doi:10.1080/17461391.2011.573580

Prado, J., Carp, J., & Weissman, D. H. (2011). Variations of response time in a selective attention task are linked to variations of functional connectivity in the attentional network. *NeuroImage, 54,* 541–549. doi:10.1016/j.neuroimage.2010.08.022

Pribram, K. H., & McGuinness, D. (1992). Attention and para-attentional processing. Event-related brain potentials as tests of a model. *Annals of the New York Academy of Sciences, 658,* 65–92.

Price, H., Mountney, V., & Knouss, R. (1950). Selection of music to accompany electro-shock therapy. *Occupational Therapy and Rehabilitation, 29,* 220–223.

Priest, D.-L., & Karageorghis, C. I. (2008). A qualitative investigation into the characteristics and effects of music accompanying exercise. *European Physical Education Review, 14,* 347–366. doi:10.1177/1356336X08095670

Prinzmetal, W., McCool, C., & Park, S. (2005). Attention: Reaction time and accuracy reveal different mechanisms. *Journal of Experimental Psychology General, 134,* 73–92. doi:10.1037/0096-3445.134.1.73

Ptak, R. (2012). The frontoparietal attention network of the human brain: Action, saliency, and a priority map of the environment. *The Neuroscientist, 18,* 502–515. doi:10.1177/1073858411409051

Quartana, P. J., Burns, J. W., & Lofland, K. R. (2007). Attentional strategy moderates effects of pain catastrophizing on symptom-specific physiological responses in chronic low back pain patients. *Journal of Behavioral Medicine, 30,* 221–231. doi:10.1007/s10865-007-9101-z

Raichle, M. (2003). Functional brain imaging and human brain function. *The Journal of Neuroscience, 23,* 3959–3962.

Raichle, M. E. (1998). Behind the scenes of functional brain imaging: A historical and physiological perspective. *Proceedings of the National Academy of Sciences of the United States of America, 95,* 765–772.

Rajendra Acharya, U., Paul Joseph, K., Kannathal, N., Lim, C. M., & Suri, J. S. (2006). Heart rate variability: A review. *Medical & Biological Engineering & Computing, 44,* 1031–1051. doi:10.1007/s11517-006-0119-0

Rapela, J., Gramann, K., Westerfield, M., Townsend, J., & Makeig, S. (2012). Brain oscillations in switching vs. focusing audio-visual attention. In *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS* (pp. 352–355). doi:10.1109/EMBC.2012.6345941

Rasch, D., & Guiard, V. (2004). The robustness of parametric statistical methods. *Psychology Science, 46,* 175–208.

Ray, W. J., & Cole, H. W. (1985). EEG activity during cognitive processing: Influence of attentional factors. *International Journal of Psychophysiology, 3,* 43–48. doi:10.1016/0167-8760(85)90018-2

Razon, S., Basevitch, I., Land, W., Thompson, B., & Tenenbaum, G. (2009). Perception of exertion and attention allocation as a function of visual and auditory conditions. *Psychology of Sport and Exercise, 10,* 636–643. doi:10.1016/j.psychsport.2009.03.007

Reaz, M. B. I., Hussain, M. S., & Mohd-Yasin, F. (2006). Techniques of EMG signal analysis: detection, processing, classification and applications. *Biological Procedures Online, 8,* 163. doi:10.1251/bpo115

Reckless, G. E., Ousdal, O. T., Server, A., Walter, H., Andreassen, O. A., & Jensen, J. (2014). The left inferior frontal gyrus is involved in adjusting response bias during a perceptual decision-making task. *Brain and Behavior, 4,* 398–407. doi:10.1002/brb3.223

Reddon, H., Gerstein, H. C., Engert, J. C., Mohan, V., Bosch, J., Desai, D., … Meyre, D. (2016). Physical activity and genetic predisposition to obesity in a multiethnic longitudinal study. *Scientific Reports, 6,* 18672. doi:10.1038/srep18672

Rees, G., Russell, C., Frith, C., & Driver, J. (1999). Inattentional blindness versus inattentional amnesia for fixated but ignored words. *Science, 286,* 2504–2507. doi:10.1126/science.286.5449.2504

Rejeski, W. (1985). Perceived exertion: An active or passive process? *Journal of Sport Psychology, 7,* 371–378. doi:10.1123/jsp.7.4.371

Rendi, M., Szabo, A., Szabó, T., Velenczei, A., & Kovács, A. (2008). Acute psychological benefits of aerobic exercise: A field study into the effects of exercise characteristics. *Psychology, Health & Medicine, 13,* 180–184. doi:10.1080/13548500701426729

Rennie, K. L. (2003). Effects of moderate and vigorous physical activity on heart rate variability in a British study of civil servants. *American Journal of Epidemiology, 158,* 135–143. doi:10.1093/aje/kwg120

Ring, C., Kavussanu, M., & Willoughby, A. (2016). Pain thresholds, pain-induced frontal alpha activity and pain-related evoked potentials are associated with antisocial behavior and aggressiveness in athletes. *Psychology of Sport and Exercise, 22,* 303–311. doi: 10.1016/j.psychsport.2015.09.003

Robinson, B. B. F., Epstein, S. E., Beiser, G. D., & Braunwald, E. (2015). Control of heart rate by the autonomic nervous system: Studies in man on the interrelation between baroreceptor mechanisms and exercise. *Circulation Research, 19,* 400–411. doi:10.1161/01.RES.19.2.400

Rushworth, M., Buckley, M., Gough, P., Alexander, I., Kyriazis, D., McDonald, K., & Passingham, R. (2005). Attentional selection and action selection in the ventral and orbital prefrontal cortex. *Journal of Neuroscience, 25,* 11628–11636. doi:10.1523/JNEUROSCI.2765-05.2005

Russell, J. (1980). A circumplex model of affect. *Journal of Personality and Social Psychology, 39,* 1161–1178. doi:10.1037/h0077714

Russell, J. A. (2003). Core affect and the psychological construction of emotion. *Psychological Review, 110,* 145–172. doi:10.1037/0033-295X.110.1.145

Russell, J. A. (2009). Emotion, core affect, and psychological construction. *Cognition & Emotion, 23,* 1259–1283. doi:10.1080/02699930902809375

Russell, J. A., Weiss, A., & Mendelsohn, G. A. (1989). Affect Grid: A single-item scale of pleasure and arousal. *Journal of Personality and Social Psychology, 57,* 493–502. doi:10.1037//0022-3514.57.3.493

Ruz, M., Worden, M., Tudela, P., & McCandliss, B. (2005). Inattentional amnesia to words in a high attentional load task. *Journal of Cognitive Neuroscience, 17,* 768–776. doi:10.1162/0898929053747685

Sadja, J., Tomfohr, L., Jiménez, J. A., Edwards, K. M., Rock, C. L., Calfas, K., & Mills, P. J. (2012). Higher physical fatigue predicts adherence to a 12-week exercise intervention in women with elevated blood pressure. *Health Psychology, 31,* 156–163. doi:10.1037/a0025785.

Salisbury, D. F., Griggs, C. B., Shenton, M. E., & McCarley, R. W. (2004). The NoGo P300 “anteriorization” effect and response inhibition. *Clinical Neurophysiology, 115,* 1550–1558. doi:10.1016/j.clinph.2004.01.028

Sammler, D., Grigutsch, M., Fritz, T., & Koelsch, S. (2007). Music and emotion: Electrophysiological correlates of the processing of pleasant and unpleasant music. *Psychophysiology, 44,* 293–304. doi:10.1111/j.1469-8986.2007.00497.x

Sarmiento, S., García-Manso, J. M., Martín-González, J. M., Vaamonde, D., Calderón, J., & Da Silva-Grigoletto, M. E. (2013). Heart rate variability during high-intensity exercise. *Journal of Systems Science and Complexity, 26,* 104–116. doi:10.1007/s11424-013-2287-y

Sayorwan, W., Ruangrungsi, N., Piriyapunyporn, T., Hongratanaworakit, T., Kotchabhakdi, N., & Siripornpanich, V. (2013). Effects of inhaled rosemary oil on subjective feelings and activities of the nervous system. *Scientia Pharmaceutica, 81,* 531–542. doi:10.3797/scipharm.1209-05

Scanlon, J. E. M., Sieben, A. J., Holyk, K. R., & Mathewson, K. E. (2017). Your brain on bikes: P3, MMN/N2b, and baseline noise while pedaling a stationary bike. *Psychophysiology, 54,* 927–937. doi:10.1111/psyp.12850

Schneider, S., Askew, C. D., Abel, T., Mierau, A., & Strüder, H. K. (2010). Brain and exercise: A first approach using electrotomography. *Medicine & Science in Sports & Exercise, 42*, 600–607. doi:10.1249/MSS.0b013e3181b76ac8

Sclocco, R., Tana, M. G., Visani, E., Gilioli, I., Panzica, F., Franceschetti, S., … Bianchi, A. M. (2014). EEG-informed *f*MRI analysis during a hand grip task. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 8,* 186. doi:10.1109/EMBC.2012.6347019

Secher, N. H., Seifert, T., & Van Lieshout, J. J. (2008). Cerebral blood flow and metabolism during exercise: Implications for fatigue. *Journal of Applied Physiology, 104,* 306–314. doi:10.1152/japplphysiol.00853.2007

Shafir, T., Taylor, S. F., Atkinson, A. P., Langenecker, S. A., & Zubieta, J. K. (2013). Emotion regulation through execution, observation, and imagery of emotional movements. *Brain and Cognition, 82,* 219–227. doi:10.1016/j.bandc.2013.03.001

Shahabi, H., & Moghimi, S. (2016). Toward automatic detection of brain responses to emotional music through analysis of EEG effective connectivity. *Computers in Human Behavior, 58,* 231–239. doi:10.1016/j.chb.2016.01.005

Shephard, R. J. (1988). PAR-Q, Canadian home fitness test and exercise: Screening alternatives. *Sports Medicine, 5,* 185–195. doi:https://doi.org/10.2165/00007256-198805030-00005

Sherman, M. A., Lee, S., Law, R., Haegens, S., Thorn, C. A., Hämäläinen, M. S., … Jones, S. R. (2016). Neural mechanisms of transient neocortical beta rhythms: Converging evidence from humans, computational modeling, monkeys, and mice. *Proceedings of the National Academy of Sciences,* 4885–4894. doi:10.1073/pnas.1604135113

Shigihara, Y., Tanaka, M., Ishii, A., Kanai, E., Funakura, M., & Watanabe, Y. (2013). Two types of mental fatigue affect spontaneous oscillatory brain activities in different ways. *Behavioral and Brain Functions, 9,* e2. doi:10.1186/1744-9081-9-2

Snowdon, D., Greiner, L., Kemper, S., Nanayakkara, N., & Mortimer, J. (1999). Linguistic ability in early life and longevity: Findings from the Nun Study. In J.-M. Robine, B. Forette, C. Francheschi, & M. Allard (Eds.), *The paradoxes of longevity* (pp. 103–113). Berlin: Springer-Verlag Heidelberg. doi:10.1007/978-3-642-60100-2_9

Sommer, M. A., & Wurtz, R. H. (2008). Brain circuits for the internal monitoring of movements. *Annual Review of Neuroscience, 31,* 317–338. doi:10.1146/annurev.neuro.31.060407.125627

Spielmann, M. I., Schroger, E., Kotz, S. A., & Bendixen, A. (2014). Attention effects on auditory scene analysis: Insights from event-related brain potentials. *Psychological Research, 78,* 361–378. doi:10.1007/s00426-014-0547-7

Squire, L. (1992). Nondeclarative memory: Multiple brain systems supporting learning. *Journal of Cognitive Neuroscience, 4,* 232–243. doi:10.1162/jocn.1992.4.3.232

Squire, L., & Zola, S. (1996). Structure and function of declarative and nondeclarative memory systems. *Proceedings of the National Academy of Sciences of the United States of America, 93,* 13515–13522.

St Clair Gibson, A., Baden, D. A., Lambert, M. I., Lambert, E. V., Harley, X. R., Hampson, D., … Noakes, T. D. (2003). The conscious perception of the sensation of fatigue. *Sports Medicine, 33,* 167–176.

Stegeman, D., & Hermens, H. (1999). Standards for surface electromyography: The European project Surface EMG for non-invasive assessment of muscles (SENIAM). In *Proceedings of 3rd General SENIAM Workshop* (pp. 108–112).

Steimer, T. (2002). The biology of fear- and anxiety-related behaviors. *Dialogues in Clinical Neuroscience, 4,* 231–249. doi:10.1097/ALN.0b013e318212ba87

Stevinson, C. D., & Biddle, S. J. (1998). Cognitive orientations in marathon running and “hitting the wall.” *British Journal of Sports Medicine, 32,* 229–234. doi:10.1136/bjsm.32.3.229

Stickgold, R. (2005). Sleep-dependent memory consolidation. *Nature, 437,* 1272–1278. doi:10.1038/nature04286

Stork, M. J., Kwan, M., Gibala, M. J., & Martin Ginis, K. A. (2015). Music enhances performance and perceived enjoyment of sprint interval exercise. *Medicine & Science in Sports & Exercise, 47,* 1052–1060. doi:10.1249/MSS.0000000000000494

Stork, M. J., & Martin Ginis, K. A. (2017). Listening to music during sprint interval exercise: The impact on exercise attitudes and intentions. *Journal of Sports Sciences, 35,* 1940–1946. doi:10.1080/02640414.2016.1242764

Strelau, J. (1998). *Temperament: A psychological perspective*. New York, NY: Kluwer Academic Publishers.

Sur, S., & Sinha, V. K. (2009). Event-related potential: An overview. *Industrial Psychiatry Journal, 18,* 70–73.

Sutoo, D., & Akiyama, K. (1996). The mechanism by which exercise modifies brain function. *Physiology and Behavior, 60,* 177–181. doi:10.1016/0031-9384(96)00011-X

Sutoo, D., & Akiyama, K. (2003). Regulation of brain function by exercise. *Neurobiology of Disease, 13,* 1–14. doi:10.1016/S0969-9961(03)00030-5

Suzuki, M., & Gottlieb, J. (2013). Distinct neural mechanisms of distractor suppression in the frontal and parietal lobe. *Nature Neuroscience, 16,* 98–104. doi:10.1038/nn.3282

Svebak, S., & Murgatroyd, S. (1985). Metamotivational dominance: A multimethod validation of reversal theory constructs. *Journal of Personality and Social Psychology, 48,* 107–116. doi:10.1037/0022-3514.48.1.107

Szmedra, L., & Bacharach, D. W. (1998). Effect of music on perceived exertion, plasma lactate, norepinephrine and cardiovascular hemodynamics during treadmill running. *International Journal of Sports Medicine, 19,* 32–37. doi:10.1055/s-2007-971876

Sztajzel, J. (2004). Heart rate variability: A noninvasive electrocardiographic method to measure the autonomic nervous system. *Swiss Medical Weekly, 134,* 514–523.

Szu, H., Hsu, C., Moon, G., Yamakawa, T., & Tran, B. (2013). Household wireless electroencephalogram hat. *Applied Computational Intelligence and Soft Computing, 2013,* 8. doi:10.1117/12.923669

Tabachnick, B. G., & Fidell, L. S. (2014). *Using multivariate statistics* (6th ed.). Boston, MA: Pearson.

Tabei, K. I., Satoh, M., Ogawa, J. I., Tokita, T., Nakaguchi, N., Nakao, K., … Tomimoto, H. (2017). Physical exercise with music reduces gray and white matter loss in the frontal cortex of elderly people: The Mihama-Kiho can project. *Frontiers in Aging Neuroscience, 9,* e174. doi:10.3389/fnagi.2017.00174

Tadel, F., Baillet, S., Mosher, J. C., Pantazis, D., & Leahy, R. M. (2011). Brainstorm: A user-friendly application for MEG/EEG analysis. *Computational Intelligence and Neuroscience, 2011,* 13. doi:10.1155/2011/879716

Takeuchi, N., Mori, T., Suzukamo, Y., Tanaka, N., & Izumi, S.-I. (2016). Parallel processing of cognitive and physical demands in left and right prefrontal cortices during smartphone use while walking. *BMC Neuroscience, 17,* 9. doi:10.1186/s12868-016-0244-0

Tam, W. W., Wong, E., & Twinn, S. (2008). Effect of music on procedure time and sedation during colonoscopy: A meta-analysis. *World Journal of Gastroenterology, 14,* 5336–5643. doi:10.3748/wjg.14.5336

Tammen, V. (1996). Elite middle and long distance runners associative/dissociative coping. *Journal of Applied Sport Psychology, 8,* 1–8. doi:10.1080/10413209608406304

Tanaka, H., Monahan, K. D., & Seals, D. R. (2001). Age-predicted maximal heart rate revisited. *Journal of the American College of Cardiology, 37,* 153–156. doi:10.1016/S0735-1097(00)01054-8

Tanaka, M., Shigihara, Y., Ishii, A., Funakura, M., Kanai, E., & Watanabe, Y. (2012). Effect of mental fatigue on the central nervous system: An electroencephalography study. *Behavioral and Brain Functions, 8,* e48. doi:10.1186/1744-9081-8-48

Tarvainen, M. P., Niskanen, J.-P., Lipponen, J. A., Ranta-Aho, P. O., & Karjalainen, P. A. (2014). Kubios HRV--heart rate variability analysis software. *Computer Methods and Programs in Biomedicine, 113,* 210–220. doi:10.1016/j.cmpb.2013.07.024

Tempest, G. D., Eston, R. G., & Parfitt, G. (2014). Prefrontal cortex haemodynamics and affective responses during exercise: A multi-channel near infrared spectroscopy study. *PloS One, 9,* e95924. doi:10.1371/journal.pone.0095924

Tenenbaum, G. (2001). A social-cognitive perspective of perceived exertion and exertion tolerance. In R. N. Singer, H. A. Hausenblas, & C. Janelle (Eds.), *Handbook of sport psychology* (pp. 810–822). New York, NY: Wiley.

Tenenbaum, G., & Connolly, C. T. (2008). Attention allocation under varied workload and effort perception in rowers. *Psychology of Sport and Exercise, 9,* 704–717. doi:10.1016/j.psychsport.2007.09.002

Tenenbaum, G., Kamata, A., & Hayashi, K. (2007). Measurement in sport and exercise psychology: A new outlook on selected issues of reliability and validity. In G. Tenenbaum & R. C. Eklund (Eds.), *Handbook of sport psychology* (3rd ed., pp. 757–773). Hoboken, NJ: Wiley.

Terry, P. C., Karageorghis, C. I., Mecozzi Saha, A., & D'Auria, S. (2012). Effects of synchronous music on treadmill running among elite triathletes. *Journal of Science and Medicine in Sport, 15,* 52–57. doi:10.1016/j.jsams.2011.06.003

Tervaniemi, M., Just, V., Koelsch, S., Widmann, A., & Schröger, E. (2005). Pitch discrimination accuracy in musicians vs nonmusicians: An event-related potential and behavioral study. *Experimental Brain Research, 161,* 1–10. doi:10.1007/s00221-004-2044-5

Thayer, J. F., Ahs, F., Fredrikson, M., Sollers, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health. *Neuroscience and Biobehavioral Reviews, 36,* 747–756. doi:10.1016/j.neubiorev.2011.11.009

Theurel, J., Crepin, M., Foissac, M., & Temprado, J. J. (2012). Effects of different pedalling techniques on muscle fatigue and mechanical efficiency during prolonged cycling. *Scandinavian Journal of Medicine & Science in Sports, 22,* 714–721. doi:10.1111/j.1600-0838.2011.01313.x

Thickbroom, G. W., Phillips, B. A., Morris, I., Byrnes, M. L., & Mastaglia, F. L. (1998). Isometric force-related activity in sensorimotor cortex measured with functional MRI. *Experimental Brain Research, 121,* 59–64. doi:10.1007/s002210050437

Thompson, T., Steffert, T., Ros, T., Leach, J., & Gruzelier, J. (2008). EEG applications for sport and performance. *Methods, 45,* 279–288. doi:10.1016/j.ymeth.2008.07.006

Thongpanja, S., Phinyomark, A., Phukpattaranont, P., & Limsakul, C. (2012). A feasibility study of fatigue and muscle contraction indices based on EMG time-dependent spectral analysis. *Procedia Engineering, 32,* 239–245. doi:10.1016/j.proeng.2012.01.1263

Thornton, T. L., & Gilden, D. L. (2007). Parallel and serial processes in visual search. *Psychological Review, 114,* 71–103. doi:10.1037/0033-295X.114.1.71

Tikkanen, O., Hu, M., Vilavuo, T., Tolvanen, P., Cheng, S., & Finni, T. (2012). Ventilatory threshold during incremental running can be estimated using EMG shorts. *Physiological Measurement, 33,* 603–614. doi:10.1088/0967-3334/33/4/603

Tong, F. (2003). Primary visual cortex and visual awareness. *Nature Reviews Neuroscience, 4,* 219–229. doi:10.1038/nrn1055

Tootell, R., Hadjikhani, N., Vanduffel, W., Liu, A., Mendola, J., Sereno, M., & Dale, A. (1998). Functional analysis of primary visual cortex (V1) in humans. *Proceedings of the National Academy of Sciences of the United States of America, 95,* 811–817.

Treisman, A. (1964). Selective attention in man. *British Medical Bulletin, 20,* 12–16.

Twomey, D. M., Murphy, P. R., Kelly, S. P., & O’Connell, R. G. (2015). The classic P300 encodes a build-to-threshold decision variable. *European Journal of Neuroscience, 42,* 1636–1643. doi:10.1111/ejn.12936

Tyler, L. K., Marslen-Wilson, W. D., Randall, B., Wright, P., Devereux, B. J., Zhuang, J., … Stamatakis, E. A. (2011). Left inferior frontal cortex and syntax: Function, structure and behaviour in patients with left hemisphere damage. *Brain, 134,* 415–431. doi:10.1093/brain/awq369

Utter A. C, Kang, J., & Robertson, R. (n.d.). Medicine current comment: Perceived exertion. *American College of Sports Medicine*.

van Duinen, H., Renken, R., Maurits, N., & Zijdewind, I. (2007). Effects of motor fatigue on human brain activity, An *f*MRI study. *NeuroImage, 35,* 1438–1449. doi:10.1016/j.neuroimage.2007.02.008

Van Landuyt, L. M., Ekkekakis, P., Hall, E. E., & Petruzzello, S. J. (2000). Throwing the mountains into the lakes: On the perils of nomothetic conceptions of the exercise-affect relationship. *Journal of Sport & Exercise Psychology, 22,* 208–234. doi:10.1123/jsep.22.3.208

van Praag, H. (2009). Exercise and the brain: Something to chew on. *Trends in Neurosciences, 32,* 283–290. doi:10.1016/j.tins.2008.12.007

Vogt, B. (2005). Pain and emotion interactions in subregions of the cingulate gyrus. *Nature Reviews Neuroscience, 6,* 533–544. doi:10.1038/nrn1704.Pain

Vogt, B., Finch, D., & Olson, C. (1992). Functional heterogeneity in cingulate cortex: The anterior executive and posterior evaluative regions. *Cerebral Cortex, 2,* 435–443. doi:10.1093/cercor/2.6.435-a

Voss, M., Ingram, J. N., Haggard, P., & Wolpert, D. M. (2006). Sensorimotor attenuation by central motor command signals in the absence of movement. *Nature Neuroscience, 9,* 26–27. doi:10.1038/nn1592

Vredeveldt, A., & Perfect, T. J. (2014). Reduction of environmental distraction to facilitate cognitive performance. *Frontiers in Psychology, 5,* e860. doi:10.3389/fpsyg.2014.00860

Walker, E. J., Kozlowski, P. G., & Lawson, R. (2007). A modular activation/coherence approach to evaluating neurofeedback training: Modular insufficiences, modular excesses, disconnetctions and hyperconnections. *Journal of Neurotherapy, 11,* 25–45. doi:10.1300/J184vl1n01_03

Walker, K. M. M., Bizley, J. K., King, A. J., & Schnupp, J. W. H. (2011). Cortical encoding of pitch: Recent results and open questions. *Hearing Research, 271,* 74–87. doi:10.1016/j.heares.2010.04.015

Wang, C., & Wang, F. (2012). An emotional analysis method based on heart rate variability. *Proceedings of the IEEE-EMBS International Conference on Biomedical and Health Informatics, 25,* 104–107.

Wang, L., Zheng, J., Huang, S., & Sun, H. (2015). P300 and decision-making under risk and ambiguity. *Computational Intelligence and Neuroscience, 2015,* e108417. doi:10.1155/2015/108417

Warburton, D. E. R., Jamnik, V. K., Bredin, S. S. D., McKenzie, D. C., Stone, J., Shephard, R. J., & Gledhill, N. (2011). Evidence-based risk assessment and recommendations for physical activity clearance: Consensus document 2011. *Applied Physiology, Nutrition, and Metabolism, 36,* 266–298. doi:10.1139/h11-060

Warren, J. (2008). How does the brain process music? *Clinical Medicine, 8,* 32–36. doi:10.7861/clinmedicine.8-1-32

Wasserman, K., Hansen, J., Sue, D., Stinger, W., & Whipp, B. (2005). *Principles of exercise testing and interpretation.* Philadelphia, NJ: Lippincott, Williams & Wilkins.

Watanabe, K., & Funahashi, S. (2014). Neural mechanisms of dual-task interference and cognitive capacity limitation in the prefrontal cortex. *Nature Neuroscience, 17,* 601–611. doi:10.1038/nn.3667

Watanabe, T., Yagishita, S., & Kikyo, H. (2008). Memory of music: Roles of right hippocampus and left inferior frontal gyrus. *NeuroImage, 39,* 483–491. doi:10.1016/j.neuroimage.2007.08.024

Weijer, C., Peterson, A., Webster, F., Graham, M., Cruse, D., Fernández-Espejo, D., … Owen, A. M. (2014). Ethics of neuroimaging after serious brain injury. *BMC Medical Ethics, 20,* 15–41. doi:10.1186/1472-6939-15-41

Weinberg, L., Hasni, A., Shinohara, M., & Duarte, A. (2014). A single bout of resistance exercise can enhance episodic memory performance. *Acta Psychologica, 153C,* 13–19. doi:10.1016/j.actpsy.2014.06.011

Weisz, N., Wühle, A., Monittola, G., Demarchi, G., Frey, J., Popov, T., & Braun, C. (2014). Prestimulus oscillatory power and connectivity patterns predispose conscious somatosensory perception. *Proceedings of the National Academy of Sciences of the United States of America, 111,* E417-425. doi:10.1073/pnas.1317267111

Wennberg, R., & Cheyne, D. (2013). On noninvasive source imaging of the human K-complex. *Clinical Neurophysiology, 124,* 941–955. doi:10.1016/j.clinph.2012.10.022

Wessel, D. (1979). Timbre space as a musical control structure. *Computer Music Journal, 3,* 45–52.

Westerhof, N. (2011). A short history of physiology. *Acta Physiologica, 202,* 601–603. doi:10.1111/j.1748-1716.2011.02286.x

Whalen, P. J., Bush, G., McNally, R. J., Wilhelm, S., McInerney, S. C., Jenike, M. A., & Rauch, S. L. (1998). The emotional counting stroop paradigm: a functional magnetic resonance imaging probe of the anterior cingulate affective division. *Biological Psychiatry, 44,* 1219–1228. doi:10.1016/S0006-3223(98)00251-0

Wierzbicka, A. (1992). Defining emotion concepts. *Cognitive Science, 539581,* 539–581.

William, E., & Kurt, M. (2013). Ventilatory anaerobic theresholds of individuals recovering from traumatic brain injury compared with noninjured controls. *Journal of Head Trauma Rehabilitation, 28,* 13–20.

Williamson, J., McColl, R., Mathews, D., Mitchell, J. H., Raven, P. B., & Morgan, W. P. (2002). Brain activation by central command during actual and imagined handgrip under hypnosis. *Journal of Applied Physiology, 92,* 1317–1324. doi:10.1152/japplphysiol.00939.2001

Williamson, J., McColl, R., Mathews, D., Mitchell, J., Raven, P., & Morgan, W. (2001). Hypnotic manipulation of effort sense during dynamic exercise: Cardiovascular responses and brain activation. *Journal of Applied Physiology, 90,* 1392–1399.

Wilson, M. R., Vine, S. J., & Wood, G. (2009). The influence of anxiety on visual attentional control in basketball free throw shooting. *Journal of Sport & Exercise Psychology, 31,* 152–168.

Wise, E. K., Hoffman, J. M., Powell, J. M., Bombardier, C. H., & Bell, K. R. (2012). Benefits of exercise maintenance after traumatic brain injury. *Archives of Physical Medicine and Rehabilitation, 93,* 1319–1323. doi:10.1016/j.apmr.2012.05.009

Wittekind, A. L., Micklewright, D., & Beneke, R. (2011). Teleoanticipation in all-out short-duration cycling. *British Journal of Sports Medicine, 45,* 114–119. doi:10.1136/bjsm.2009.061580

Wolfe, J. M. (1998). Visual memory: What do you know about what you saw? *Current Biology, 8,* 303–304. doi:10.1016/S0960-9822(98)70192-7

Wood, G., & Wilson, M. R. (2010). A moving goalkeeper distracts penalty takers and impairs shooting accuracy. *Journal of Sports Sciences, 28,* 937–946. doi:10.1080/02640414.2010.495995

Wood, J. N., & Grafman, J. (2003). Human prefrontal cortex: processing and representational perspectives. *Nature Reviews Neuroscience, 4,* 139–147. doi:10.1038/nrn1033

Wright, M. J., Gobet, F., Chassy, P., & Ramchandani, P. N. (2013). ERP to chess stimuli reveal expert-novice differences in the amplitudes of N2 and P3 components. *Psychophysiology, 50,* 1023–1033. doi:10.1111/psyp.12084

Wulf, G., Chiviacowsky, S., Schiller, E., & Avila, L. T. G. (2010). Frequent external-focus feedback enhances motor learning. *Frontiers in Psychology, 1,* e190. doi:10.3389/fpsyg.2010.00190

Yanagisawa, H., Dan, I., Tsuzuki, D., Kato, M., Okamoto, M., Kyutoku, Y., & Soya, H. (2010). Acute moderate exercise elicits increased dorsolateral prefrontal activation and improves cognitive performance with Stroop test. *NeuroImage, 50,* 1702–1710. doi:10.1016/j.neuroimage.2009.12.023

Yantis, S. (2008). The neural basis of selective attention: Cortical sources and targets of attentional modulation. *Current Directions in Psychological Science, 17,* 86–90. doi:10.1111/j.1467-8721.2008.00554.x

Yelloly, J. (1809). A case of tumour in the brain, with remarks on the propagation of nervous influence. *Medico-Chirurgical Transactions, 1,* 183–223.

Yin, X., Zhao, L., Xu, J., Evans, A. C., Fan, L., Ge, H., … Liu, S. (2012). Anatomical substrates of the alerting, orienting and executive control components of attention: Focus on the posterior parietal lobe. *PloS ONE, 7,* e50590. doi:10.1371/journal.pone.0050590

Yost, W. (2009). Pitch perception. *Attention, Perception, & Psychophysics, 71,* 1701–1715. doi:10.3758/APP.71.8.1701

Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: Auditory-motor interactions in music perception and production. *Nature Reviews Neuroscience, 8,* 547–558. doi:10.1038/nrn2152

Zatorre, R. J., & Salimpoor, V. N. (2013). From perception to pleasure: Music and its neural substrates. *Proceedings of the National Academy of Sciences of the United States of America, 18,* 10430–10437. doi:10.1073/pnas.1301228110

Zénon, A., Sidibé, M., Olivier, E., Zenon, A., Sidibe, M., Olivier, E., … Olivier, E. (2015). Disrupting the supplementary motor area makes physical effort appear less effortful. *Journal of Neuroscience, 35,* 8737–8744. doi:10.1523/JNEUROSCI.3789-14.2015

Zentner, M., & Eerola, T. (2010). Rhythmic engagement with music in infancy. *Proceedings of the National Academy of Sciences of the United States of America, 107,* 5768–5773. doi:10.1073/pnas.1000121107

Zhang, J.-M., Wang, P., Yao, J., Zhao, L., Davis, M. P., Walsh, D., & Yue, G. H. (2012). Music interventions for psychological and physical outcomes in cancer: A systematic review and meta-analysis. *Supportive Care in Cancer, 20,* 3043–3053. doi:10.1007/s00520-012-1606-5

Zhao, W., Martin, a D., & Davenport, P. W. (2003). Magnitude estimation of inspiratory resistive loads by double-lung transplant recipients. *Journal of Applied Physiology, 94,* 576–582. doi:10.1152/japplphysiol.00564.2002

Zhou, W., & Gotman, J. (2009). Automatic removal of eye movement artifacts from the EEG using ICA and the dipole model. *Progress in Natural Science, 19,* 1165–1170. doi:10.1016/j.pnsc.2008.11.013

Publications by the Author

Manuscripts Published in Peer-Reviewed Journals During the PhD Programme

Barreto-Silva, V., Bigliassi, M., Santos, P. C., & Altimari, L. R. (2018). Psychophysiological effects of audiovisual stimuli during cycle exercise. *European Journal of Sport Science, 18,* 560–568. doi: 10.1080/17461391.2018.1439534

Bigliassi, M., Karageorghis, C. I., Bishop, D. T., Nowicky, A. V., & Wright, M. J. (2018). Cerebral effects of music during isometric exercise: An *f*MRI study. *International Journal of Psychophysiology*. Accepted for publication.

Bigliassi, M., Karageorghis, C. I., Hoy, G. K., & Layne, G. S. (2018). *The Way You Make Me Feel*: Psychological and cerebral responses to music during real-life physical activity. *Psychology of Sport and Exercise*. Advance online publication. doi:10.1016/j.psychsport.2018.01.010

Bigliassi, M., Karageorghis, C. I., Nowicky, A. V., Wright, M. J., & Orgs, G. (2018). Effects of auditory distraction on voluntary movements: Exploring the underlying mechanisms associated with parallel processing. *Psychological Research*. Advance online publication. doi:10.1007/s00426-017-0859-5

Bigliassi, M., Karageorghis, C. I., Wright, M. J., Orgs, G., & Nowicky, A. V. (2017). Effects of auditory stimuli on electrical activity in the brain during cycle ergometry. *Physiology & Behavior, 177,* 135-147. doi:10.1016/j.physbeh.2017.04.023

Bigliassi, M., Karageorghis, C. I., Nowicky, A. V., Orgs, G., & Wright, M. J., (2016). Cerebral mechanisms underlying the effects of music during a fatiguing isometric ankle-dorsiflexion task. *Psychophysiology, 53,* 1472–1483. doi:10.1111/psyp.12693

Bigliassi, M., Silva, V. B., Karageorghis, C. I., Bird, J. M., Santos, P. C., & Altimari, L. R. (2016). Brain mechanisms that underlie the effects of motivational audiovisual stimuli on psychophysiological responses during exercise. *Physiology & Behavior, 158,* 128–136. doi:10.1016/j.physbeh.2016.03.001

Bigliassi, M. (2015). Corollary discharges and fatigue-related symptoms: the role of attentional focus. *Frontiers in Psychology, 6,* e1002. doi:10.3389/fpsyg.2015.01002

Bigliassi, M. (2015). Use the brain: complementary methods to analyze the effects of motivational music. *Frontiers in Human Neuroscience, 9,* e508. doi:10.3389/fnhum.2015.00508

Bigliassi, M., Barreto-Silva, V., Altimari, L., Vandoni, M., Codrons, E., & Buzzachera, C. (2015). How motivational and calm music may affect the prefrontal cortex area and emotional responses: A functional near-infrared spectroscopy (*f*NIRS) study. *Perceptual & Motor Skills, 120,* 202–218. doi:10.2466/27.24.PMS.120v12x5

Bigliassi, M., León-Domínguez, U., Buzzachera, C. F., Barreto-Silva, V., & Altimari, L. R. (2015). How does music aid 5 km of running? *Journal of Strength and Conditioning Research, 29,* 305–314. doi:10.1519/JSC.0000000000000627

Karageorghis, C. I., Bigliassi, M., Tayara, K., Priest, D.-L., & Bird, J. M. (2018). A grounded theory of music use in the psychological preparation of academy soccer players. *Sport, Exercise, and Performance Psychology, 7,* 109-127. doi:10.1037/spy0000110

Karageorghis, C. I., Cheek, P., Simpson, S. D., & Bigliassi, M. (2018). Interactive effects of music tempi and intensities on grip strength and subjective affect. *Scandinavian Journal of Medicine & Science in Sports. 28,* 1166-1175. doi: 10.1111/sms.12979

Karageorghis, C. I., Bruce, A. C., Pottratz, S. T., Stevens, R. C., Bigliassi, M., & Hamer, M. (2018). Psychological and psychophysiological effects of recuperative music postexercise. *Medicine & Science in Sports & Exercise*. *50*, 739-746. doi: 10.1249/MSS.0000000000001497

Triana, R. O., Bigliassi, M., Fontes, E. B., Altimari, L. R., Bankoff, A. D. P., & Moraes, A. C. (2015). Can information on remaining time modulate psychophysiological parameters during an intermittent exercise? *Journal of Sports Medicine and Physical Fitness, 55,* 439–445.

Book Chapters Published During the PhD Programme

Karageorghis, C. I., Ekkekakis, P., Bird, J. M., & Bigliassi, M. (2017). Music in the exercise and sport domain: Conceptual approaches and underlying mechanisms. In M. Lesaffre, P.-J. Maes, & M. Leman (Eds.), *Routledge companion to embodied music interaction* (pp. 284–293). New York, NY: Routledge.

Karageorghis, C. I., Bigliassi, M., Guérin, S. M. R., & Delevoye-Turrell, Y. (in press). Cerebral mechanisms underlying music-related interventions in the exercise domain: Methodological considerations and empirical findings. In S. Marcora & M. Sarkar (Eds.), *Progress in brain research on sport/exercise and the brain (Vol. 3)*. Amsterdam, Netherlands: Elsevier.

Abstracts Published in Conference Proceedings During the PhD Programme

Barreto-Silva, V., Altimari, L. R., Santos, P. C., & Bigliassi, M. (2018). O que os olhos vêem os músculos não sentem: Efeitos da estimulação audiovisual durante exercício físico em obesos. *VII Congresso Brasileiro de Metabolismo, Nutrição e Exercício*, Londrina, Brazil.

Barreto-Silva, V., Santos, P. C., Altimari, L. R., & Bigliassi, M. (2016). Mecanismos cerebrais que explicam os efeitos dos estímulos motivacionais durante exercício. *II Congresso Internacional de Psicologia do Esporte*, Rio Claro, Brazil.

Barreto-Silva, V., Santos, P. C., Bigliassi, M., Rodrigues, D., & Altimari, L. R. (2016). Efeitos da meditação sobre o estado afetivo e desempenho motor em atletas de tiro com arco. *VI Congresso Brasileiro de Metabolismo, Nutrição e Exercício*, Londrina, Brazil.

Bigliassi, B., Karageorghis, C. I., Bishop, D. T., Nowicky, A. V., & Wright, M. (2017). *"When It Hits You, You Feel No Pain":* Exploring the neurophysiological effects of music in exercise. *III College of Health and Life Sciences Conference*, London, UK.

Bigliassi, B., & Karageorghis, C. I. (2017). The influence of music on real-life physical activity: An EEG study. *22nd Annual Congress of the European College of Sport Science*, Dresden, Germany.

Bigliassi, B., Karageorghis, C. I., Nowicky, A. V., Orgs, G., & Wright, M. (2016). *Let The Music Take Control*: The "irrational" effects of music on exercise. *3 Minute Thesis Competition*, London, UK.

Bigliassi, B., Karageorghis, C. I., Nowicky, A. V., Orgs, G., & Wright, M. (2016). Attentional suppression during movement execution: Exploring the underlying mechanisms. *North American Society for the Psychology of Sport and Physical Activity*, Montreal, Canada.

Bigliassi, B., Karageorghis, C. I., Nowicky, A. V., Orgs, G., & Wright, M. (2016). Cerebral mechanisms underlying music use during exhaustive exercise. *North American Society for the Psychology of Sport and Physical Activity*, Montreal, Canada.

Bigliassi, B., Karageorghis, C. I., Wright, M., Orgs, G., & Nowicky, A. V. (2016). Effects of music on central motor command activity during exercise: An EEG study. *British Association of Sport and Exercise Sciences Conference*, Nottingham, UK.

Bigliassi, B., Karageorghis, C. I., Wright, M., Orgs, G., & Nowicky, A. V. (2016). *The bike song*: effects of music on electrical activity in the brain during cycling exercise. *II College of Health and Life Sciences Conference*, London, UK.

Bigliassi, B., Karageorghis, C. I., Nowicky, A. V., Orgs, G., & Wright, M. (2015). This is your brain on exercise and music. *I College of Health and Life Sciences Conference*, London, UK.

Bigliassi, M. (2015). Cortical and psychophysiological effects of sensory modulation on attentional switching. *3 Minute Thesis Competition*, London, UK.

Karageorghis, C. I., Delevoye-Turrell, Y., Bigliassi, M., & Guerin, S. (2018). Neurophysiological mechanisms underlying music-related interventions in the exercise domain. *23rd Annual Congress of the European College of Sport Science*, Dublin, UK.

Karageorghis, C. I., Bruce, A. C., Pottraz, S. T., Stevens, R. C., Bigliassi, M. Hamer, M. (2017). Music hath charms to soothe the savage beast but what of the savage workout? Psychological and psychophysiological effects of recuperative music. *British Association of Sport and Exercise Sciences- European Federation of Sport Psychology Conference*, Nottingham, UK.

Karageorghis, C. I., Ekkekakis, P., Bird, J., & Bigliassi, B. (2016). Music in the exercise domain: An update on conceptual approaches, underlying mechanisms and applications. *British Association of Sport and Exercise Sciences Conference*, Nottingham, UK.

Santos, P. C., Barreto-Silva, V., Altimari, L. R., & Bigliassi, M. (2016). Efeitos da estimulação audiovisual sobre o estado de excitação e desempenho esportivo em atletas de tiro com arco. *VI Congresso Brasileiro de Metabolismo, Nutrição e Exercício*, Londrina, Brazil.

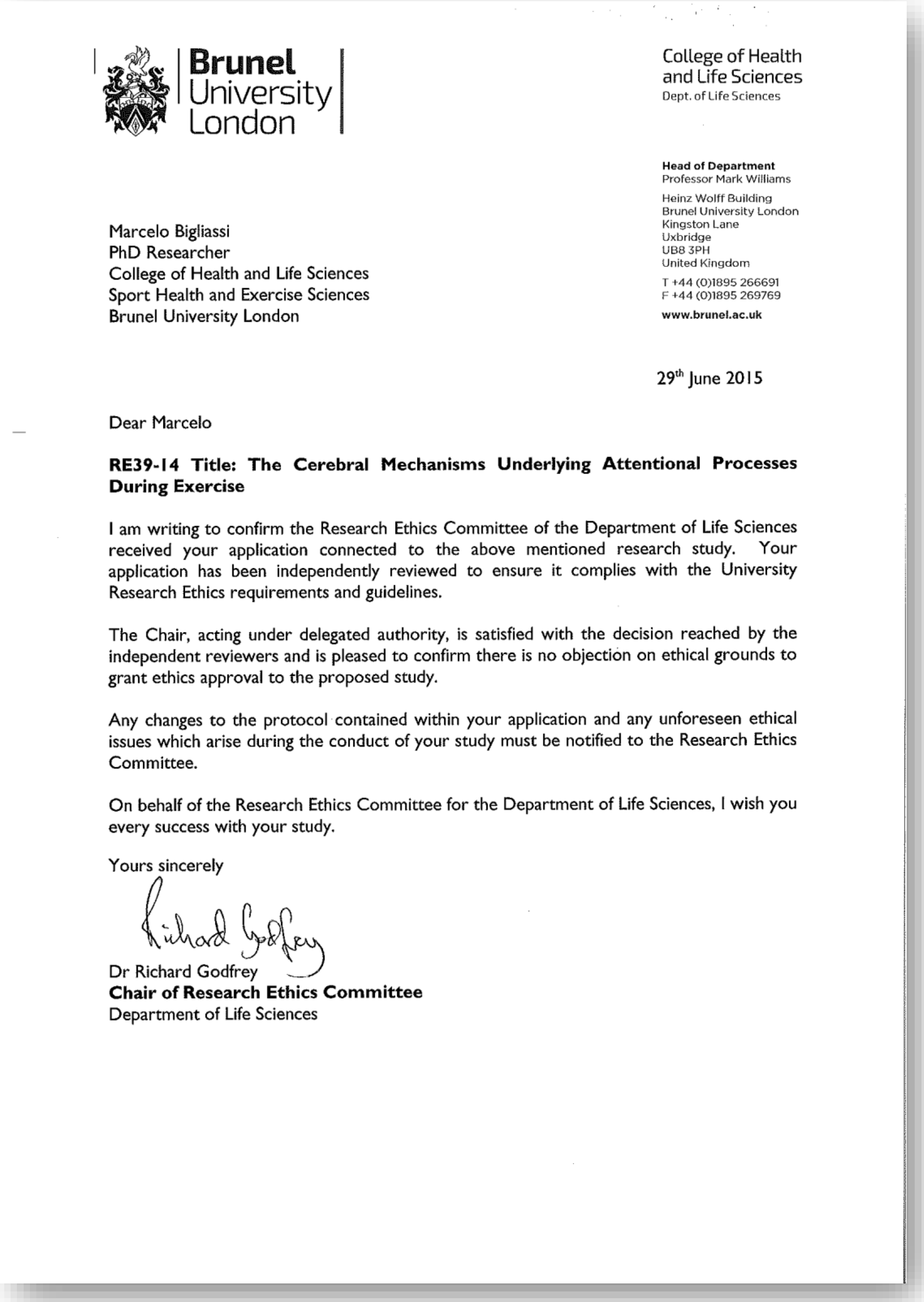
Santos, P. C., Barreto-Silva, V., Altimari, L. R., & Bigliassi, M. (2016). Efeitos da percepção de realidade sobre respostas psicofisiológicas durante exercício físico. *II Congresso Internacional de Psicologia do Esporte*, Rio Claro, Brazil.

Santos, P. C., Barreto-Silva, V., Altimari, L. R., & Bigliassi, M. (2016). Efeitos da estimulação audiovisual sobre o estado de excitação e desempenho esportivo em atletas de tiro com arco. *VI Congresso Brasileiro de Metabolismo, Nutrição e Exercício*, Londrina, Brazil.

Santos, P. C., Barreto-Silva, V., Altimari, L. R., & Bigliassi, M. (2015). O cérebro motivacional: Desvendando os mecanismos que suportam o uso de estrategias sensoriais durante o exercicio fisico. *38 Simpósio Internacional de Ciências do Esporte,* São Paulo, Brazil.

Appendices

Appendix A



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Marcelo Bigliassi
PhD Researcher
College of Health and Life Sciences
Sport Health and Exercise Sciences
Brunel University London

29th June 2015

Dear Marcelo

RE39-14 Title: The Cerebral Mechanisms Underlying Attentional Processes During Exercise

I am writing to confirm the Research Ethics Committee of the Department of Life Sciences received your application connected to the above mentioned research study. Your application has been independently reviewed to ensure it complies with the University Research Ethics requirements and guidelines.

The Chair, acting under delegated authority, is satisfied with the decision reached by the independent reviewers and is pleased to confirm there is no objection on ethical grounds to grant ethics approval to the proposed study.

Any changes to the protocol contained within your application and any unforeseen ethical issues which arise during the conduct of your study must be notified to the Research Ethics Committee.

On behalf of the Research Ethics Committee for the Department of Life Sciences, I wish you every success with your study.

Yours sincerely

Richard Godfrey

Dr Richard Godfrey
Chair of Research Ethics Committee
Department of Life Sciences

Appendix B

PARTICIPANT INFORMATION SHEET

Study title
Cerebral Mechanisms Underlying Attentional Processes during Exercise

Your participation
We would like to invite you to take part in an experimental study. The research will examine the cerebral and psychophysiological changes associated with attentional processes during exercise.

It is important to emphasise that you do not have to take part in the present study, and your participation is voluntary. You can also withdraw from the present study at any time without penalties.

If you take part, you will be submitted to ankle-dorsiflexion tasks and non-invasive techniques will be used to measure your brain and muscular electrical activity. During the physical exams, you will have to perform a sequence of low-intensity exercises involving isometric contractions (without movement). The physical exam involves no risk because of the simple type of movement involved. The sensations of exertion will disappear within 2 or 3 min after the physical exercise is completed. Any extreme discomfort or pain will be used as an index to interrupt the exercise bout.

Your participation will be confidential and your name will never be published or disclosed. The original data will be destroyed 5 years after the research is published. Only the researcher will be present during the trials. The results of the present study will be published in international journals and participants will not be identified. The research team is composed by Marcelo Bigliassi and Drs Costas Karageorghis, Alexander Nowicky, Guido Orgs, Adrian Williams and Michael Wright.

Contact for further information
Marcelo Bigliassi Tel: +44 (0) 7448717548 Email: marcelo.bigliassi@brunel.ac.uk
Dr Costas I. Karageorghis (primary supervisor) Tel: 01895-266 476, Email: costas.karageorghis@brunel.ac.uk

Appendix C

The participant should complete the whole of this sheet

Please tick the appropriate box

	YES	NO
Have you read the Research Participant Information Sheet?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Have you received satisfactory answers to all your questions?	☐	☐
Who have you spoken to?		
Do you understand that you will not be referred to by name in any report concerning the study?	☐	☐
Do you understand that you are free to withdraw from the study:		
• **at any time?**	☐	☐
• **without having to give a reason for withdrawing?**	☐	☐
• **(where relevant, adapt if necessary) without affecting your future care?**	☐	☐
(Where relevant) I agree to my interview being recorded.	☐	☐
(Where relevant) I agree to the use of non-attributable direct quotes when the study is written up or published.	☐	☐
Do you agree to take part in this study?	☐	☐

Signature of Research Participant:

Date:

Name in capitals:

<u>Witness statement</u>

I am satisfied that the above-named has given informed consent.

Witnessed by:

Date:

Name in capitals:

Researcher name:	**Signature:**
Supervisor name:	**Signature:**

Appendix D

Physical Activity Readiness Questionnaire (PAR-Q)

If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you significantly change your physical activity patterns. If you are over 69 years of age and are not used to being very active, check with your doctor. Common sense is your best guide when answering these questions. Please read carefully and answer each one honestly: check YES or NO.

1. Has your doctor ever said you have a heart condition and that you should only do physical activity recommended by a doctor? Yes ☐ No ☐
2. Do you feel pain in your chest when you do physical activity? Yes ☐ No ☐
3. In the past month, have you had a chest pain when you were not doing physical activity? Yes ☐ No ☐
4. Do you lose you balance because of dizziness or do you ever lose conciousness? Yes ☐ No ☐
5. Do you have a bone or joint problem (for example, back, knee, or hip) that could be made worse by a change in your physical activity? Yes ☐ No ☐
6. Is your doctor currently prescribing medication for your blood pressure or heart condition? Yes ☐ No ☐
7. Do you know of any other reason why you should not do physical activity? Yes ☐ No ☐

If yes, please comment:

YES to one or more questions:
You should consult with your doctor to clarify that it is safe for you to become physically active at this current time and in your current state of health.

NO to all questions:
It is reasonably safe for you to participate in physical activity, gradually building up from your current ability level. A fitness appraisal can help determine your ability levels.

I have read, understood and accurately completed this questionnaire. I confirm that I am voluntarily engaging in an acceptable level of exercise, and my participation involves a risk of injury.

Signature

Print name

Date

Having answered YES to one of the above, I have sought medical advice and my GP has agreed that I may exercise.

Signature

Date

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the 7 questions.

Appendix E

Demographic Questionnaire

Details about You

Family name: ________________________ First name: __________________

Age: ____________ years Sex: Male / Female (please circle)

E-mail address: ____

Contact telephone number: ____

Current Level of physical activity (please answer below):

In a typical week, on how many days do you participate in moderate-to-vigorous physical activity?
______________ days

In a typical week, for how many minutes in total do you participate in moderate-to-vigorous physical activity?
______________ minutes

Let us know of any sports that you have participated in and at what level:
____

Nationality: __________________________ (e.g. British, French, Indian, Nigerian)

First language: _______________________ (e.g. English, French, Urdu, Mandarin)

Ethnic Background: ____

In which country did you attend secondary school?
____

Please self-report your height and weight. If you are unsure about the value, please indicate an approximate number. **We will calculate the BMI** based on the information you have provided.

Height: _______ cm **Weight: _______ kg** **BMI: _______**

Appendix F

Attentional Focusing Questionnaire

Date:______________ ID Number ☐

Please put an "x" in the space that indicates how much you would engage in each of the following activities during a handgrip-squeezing task:

1. Letting your mind wander (daydreaming)

   would not would do
   do at all :___:___ :___ :___ :___ :___ :___ a lot

2. Monitoring specific body sensations (e.g. leg tension, breathing rate)

   would not would do
   do at all :___:___ :___ :___ :___ :___ :___ a lot

3. Trying to solve problems in your life

   would not would do
   do at all :___:___ :___ :___ :___ :___ :___ a lot

4. Paying attention to your general level of fatigue

   would not would do
   do at all :___:___ :___ :___ :___ :___ :___ a lot

5. Focusing on how much you are suffering

   would not would do
   do at all :___:___ :___ :___ :___ :___ :___ a lot

6. Singing a song in your head

   would not would do
   do at all :___:___ :___ :___ :___ :___ :___ a lot

7. Focusing on staying loose and relaxed

   would not would do
   do at all :___:___ :___ :___ :___ :___ :___ a lot

8. Wishing the exercise would end

   would not would do
   do at all :___:___ :___ :___ :___ :___ :___ a lot

9. Thinking about school, work, social relationships, etc

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

10. Focusing on your performance goal

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

11. Wondering why you are even contracting your leg in the first place

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

12. Making plans for the future (e.g. a shopping list)

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

13. Getting frustrated at yourself over your performance

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

14. Writing a letter or a paper in your head

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

15. Paying attention to your form or technique

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

16. Reflecting on past experiences

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

17. Paying attention to your muscular contraction

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

18. Thinking about how much you want to quit

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

19. Focusing on the surrounding environment

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

20. Thinking about strategy or tactics

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

21. Counting (e.g. objects in the environment)

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

22. Monitoring your contraction

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

23. Thinking about how much the rest of the contraction will hurt

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

24. Meditating (focusing on a mantra)

would not   would do
do at all   :___:___ :___ :___ :___ :___ :___ a lot

Appendix G

Rating of Perceived Exertion (RPE) Scale

The RPE scale is used to measure the intensity of your exercise. The RPE scale runs from 0-11. The numbers below relate to phrases used to rate how easy or difficult you find an activity. For example, 0 (nothing at all) would be how you feel when sitting in a chair; 10 (very, very heavy) is how you feel at the end of an exercise stress test or after a very difficult activity.

0	**Nothing at all**
0.5	**Very, very light**
1	**Very Light**
2	**Light**
3	**Moderate**
4	**Somewhat Heavy**
5	**Heavy**
6	
7	**Very Heavy**
8	
9	
10	**Very, Very Heavy**
.	**Maximal**

Appendix H

Motivation Scale

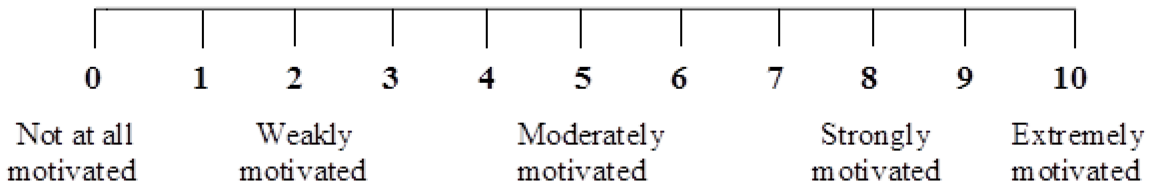
Instructions

Motivation refers to the how much you want to keep going (persistence) and the extent to which you want to push yourself to work harder (effort).

Look at the rating scale; we want you to use this scale from 0 to 10, where 0 means “not motivated at all” (i.e. you are not at all motivated to keep going or to work hard) and 10 means “extremely motivated” (i.e. you are extremely motivated to keep going or to work hard).

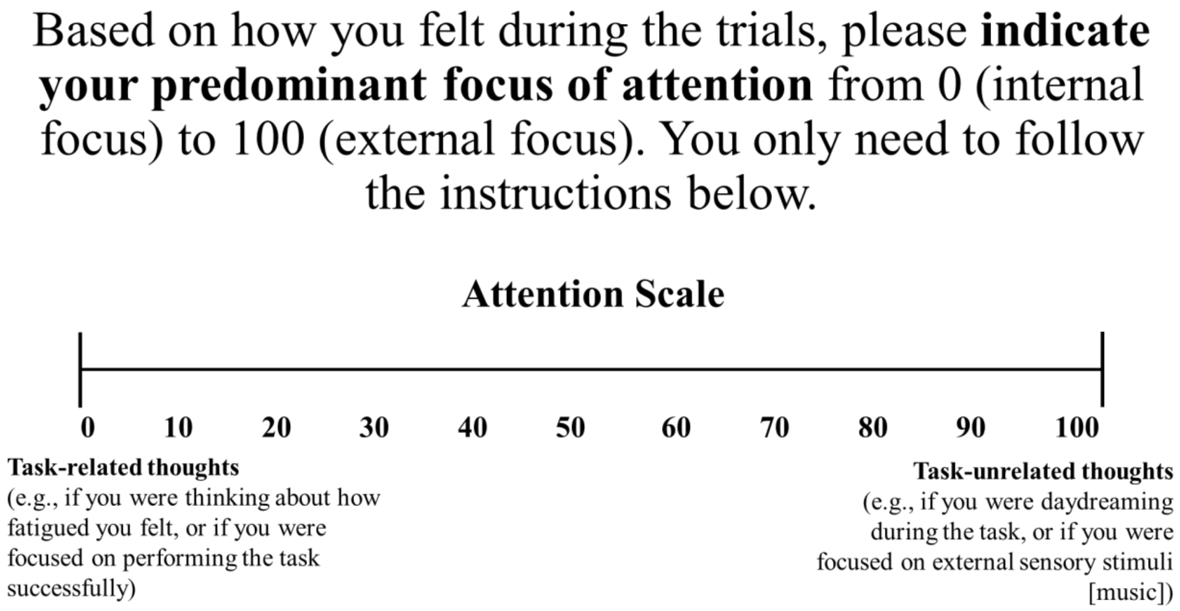
Try to appraise your feelings of motivation as honestly as possible. Don’t underestimate it but don’t overestimate it either. It is your <u>own</u> feeling of motivation that it important, not how it compares to other peoples. What other people think is not important either. Look at the scale and the expressions and then give a number.

Motivation



Appendix I

Attention Scale



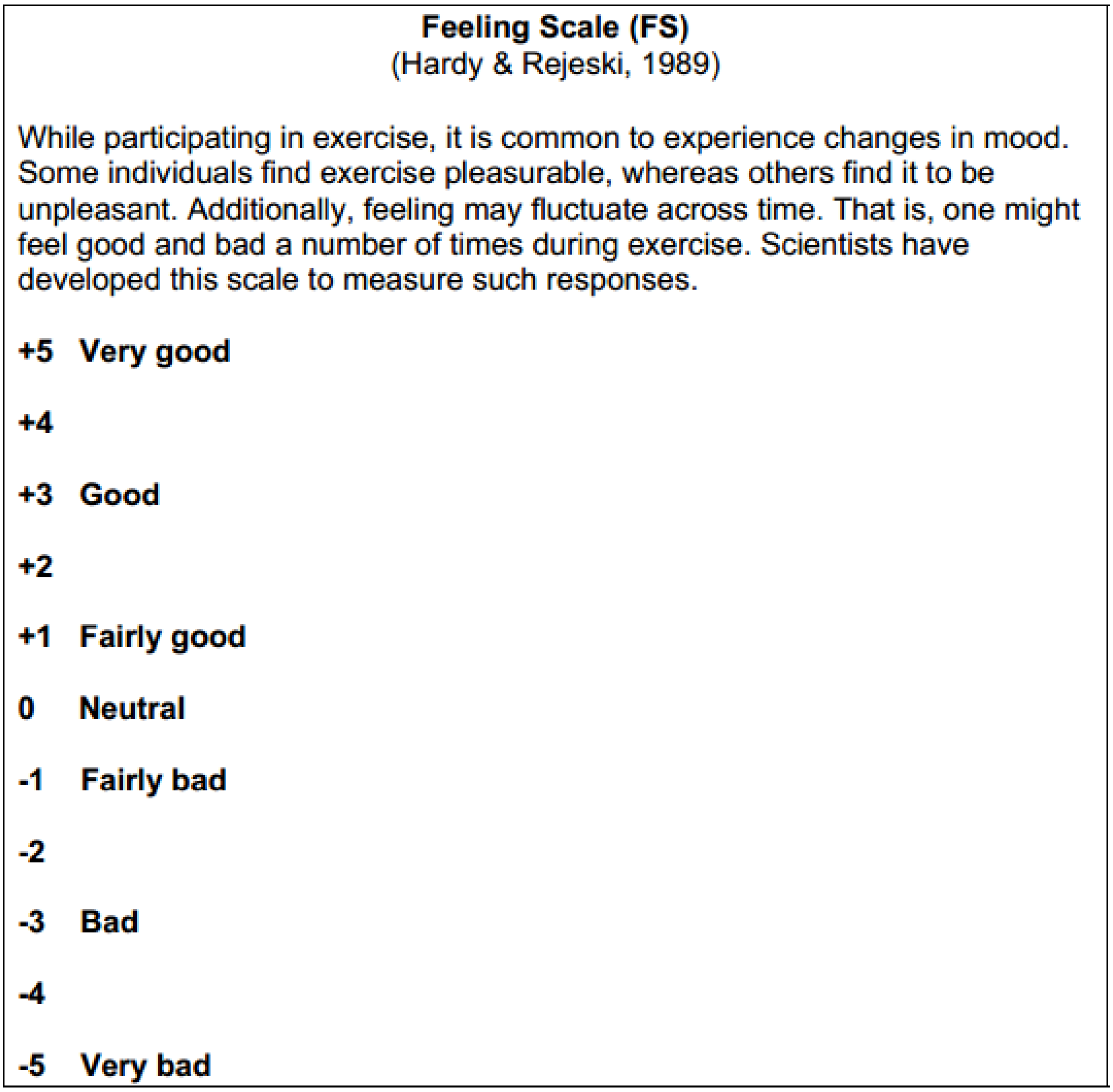
Based on how you felt during the trials, please **indicate your predominant focus of attention** from 0 (internal focus) to 100 (external focus). You only need to follow the instructions below.

Attention Scale

Task-related thoughts
(e.g., if you were thinking about how fatigued you felt, or if you were focused on performing the task successfully)

Task-unrelated thoughts
(e.g., if you were daydreaming during the task, or if you were focused on external sensory stimuli [music])

Appendix J



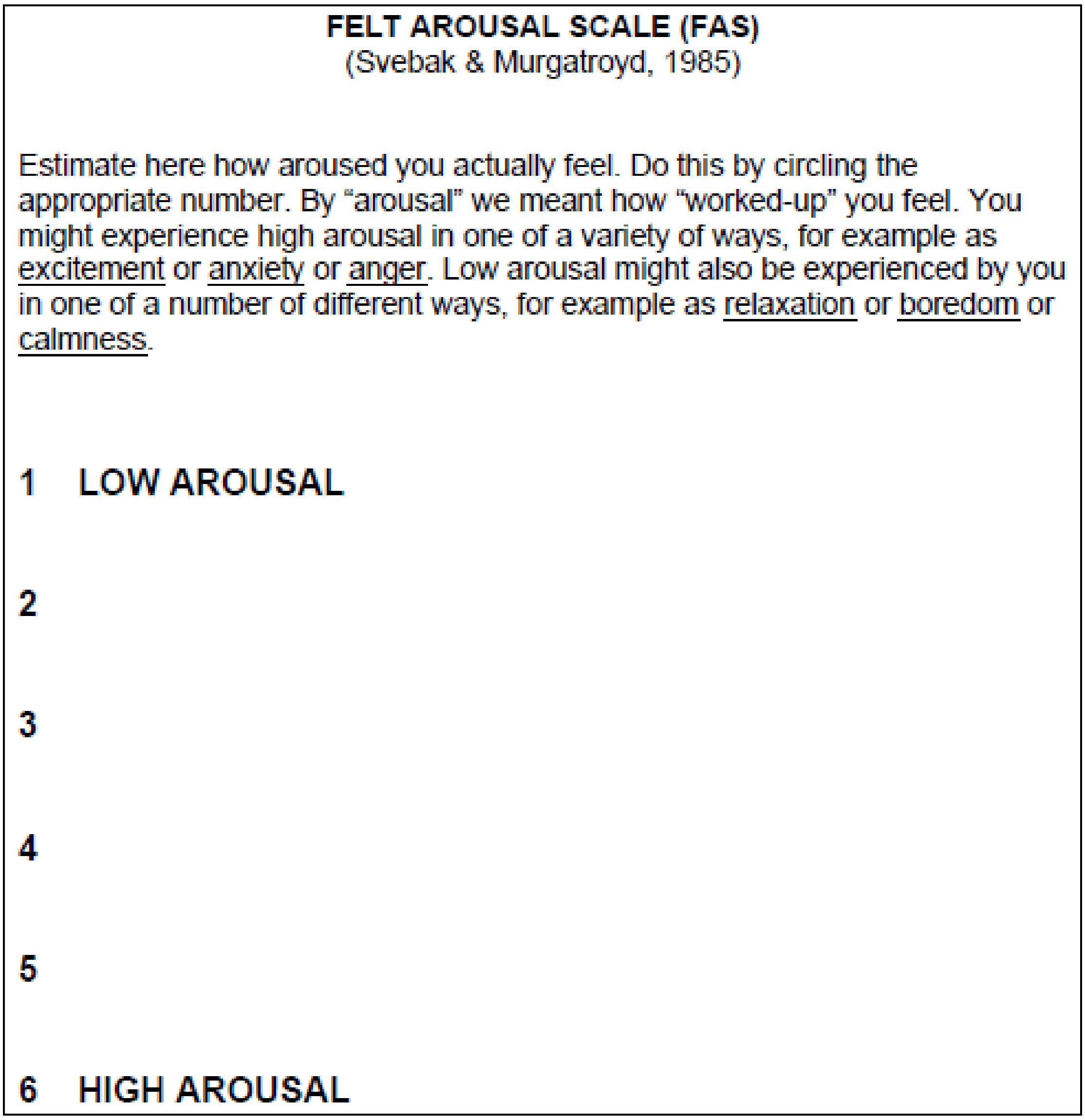
Feeling Scale (FS)

(Hardy & Rejeski, 1989)

While participating in exercise, it is common to experience changes in mood. Some individuals find exercise pleasurable, whereas others find it to be unpleasant. Additionally, feeling may fluctuate across time. That is, one might feel good and bad a number of times during exercise. Scientists have developed this scale to measure such responses.

+5	**Very good**
+4	
+3	**Good**
+2	
+1	**Fairly good**
0	**Neutral**
-1	**Fairly bad**
-2	
-3	**Bad**
-4	
-5	**Very bad**

Appendix K



FELT AROUSAL SCALE (FAS)

(Svebak & Murgatroyd, 1985)

Estimate here how aroused you actually feel. Do this by circling the appropriate number. By "arousal" we meant how "worked-up" you feel. You might experience high arousal in one of a variety of ways, for example as excitement or anxiety or anger. Low arousal might also be experienced by you in one of a number of different ways, for example as relaxation or boredom or calmness.

1 LOW AROUSAL

2

3

4

5

6 HIGH AROUSAL

Appendix L

Ethics approval

Department of Life Sciences Research Ethics Committee
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

12 April 2016

LETTER OF APPROVAL

Applicant: Mr Marcelo Bigliassi

Project Title: Exercise, Music, and Brain

Reference: 0372-MHR-Feb/2016-1860

Dear Mr Marcelo Bigliassi

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.

Please note that:

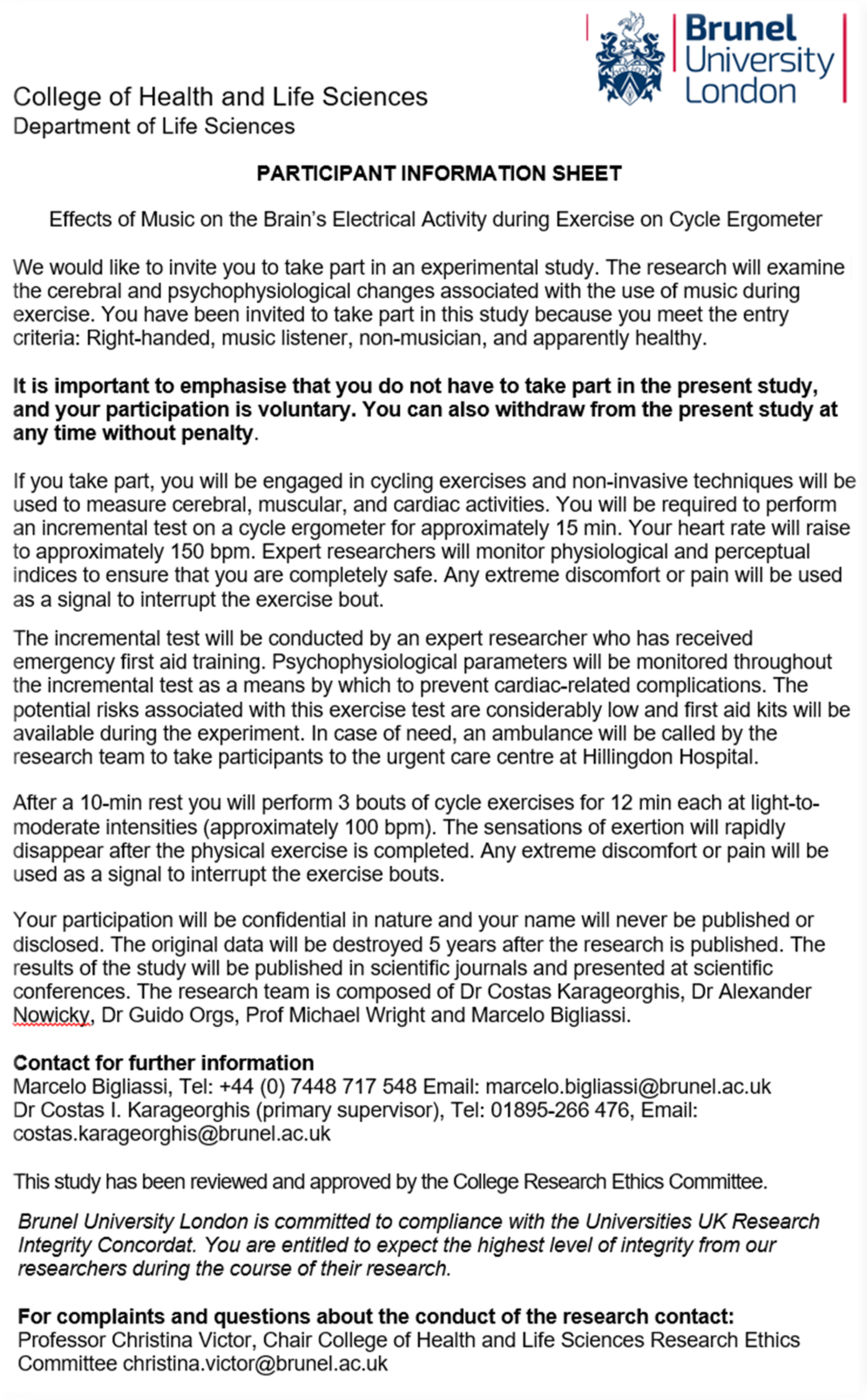
- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to receipt by the Committee of satisfactory responses to any conditions that may appear above, in addition to any subsequent changes to the protocol.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study.
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Professor Christina Victor

Chair

Department of Life Sciences Research Ethics Committee
Brunel University London

Appendix M



College of Health and Life Sciences
Department of Life Sciences

Brunel University London

PARTICIPANT INFORMATION SHEET

Effects of Music on the Brain's Electrical Activity during Exercise on Cycle Ergometer

We would like to invite you to take part in an experimental study. The research will examine the cerebral and psychophysiological changes associated with the use of music during exercise. You have been invited to take part in this study because you meet the entry criteria: Right-handed, music listener, non-musician, and apparently healthy.

It is important to emphasise that you do not have to take part in the present study, and your participation is voluntary. You can also withdraw from the present study at any time without penalty.

If you take part, you will be engaged in cycling exercises and non-invasive techniques will be used to measure cerebral, muscular, and cardiac activities. You will be required to perform an incremental test on a cycle ergometer for approximately 15 min. Your heart rate will raise to approximately 150 bpm. Expert researchers will monitor physiological and perceptual indices to ensure that you are completely safe. Any extreme discomfort or pain will be used as a signal to interrupt the exercise bout.

The incremental test will be conducted by an expert researcher who has received emergency first aid training. Psychophysiological parameters will be monitored throughout the incremental test as a means by which to prevent cardiac-related complications. The potential risks associated with this exercise test are considerably low and first aid kits will be available during the experiment. In case of need, an ambulance will be called by the research team to take participants to the urgent care centre at Hillingdon Hospital.

After a 10-min rest you will perform 3 bouts of cycle exercises for 12 min each at light-to-moderate intensities (approximately 100 bpm). The sensations of exertion will rapidly disappear after the physical exercise is completed. Any extreme discomfort or pain will be used as a signal to interrupt the exercise bouts.

Your participation will be confidential in nature and your name will never be published or disclosed. The original data will be destroyed 5 years after the research is published. The results of the study will be published in scientific journals and presented at scientific conferences. The research team is composed of Dr Costas Karageorghis, Dr Alexander Nowicky, Dr Guido Orgs, Prof Michael Wright and Marcelo Bigliassi.

Contact for further information
Marcelo Bigliassi, Tel: +44 (0) 7448 717 548 Email: marcelo.bigliassi@brunel.ac.uk
Dr Costas I. Karageorghis (primary supervisor), Tel: 01895-266 476, Email: costas.karageorghis@brunel.ac.uk

This study has been reviewed and approved by the College Research Ethics Committee.

Brunel University London is committed to compliance with the Universities UK Research Integrity Concordat. You are entitled to expect the highest level of integrity from our researchers during the course of their research.

For complaints and questions about the conduct of the research contact:
Professor Christina Victor, Chair College of Health and Life Sciences Research Ethics Committee christina.victor@brunel.ac.uk

Appendix N

College of Health and Life Sciences
Department of Life Sciences

CONSENT FORM

Effects of Music on the Brain’s Electrical Activity during Exercise on Cycle Ergometer

The participant should complete the whole of this sheet		
	Please tick the appropriate box	
	YES	NO
Have you read the Research Participant Information Sheet?		
Have you had an opportunity to ask questions and discuss this study?		
Have you received satisfactory answers to all your questions?		
Who have you spoken to?		
Do you understand that you will not be referred to by name in any report concerning the study?		
Do you understand that you are free to withdraw from the study:		
• at any time?		
• without having to give a reason for withdrawing?		
• (where relevant, adapt if necessary) without affecting your future care?		
Do you understand that you will be submitted to incremental tests?		
Do you understand that incremental tests may cause tachycardia, hyperventilation, sweating and dizziness?		
Do you agree to take part in this study?		
Signature of Research Participant:		
Date:		
Name in capitals:		
I am satisfied that the above-named has given informed consent.		

Researcher name:	Signature:
Supervisor name:	Signature:

Appendix O

Music Preference Scale

Based on how you feel right now, rate how much you like this track:

1	I do not like it at all
2	
3	
4	
5	
6	
7	
8	
9	
10	I like it very much

Appendix P

Audiobook Preference Scale

Based on how you feel right now, rate how much you like this audiobook:

1 I do not like it at all

2

3

4

5

6

7

8

9

10 I like it very much

Appendix Q

Brunel University London

College of Health and Life Sciences Research Ethics Committee (DLS)
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

19 September 2016

LETTER OF APPROVAL

Applicant: Mr Marcelo Bigliassi

Project Title: Brain, Music, and Physical Activity

Reference: 3428-MHR-Aug/2016- 3864-2

Dear Mr Marcelo Bigliassi

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment

Please note that:

- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to receipt by the Committee of satisfactory responses to any conditions that may appear above, in addition to any subsequent changes to the protocol.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study.
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Professor Christina Victor

Chair

College of Health and Life Sciences Research Ethics Committee (DLS)
Brunel University London

Appendix R

College of Health and Life Sciences
Department of Life Sciences

PARTICIPANT INFORMATION SHEET

Brain Activation during Real-Life Physical Activity with Music

We would like to invite you to take part in an experimental study. The research will examine the cerebral and psychophysiological changes associated with the use of music during exercise. You have been invited to take part in this study because you meet the entry criteria: Right-handed, non-musician, and apparently healthy.

It is important to emphasise that you do not have to take part in the present study, and your participation is entirely voluntary. You can also withdraw from the present study at any time without penalty.

If you take part, you will be engaged in walking exercises and non-invasive techniques will be used to measure your brain activity. You will need to visit the Brunel Sports Park on one occasion. You will be asked to perform three bouts of light-intensity exercises (~5 min each) separated by 4 min. The sensations of exertion will rapidly disappear after the physical exercise is completed. Any extreme discomfort or pain will be used as a signal to interrupt the exercise bouts.

Your participation will be confidential in nature and your name will not be published or disclosed to a third party. The data derived from this study will be destroyed 5 years after the research is published. The results of the study will be published in scientific journals and presented at scientific conferences. The research team is composed of Marcelo Bigliassi, Dr Costas Karageorghis, Dr Alexander Nowicky, Prof Michael Wright, Georgia Layne, and George Hoy

Contact for further information
Marcelo Bigliassi, Tel: +44 (0) 7448 717 548 Email: marcelo.bigliassi@brunel.ac.uk
Dr Costas I. Karageorghis (primary supervisor), Tel: 01895-266 476, Email: costas.karageorghis@brunel.ac.uk

This study has been reviewed and approved by the College Research Ethics Committee.

Brunel University London is committed to compliance with the Universities UK Research Integrity Concordat. You are entitled to expect the highest level of integrity from our researchers during the course of their research.

For complaints and questions about the conduct of the research contact:
Professor Christina Victor, Chair, College of Health and Life Sciences Research Ethics Committee christina.victor@brunel.ac.uk

Appendix S

College of Health and Life Sciences
Department of Life Sciences

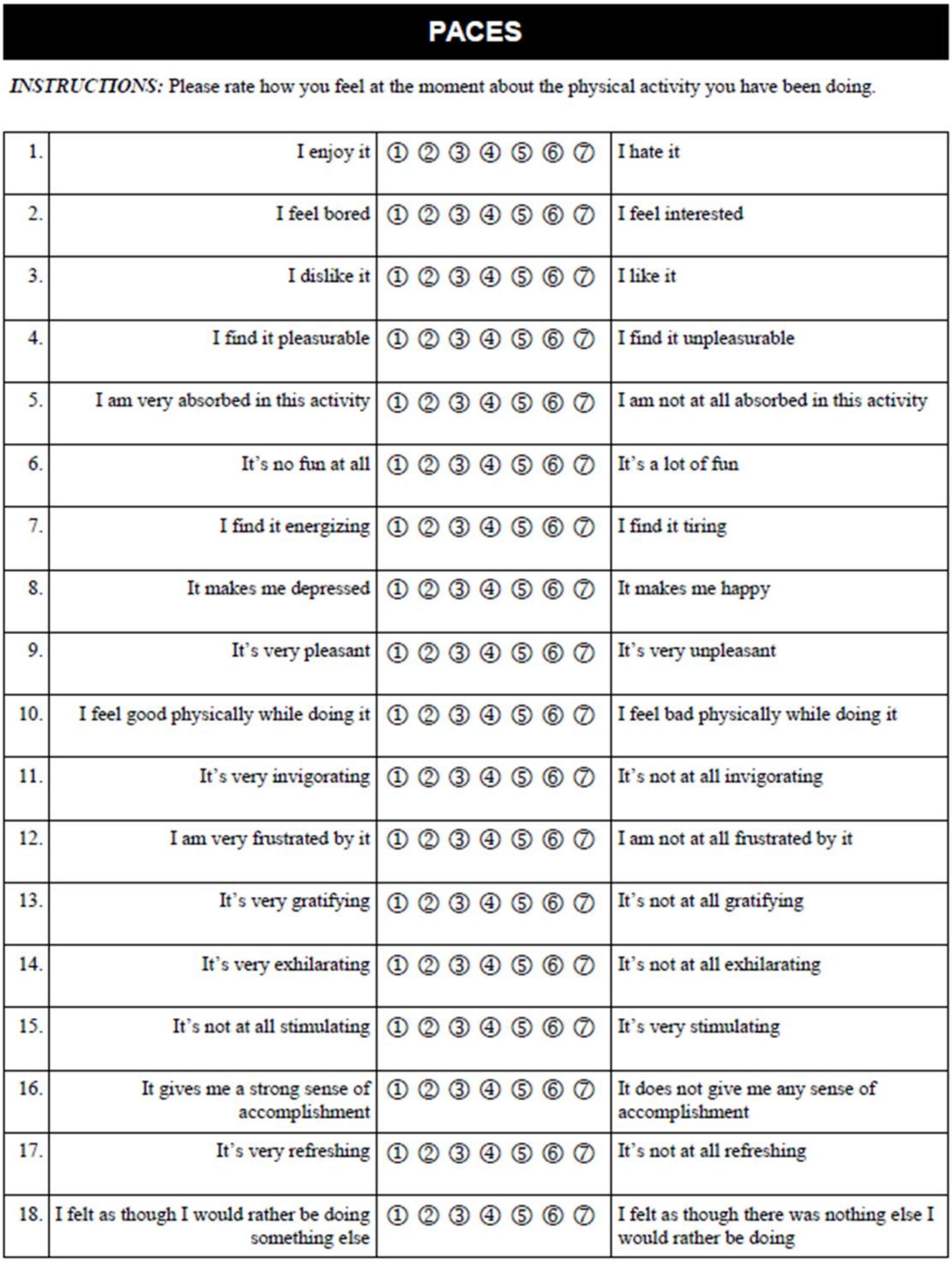
CONSENT FORM

Brain Activation during Real-Life Physical Activity with Music

The participant should complete the whole of this sheet		
	Please tick the appropriate box	
	YES	NO
Have you read the Research Participant Information Sheet?		
Have you had an opportunity to ask questions and discuss this study?		
Have you received satisfactory answers to all your questions?		
Who have you spoken to?		
Do you understand that you will not be referred to by name in any report concerning the study?		
Do you understand that you are free to withdraw from the study:		
• at any time?		
• without having to give a reason for withdrawing?		
Do you agree to take part in this study?		
Signature of Research Participant:		
Date:		
Name in capitals:		
I am satisfied that the above-named has given informed consent.		
Date:		
Name in capitals:		

Researcher name:	Signature:
Supervisor name:	Signature:

Appendix T



PACES

INSTRUCTIONS: Please rate how you feel at the moment about the physical activity you have been doing.

1.	I enjoy it	① ② ③ ④ ⑤ ⑥ ⑦	I hate it
2.	I feel bored	① ② ③ ④ ⑤ ⑥ ⑦	I feel interested
3.	I dislike it	① ② ③ ④ ⑤ ⑥ ⑦	I like it
4.	I find it pleasurable	① ② ③ ④ ⑤ ⑥ ⑦	I find it unpleasurable
5.	I am very absorbed in this activity	① ② ③ ④ ⑤ ⑥ ⑦	I am not at all absorbed in this activity
6.	It's no fun at all	① ② ③ ④ ⑤ ⑥ ⑦	It's a lot of fun
7.	I find it energizing	① ② ③ ④ ⑤ ⑥ ⑦	I find it tiring
8.	It makes me depressed	① ② ③ ④ ⑤ ⑥ ⑦	It makes me happy
9.	It's very pleasant	① ② ③ ④ ⑤ ⑥ ⑦	It's very unpleasant
10.	I feel good physically while doing it	① ② ③ ④ ⑤ ⑥ ⑦	I feel bad physically while doing it
11.	It's very invigorating	① ② ③ ④ ⑤ ⑥ ⑦	It's not at all invigorating
12.	I am very frustrated by it	① ② ③ ④ ⑤ ⑥ ⑦	I am not at all frustrated by it
13.	It's very gratifying	① ② ③ ④ ⑤ ⑥ ⑦	It's not at all gratifying
14.	It's very exhilarating	① ② ③ ④ ⑤ ⑥ ⑦	It's not at all exhilarating
15.	It's not at all stimulating	① ② ③ ④ ⑤ ⑥ ⑦	It's very stimulating
16.	It gives me a strong sense of accomplishment	① ② ③ ④ ⑤ ⑥ ⑦	It does not give me any sense of accomplishment
17.	It's very refreshing	① ② ③ ④ ⑤ ⑥ ⑦	It's not at all refreshing
18.	I felt as though I would rather be doing something else	① ② ③ ④ ⑤ ⑥ ⑦	I felt as though there was nothing else I would rather be doing

Appendix U

Brunel University London

College of Health and Life Sciences Research Ethics Committee (DLS)
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

31 May 2017

LETTER OF APPROVAL

Applicant: Mr Marcelo Bigliassi

Project Title: Exercise and music: An fMRI Study

Reference: 6586-MHR-May/2017- 7172-1

Dear Mr Marcelo Bigliassi

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- A18 – Consent Form – why do you feel it necessary to include a witness statement when you are only recruiting over 18 year olds with capacity to consent? You can leave or remove as you see fit.

- The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.

Please note that:

- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to receipt by the Committee of satisfactory responses to any conditions that may appear above, in addition to any subsequent changes to the protocol.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study.
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Professor Christina Victor

Chair

College of Health and Life Sciences Research Ethics Committee (DLS)
Brunel University London

Appendix V

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ROYAL HOLLOWAY, UNIVERSITY OF LONDON - MAGNETIC RESONANCE IMAGING UNIT

INFORMATION FORM - ADULTS

These notes give some information about an (f)MRI study in which you are invited to take part.

FMRI is a method for producing images of the activity in the brain as people carry out various mental tasks. It involves placing the participant inside a large, powerful magnet which forms part of the brain scanner. When particular regions of the brain are active, they require more oxygen, which comes from red corpuscles in the blood. As a result, the flow of blood increases. This can be detected as changes in the echoes from brief pulses of radio waves. These changes can then be converted by a computer into 3D images. This enables us to determine which parts of the brain are active during different tasks.

MRI is a method for producing images of the grey and white matter of the brain. This is made possible due to the fact that regions containing gray or white matter have different effects on the echoes from brief pulses of radio waves, which we can visualize as 3D images.

DTI is a method for visualizing anatomical connections between different brain regions. This is made possible due to the fact that water molecules tend to move along a major direction in areas that are part of a fibre bundle, whereas they tend to move in random directions outside such fibre bundles. This difference can be visualized in 3D images.

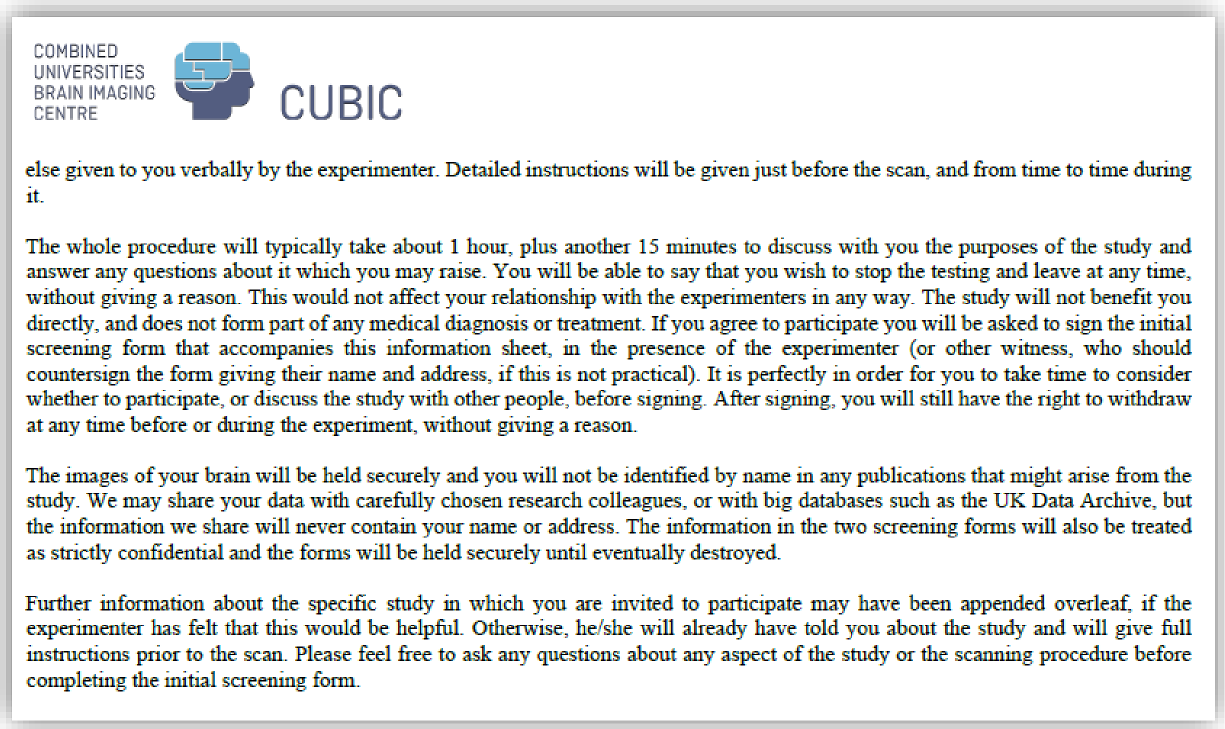
MRS is a method for measuring the amount of certain metabolites (e.g. GABA) in a specific region of the brain. This is made possible by the fact that different metabolites have different effects on the echoes from brief pulses of radio waves, and these differences can be measured.

In a typical experiment, you may be scanned with just one or a combination of the methods described above. In some research projects, other body parts such as the lower leg, knee, thigh or ankle may be scanned. The researcher will be able to provide you with more details about these scans. In those cases, the body part being scanned will be put in the centre of the scanner, so your head might be just outside.

As far as we know, this procedure poses no direct health risks. However, the Department of Health advises that certain people should NOT be scanned. Because the scanner magnet is very powerful, it can interfere with heart pacemakers and clips or other metal items which have been implanted into the body by a surgeon, or with body-piercing items. If you have had surgery which may have involved the use of metal items you should NOT take part. Note that only ferro-magnetic materials (e.g. steel) are likely to cause significant problems. Thus normal dental amalgam fillings do not prohibit you from being scanned, though a dental plate which contained metal would do so, and you would be asked to remove it. You will be asked to remove metal from your pockets (coins, keys), remove articles of clothing which have metal fasteners (belts, bras, etc), as well as most jewellery. Alternative clothing will be provided as necessary. Watches and credit cards should not be taken into the scanner since it can interfere with their operation. You will be asked to complete a questionnaire (the Initial Screening Form) which asks about these and other matters to determine whether it is safe for you to be scanned. In addition, you are asked to give the name and address of your Family Doctor. This is because there is a very small chance that the scan could reveal something which required investigation by a doctor. If that happened, we would seek advice from a specialist, using anonymised data, whether or not a follow-up is suggested, and if so, contact your doctor directly. By signing the consent form, you authorise us to do this. You will also be asked to complete a second, shorter, screening form immediately before the scan.

To be scanned, you would lie on your back on a narrow bed on runners, on which you would be moved until your head was inside the magnet. This is rather like having your head put inside the drum of a very large front-loading washing machine. The scanning process itself creates intermittent loud noises, and you would wear ear-plugs or sound-attenuating headphones. We would be able to talk to you while you are in the scanner through an intercom. If you are likely to become very uneasy in this relatively confined space (suffer from claustrophobia), you should NOT take part in the study. If you do take part and this happens, you will be able to alert the experimenters by activating an alarm and will then be removed from the scanner quickly. It is important that you keep your head as still as possible during the scan, and to help you with this, your head will be partially restrained with padded headrests. We shall ask you to relax your head and keep it still for a period that depends on the experiment but may be more than one hour, which may require some effort on your part. If this becomes unacceptably difficult or uncomfortable, you may demand to be removed from the scanner.

You may be asked to look at a screen through a small mirror (or other optical device) placed just above your eyes and/or be asked to listen to sounds through headphones. You may be asked to make judgements about what you see or asked to perform some other kind of mental task. Details of the specific experiment in which you are invited to participate will either be appended to this sheet or



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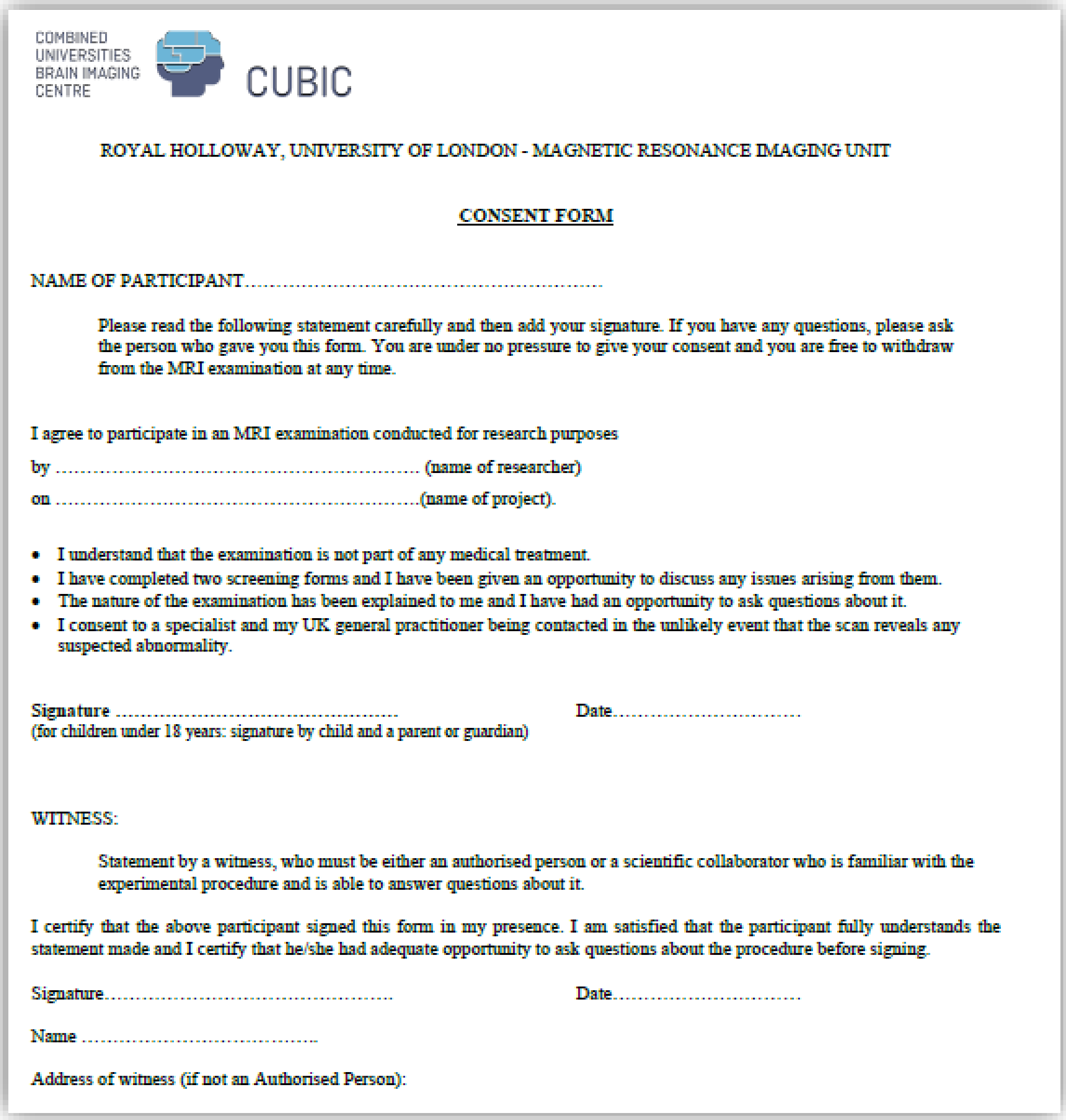
else given to you verbally by the experimenter. Detailed instructions will be given just before the scan, and from time to time during it.

The whole procedure will typically take about 1 hour, plus another 15 minutes to discuss with you the purposes of the study and answer any questions about it which you may raise. You will be able to say that you wish to stop the testing and leave at any time, without giving a reason. This would not affect your relationship with the experimenters in any way. The study will not benefit you directly, and does not form part of any medical diagnosis or treatment. If you agree to participate you will be asked to sign the initial screening form that accompanies this information sheet, in the presence of the experimenter (or other witness, who should countersign the form giving their name and address, if this is not practical). It is perfectly in order for you to take time to consider whether to participate, or discuss the study with other people, before signing. After signing, you will still have the right to withdraw at any time before or during the experiment, without giving a reason.

The images of your brain will be held securely and you will not be identified by name in any publications that might arise from the study. We may share your data with carefully chosen research colleagues, or with big databases such as the UK Data Archive, but the information we share will never contain your name or address. The information in the two screening forms will also be treated as strictly confidential and the forms will be held securely until eventually destroyed.

Further information about the specific study in which you are invited to participate may have been appended overleaf, if the experimenter has felt that this would be helpful. Otherwise, he/she will already have told you about the study and will give full instructions prior to the scan. Please feel free to ask any questions about any aspect of the study or the scanning procedure before completing the initial screening form.

Appendix W



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ROYAL HOLLOWAY, UNIVERSITY OF LONDON - MAGNETIC RESONANCE IMAGING UNIT

CONSENT FORM

NAME OF PARTICIPANT……………………………………………………

Please read the following statement carefully and then add your signature. If you have any questions, please ask the person who gave you this form. You are under no pressure to give your consent and you are free to withdraw from the MRI examination at any time.

I agree to participate in an MRI examination conducted for research purposes

by …………………………………………………… (name of researcher)

on ……………………………………………………(name of project).

- I understand that the examination is not part of any medical treatment.
- I have completed two screening forms and I have been given an opportunity to discuss any issues arising from them.
- The nature of the examination has been explained to me and I have had an opportunity to ask questions about it.
- I consent to a specialist and my UK general practitioner being contacted in the unlikely event that the scan reveals any suspected abnormality.

Signature ……………………………………………… Date……………………………
(for children under 18 years: signature by child and a parent or guardian)

WITNESS:

Statement by a witness, who must be either an authorised person or a scientific collaborator who is familiar with the experimental procedure and is able to answer questions about it.

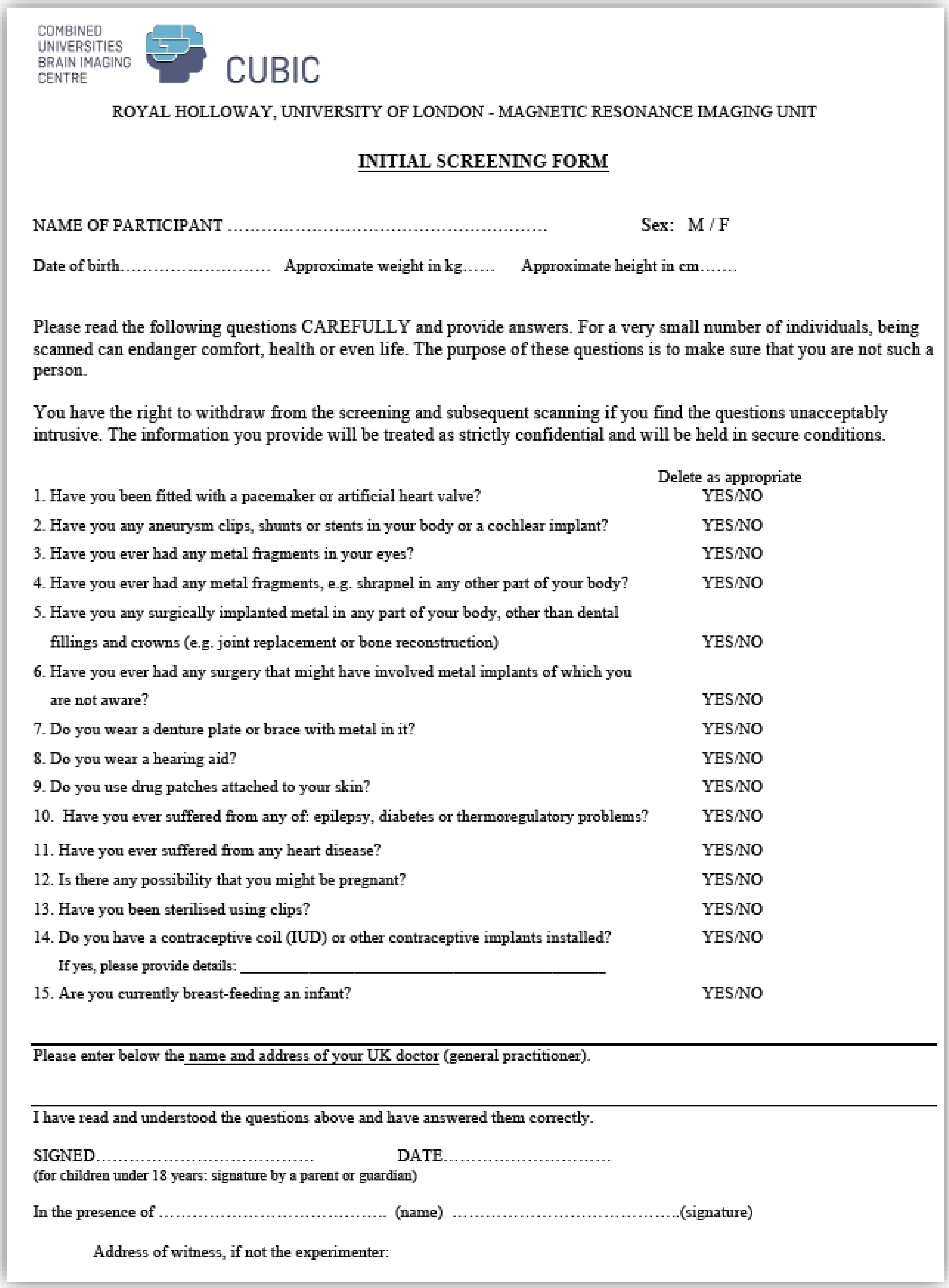
I certify that the above participant signed this form in my presence. I am satisfied that the participant fully understands the statement made and I certify that he/she had adequate opportunity to ask questions about the procedure before signing.

Signature……………………………………………… Date……………………………

Name ……………………………………..

Address of witness (if not an Authorised Person):

Appendix X



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INITIAL SCREENING FORM

NAME OF PARTICIPANT ………………………………………………… Sex: M / F

Date of birth……………………… Approximate weight in kg…… Approximate height in cm……

Please read the following questions CAREFULLY and provide answers. For a very small number of individuals, being scanned can endanger comfort, health or even life. The purpose of these questions is to make sure that you are not such a person.

You have the right to withdraw from the screening and subsequent scanning if you find the questions unacceptably intrusive. The information you provide will be treated as strictly confidential and will be held in secure conditions.

	Delete as appropriate
1. Have you been fitted with a pacemaker or artificial heart valve?	YES/NO
2. Have you any aneurysm clips, shunts or stents in your body or a cochlear implant?	YES/NO
3. Have you ever had any metal fragments in your eyes?	YES/NO
4. Have you ever had any metal fragments, e.g. shrapnel in any other part of your body?	YES/NO
5. Have you any surgically implanted metal in any part of your body, other than dental fillings and crowns (e.g. joint replacement or bone reconstruction)	YES/NO
6. Have you ever had any surgery that might have involved metal implants of which you are not aware?	YES/NO
7. Do you wear a denture plate or brace with metal in it?	YES/NO
8. Do you wear a hearing aid?	YES/NO
9. Do you use drug patches attached to your skin?	YES/NO
10. Have you ever suffered from any of: epilepsy, diabetes or thermoregulatory problems?	YES/NO
11. Have you ever suffered from any heart disease?	YES/NO
12. Is there any possibility that you might be pregnant?	YES/NO
13. Have you been sterilised using clips?	YES/NO
14. Do you have a contraceptive coil (IUD) or other contraceptive implants installed?	YES/NO
If yes, please provide details: ____	
15. Are you currently breast-feeding an infant?	YES/NO

Please enter below the name and address of your UK doctor (general practitioner).

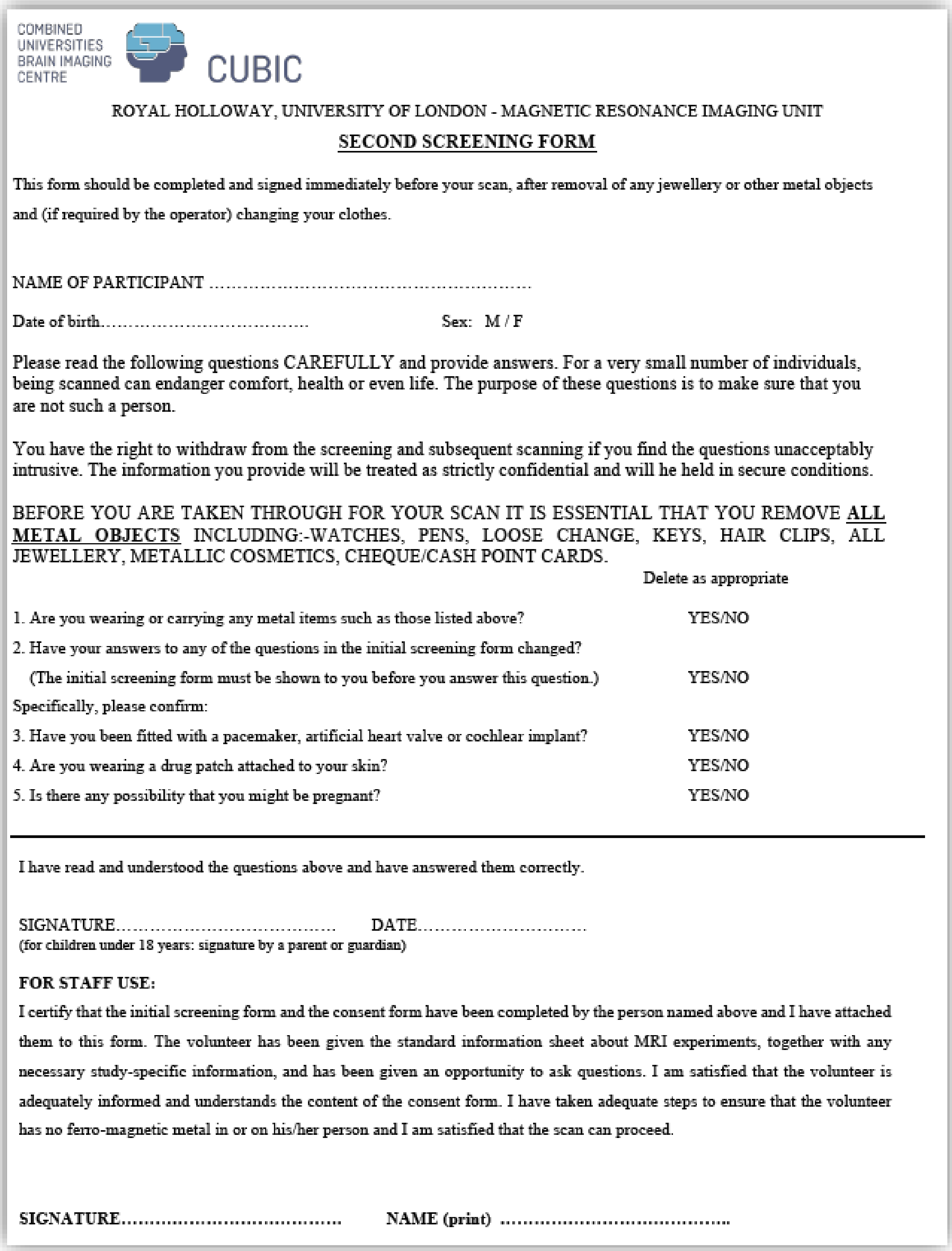
I have read and understood the questions above and have answered them correctly.

SIGNED…………………………………… DATE…………………………
(for children under 18 years: signature by a parent or guardian)

In the presence of …………………………………… (name) …………………………………..(signature)

Address of witness, if not the experimenter:

Appendix Y



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SECOND SCREENING FORM

This form should be completed and signed immediately before your scan, after removal of any jewellery or other metal objects and (if required by the operator) changing your clothes.

NAME OF PARTICIPANT ……………………………………………………

Date of birth……………………………… Sex: M / F

Please read the following questions CAREFULLY and provide answers. For a very small number of individuals, being scanned can endanger comfort, health or even life. The purpose of these questions is to make sure that you are not such a person.

You have the right to withdraw from the screening and subsequent scanning if you find the questions unacceptably intrusive. The information you provide will be treated as strictly confidential and will he held in secure conditions.

BEFORE YOU ARE TAKEN THROUGH FOR YOUR SCAN IT IS ESSENTIAL THAT YOU REMOVE **ALL METAL OBJECTS** INCLUDING:-WATCHES, PENS, LOOSE CHANGE, KEYS, HAIR CLIPS, ALL JEWELLERY, METALLIC COSMETICS, CHEQUE/CASH POINT CARDS.

	Delete as appropriate
1. Are you wearing or carrying any metal items such as those listed above?	YES/NO
2. Have your answers to any of the questions in the initial screening form changed? (The initial screening form must be shown to you before you answer this question.)	YES/NO
Specifically, please confirm:	
3. Have you been fitted with a pacemaker, artificial heart valve or cochlear implant?	YES/NO
4. Are you wearing a drug patch attached to your skin?	YES/NO
5. Is there any possibility that you might be pregnant?	YES/NO

I have read and understood the questions above and have answered them correctly.

SIGNATURE………………………………… DATE…………………………
(for children under 18 years: signature by a parent or guardian)

FOR STAFF USE:

I certify that the initial screening form and the consent form have been completed by the person named above and I have attached them to this form. The volunteer has been given the standard information sheet about MRI experiments, together with any necessary study-specific information, and has been given an opportunity to ask questions. I am satisfied that the volunteer is adequately informed and understands the content of the consent form. I have taken adequate steps to ensure that the volunteer has no ferro-magnetic metal in or on his/her person and I am satisfied that the scan can proceed.

SIGNATURE…………………………………. NAME (print) ………………………………….

Appendix Z

College of Health and Life Sciences
Department of Life Sciences

PARTICIPANT INFORMATION SHEET

Effects of Music on Brain Activity during Exercise

We would like to invite you to take part in an experimental study. The research will examine the cerebral and psychological changes associated with the use of sound during exercise. You have been invited to take part in this study because you meet the entry criteria: An apparently healthy individual who does not present visual- or hearing-related disorders. **It is important to emphasise that you do not have to take part in the present study, and your participation is entirely voluntary. You can also withdraw from the study at any time without penalty**. **Individuals 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, weight of 113 kg or more, or claustrophobia will not be allowed to take part in this study.**

If you take part, you will be engaged in a series of isometric exercises (i.e., static contractions) and non-invasive techniques will be used to measure your brain activity. You will need to visit the Brain Imaging Centre at Royal Holloway, University of London on just one occasion. During the visit you will be asked to execute some handgrip-squeezing exercises* while listening to various sounds. Your brain will be analysed by use of an *f*MRI scanner throughout the experiment. You will not be allowed to bring metallic objects inside the laboratory (e.g., jewellery, hair ornaments, watches, and coins). A researcher will monitor perceptual indices to ensure that you are completely safe. Any extreme discomfort or pain will be used as a signal to interrupt the exercise bouts. The intensity of the exercises will be light-to-moderate and there will be frequent rest periods to allow you to recover fully. The sensations of exertion will slowly disappear once the physical exercise is completed. The experimental procedures will take no longer than 40 min.

Your participation in the study will be confidential in nature and your name will never be published or disclosed to a third party. The original data will be destroyed 5 years after the research is published. The results of the study will be published in scientific journals and presented at scientific conferences. The research team is composed of Marcelo Bigliassi, Drs Costas Karageorghis, Daniel Bishop, Alexander Nowicky, and Prof Michael Wright.

Contact for further information
Marcelo Bigliassi, Tel: +44 (0)7448-717 548 Email: marcelo.bigliassi@brunel.ac.uk
Dr Costas I. Karageorghis (first supervisor), Tel: 01895-266 476, Email: costas.karageorghis@brunel.ac.uk

☆ This study has been reviewed and approved by the College Research Ethics Committee. *Brunel University London is committed to compliance with the Universities UK Research Integrity Concordat. You are entitled to expect the highest level of integrity from our researchers during the course of their research.*

For complaints and questions about the conduct of the research contact:
Professor Christina Victor, Chair College of Health and Life Sciences Research Ethics Committee
christina.victor@brunel.ac.uk
* The researcher will give you an easy-to-follow demonstration.

Appendix AA

College of Health and Life Sciences
Department of Life Sciences

CONSENT FORM

Effects of Music on Brain Activity during Exercise

The participant should complete the whole of this sheet		
	Please tick the appropriate box	
	YES	NO
Have you read the Research Participant Information Sheet?		
Have you had an opportunity to ask questions and discuss this study?		
Have you received satisfactory answers to all your questions?		
Who have you spoken to?		
Do you understand that you will not be referred to by name in any report concerning the study?		
Do you understand that you are free to withdraw from the study:		
• at any time?		
• without having to give a reason for withdrawing?		
Do you agree to take part in this study?		
Signature of Research Participant:		
Date:		
Name in capitals:		
(Researcher) I am satisfied that the above-named has given informed consent.		
Date:		
Name in capitals:		

Researcher’s name:	Signature:
Supervisor’s name:	Signature:

The End

The Circumplex Model of Affect, a painting by Marcelo Bigliassi