

1 **Effects of Auditory Stimuli During Submaximal Exercise on Cerebral**
2 **Oxygenation**

3 _____¹, _____², _____¹, _____³ and _____¹

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8 **Author Note**

9 The study data and materials will be shared openly as part of the publication of
10 the article. The proposed protocol has been reviewed and accepted by the ethics
11 committee of the University of _____ (ref. D2021-001). The study will receive
12 financial support from _____. The authors have no competing financial interests to
13 declare.

14

Abstract

15 Asynchronous music has been commonly used to reduce perceived exertion and render
16 the exercise experience more pleasant. Research has indicated that in-task asynchronous
17 music can reallocate an individual's attentional focus to task-unrelated signals and
18 increase the use of dissociative thoughts. Nonetheless, the brain mechanisms that
19 underlie the purported benefits of music during exercise remain largely unknown due to
20 the severe motion-related restrictions of popular neuroimaging techniques. *fNIRS*
21 represents a non-invasive imaging method that is particularly suited to exercise-related
22 protocols given its high tolerance to motion artifacts. With use of *fNIRS*, the purpose
23 of the proposed study will be to determine the point of onset of cerebral oxygenation
24 decline during exercise and how this is influenced by the presence of asynchronuous
25 (ambient) motivational music. A continuous-wave *fNIRS* system will be used to record
26 the prefrontal, motor, and parietal hemodynamic responses of 24 participants who will
27 perform a cycle-ergometry exercise protocol. The objective will be to test the hypothesis
28 that brain oxygenation changes will be observed earlier when participants exercise with
29 an audiobook or in silence, when compared with exposure to asynchronous music. The
30 results will shed light on the neurophysiological mechanisms that underlie the
31 well-documented ergogenic and psychological effects of music.

32 *Keywords:* cerebral oximetry; cycling; physical activity; prefrontal activity;
33 ventilatory threshold

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36 Casual observers cannot help but notice the almost symbiotic relationship that
37 exists between music and physical activity. This relationship has been fuelled by rapid
38 development in the digital technology that underlies music delivery and a growing
39 recognition that well-selected music can enhance the experience of physical activity
40 (Terry et al., 2020). In the exercise domain, music is used to partially block negative
41 bodily signals from entering focal awareness, [elevate](#) affective states, and provide a
42 rhythmic cue that can prolong physical effort (Bigliassi et al., 2017; Karageorghis et al.,
43 2018).

44 In the exercise context, an ergogenic aid can be broadly defined as a technique or
45 substance used for the purpose of enhancing or prolonging performance (Thein et al.,
46 1995). Music is an oft-used ergogenic aid in [this](#) context (see Karageorghis, 2020, for a
47 review). During an exercise task, there are two main ways in which music can be
48 applied: synchronously and asynchronously. The phenomenon observed when an
49 exerciser synchronises their movements with the rhythmical qualities of music is
50 commonly referred to as auditory-motor synchronisation (Karageorghis & Terry, 1997).
51 In recent years, two main forms of auditory-motor synchronisation have been proposed:
52 (a) *active synchronisation*, in which individuals consciously synchronise their movement
53 rate with the music tempo; and (b) *passive synchronisation*, in which the music tempo
54 is automatically adjusted to match the movement rate of the exerciser (Karageorghis,
55 2020). The application of asynchronous or ambient music, by way of contrast, does not
56 involve synchronisation between an exerciser's movements and the rhythmical qualities
57 of a piece of music. Asynchronous music represents the most widely used form of music
58 application during individual exercise routines (Karageorghis, 2020).

59 Asynchronous music has been commonly used to reduce perceived exertion and
60 render the exercise experience more pleasant (Karageorghis et al., 2017; Kawabata &
61 Chua, 2021). Collectively, studies have indicated that in-task asynchronous music can
62 reallocate an individual's attentional focus to task-unrelated signals, increase the

63 frequency of dissociative thoughts, and consequently ameliorate the effects of
64 fatigue-related symptoms (e.g., limb discomfort, increased respiration rate; Bigliassi
65 et al., 2018; Karageorghis & Priest, 2012). Jones et al. (2014) reported that even
66 high-intensity exercise performed at 5% above the first ventilatory threshold (i.e., the
67 point during exercise at which breathing becomes laboured) is rendered more pleasant
68 by the presence of asynchronous music. In the proposed study, music will be applied in
69 the asynchronous mode during an exercise protocol that concludes with volitional
70 exhaustion.

71 A clutch of studies has indicated that music-induced cerebral phenomena may
72 contribute to exercise performance (for a review, see Karageorghis, 2020). Through
73 adjustments of neural dynamics, music-related interventions were found to guide
74 attention away from the unpleasant sensations caused by exercise-related tasks
75 (Bigliassi et al., 2019; Bigliassi et al., 2016). Reallocating attention outwardly during
76 exercise was associated with reduced frontal–central connectivity (Bigliassi et al., 2017)
77 and increased activation of the left inferior frontal gyrus (Bigliassi et al., 2018).
78 Furthermore, the parietal cortex was found to be implicated in the conscious awareness
79 of bodily sensations through neural inputs from thalamocortical neurones (Crossman &
80 Neary, 2014). Most of the aforementioned electroencephalogram (EEG) and functional
81 magnetic resonance imaging (*fMRI*) studies used relatively simple motor tasks (e.g.,
82 isometric handgrip, ankle-dorsiflexion task) that are somewhat disconnected from
83 ecological physical activities (e.g., cycling, running). This is due mainly to the severe
84 motion-related methodological restrictions of current brain-imaging technologies
85 (Karageorghis et al., 2018).

86 A neuroimaging technique used to assess brain metabolism is functional
87 near-infrared spectroscopy (*fNIRS*), which entails a non-invasive imaging method that
88 quantifies chromophore concentration resolved from the measurement of near-infrared
89 light attenuation, temporal or phasic changes. This technique is particularly salient to
90 exercise-related protocols given its high tolerance for motion artefacts (Leff et al., 2011).
91 In addition, the neurophysiological mechanisms that underlie the influence of

92 attentional manipulation on [tissue oxygenation](#) during exercise can be investigated with
93 an acceptable degree of temporal resolution (up to [50 Hz](#); Vitorio et al., 2017).

94 [fNIRS](#) is a technique that has proven to be effective in the examination of
95 cortical oxygenation during exercise (Herold et al., 2017). Notably, performance of a
96 cycling task [increased](#) prefrontal (i.e., medial prefrontal cortex [mPFC] and dorsolateral
97 prefrontal cortex [dlPFC]) oxygenation that became stable over time (Tempest et al.,
98 2017). Similar results were reported by Jones and Ekkekakis (2019) across the dlPFC
99 during recumbent cycling. [Specifically](#), these authors showed that higher levels of right
100 dlPFC oxygenation were associated with lower ratings of affective valence for
101 participants who reported a preference for low-intensity exercise. [They](#) suggested that
102 the observed dlPFC activity was associated with the cognitive regulation of unpleasant
103 affective responses to exercise. This was experienced to a greater degree by participants
104 with low preference-for-exercise levels when compared to their high-preference-for-
105 exercise counterparts.

106 [The sensation of discomfort and pain is often an indication to the organism that](#)
107 [exercise should be surceased. These signals become more intense at the respiratory](#)
108 [compensation point \(RCP\); the moment during exercise at which minute ventilation](#)
109 [starts to become excessive in relation to exhaled carbon dioxide. Studies that have used](#)
110 [fNIRS to evaluate mPFC and dlPFC haemodynamics have reported a decrease in](#)
111 [cerebral oxygenation at intensities above the RCP \(e.g., Ochi et al., 2018; Rupp &](#)
112 [Perrey, 2008\). The reduced availability of oxygen in the brain might influence central](#)
113 [nervous system motor output, and constitutes a signal that eventually leads to a sharp](#)
114 [degradation in exercise performance.](#)

115 [The cerebral haemodynamic phenomena that are observed during high-intensity](#)
116 [exercise have blood-related concomitants, insofar as blood pH is reduced with the onset](#)
117 [of anaerobic metabolism \(Bhambhani et al., 2007\). Nonetheless, the directionality of the](#)
118 [relationship between cerebral haemodynamics and blood lactate is presently only a](#)
119 [matter for speculation \(i.e., whether it is a cerebral mechanism that instigates the onset](#)
120 [of lactic acid generation; c.f. Quistorff et al., 2008\). The patterns of cerebral](#)

121 (de)oxygenation observed in the PFC at the RCP are associated with the neural control
122 of the musculature as well as processing of emotions, thoughts, and afferent feedback
123 from the working muscles and internal organs. In order to counteract the effects of
124 fatigue, the dlPFC relies on motivational signals travelling through the mesocortical
125 and mesolimbic systems. Insufficient motivation (either conscious or unconscious) to
126 maintain movement execution is likely to cause deoxygenation of the central executive
127 network and task disruption (Bigliassi et al., 2022). At acute levels of brain
128 deoxygenation, the organism is driven towards the discontinuation of exercise
129 (Ekkekakis, 2009; Perrey, 2008).

130 Music can be used to prolong physical effort, possibly through the
131 neurophysiological effects that it has at, or close to, the RCP (Bigliassi et al., 2017;
132 Karageorghis et al., 2018). Two hypotheses have been offered to account for the
133 neurophysiological mechanisms that underlie the effects of music during exercise and
134 physical activity: (a) music delays the decrease in prefrontal oxygenation and shifts "the
135 entire oxygenation curve towards higher levels of exercise intensity" (Karageorghis,
136 2020, p. 942); (b) music delays the increase in prefrontal oxygenation due to a
137 reallocation of attention towards exteroceptive cues (Karageorghis et al., 2017; see
138 Figure 1). Notably, Jones and Ekkekakis (2019) reported an increase in dlPFC
139 oxygenation over time during recumbent cycling, but no such difference was observed
140 between a music condition and a no-music control. In this study, however, participants
141 did not continue cycling until volitional exhaustion but stopped after 15 min.
142 Accordingly, it is plausible that, rather than attenuate prefrontal oxygenation, the
143 application of music delayed the decline that accompanies volitional exhaustion.

144 **Objectives and Hypotheses**

145 The purpose of the proposed study will be to determine the point of onset of
146 cerebral oxygenation decline during an incremental exercise protocol and how this is
147 modulated by the presence of asynchronous music. More specifically, we will assess the
148 effects of pleasurable auditory stimuli (i.e., music) on the cerebral oxygenation curve
149 during a cycle ergometry exercise task. The task will be executed under three

150 conditions: asynchronous music, an audiobook control and a no-audio control. The
151 audiobook condition will be included to control for the effects of auditory attentional
152 distraction that is devoid of musical components (e.g., melody and harmony). Brain
153 oxygenation will be recorded using a continuous-wave fNIRS system over the bilateral
154 mPFC, dlPFC, primary motor cortex and lateral parietal cortex.

155 We hypothesise that the decrease in prefrontal (i.e., mPFC and dlPFC)
156 oxygenation will be observed earlier under conditions in which participants exercise in
157 silence or with an audiobook when compared with exposure to asynchronous
158 motivational music (H_1). Exercise in silence or with an audiobook will lead to less
159 prefrontal (H_2) and parietal (H_3) activation when compared to exercising with music. In
160 addition, as a sanity check for the effect of music exposure on prefrontal and parietal
161 brain activity, we hypothesise that the occipital cortex activation will not differ among
162 the experimental conditions (i.e., negative control; H_4). We ran a series of pilot tests to
163 confirm that the proposed experimental protocol is logistically feasible and that planned
164 analyses will allow us to test the research hypotheses (see Methods section).

165

Methods

166 Participants

167 Volunteer adults will be eligible if in the age range 18–35 years, recreationally
168 active, and apparently healthy. Recreationally active is defined as those who engage in
169 45–90 min of moderate-intensity exercise (3–6 metabolic equivalents [METs]) 2–4 times
170 a week over the previous 6 months (see Kelleher et al., 2010). To be included in the
171 study, participants will need to have brought a recent (under 12 months) medical
172 certificate from their personal physician stating that they are fit to engage in
173 high-intensity physical exercise. Participants will be excluded from the study if they
174 self-report: (a) exercising > 5 times per week at moderate intensity, (b) incidents of
175 motor dysfunction, (c) hearing deficiency, (d) epilepsy, or (e) head trauma (i.e., loss of
176 consciousness for more than 5 min). They will be compensated for their time (i.e., €40
177 for the completion of all four trials).

178 The sample size for the critical statistical test of each research hypothesis was
179 calculated using R with the "pwr" and "TOSTER" packages (the code is available here:
180 <https://doi.org/10.5281/zenodo.6261358>). The required sample size has been computed
181 for paired-samples t tests, which are the critical statistical tests (see Table 1). The
182 fNIRS results of Ozawa et al. (2019) were used as a parameter for H_1-H_2 across the
183 mPFC. For H_1-H_2 across the dlPFC and H_3 , the fNIRS results of Oh et al. (2018) were
184 used. For H_4 , the fNIRS results of Guérin et al. (2021) were used. For H_1-H_2 , the power
185 analysis indicated that 30 participants would be required for the mPFC ($d = 0.64$; $\alpha =$
186 $.02$; $1-\beta = .90$) and nine participants for the dlPFC ($d = 1.38$; $\alpha = .02$; $1-\beta = .90$). In
187 addition, nine participants would be required for H_3 ($d = 1.37$; $\alpha = .02$; $1-\beta = .90$) and
188 36 participants for H_4 ($d = 0.62$; $\alpha = .02$; $1-\beta = .90$; see Table 1). Accordingly, a
189 sample of 36 participants will be recruited for the proposed study.

190 The small telescopes approach was used to determine the smallest effect size of
191 interest (SESOI; i.e., the difference that is considered too small to be meaningful;
192 Simonsohn, 2015). Accordingly, the SESOI was set to the effect size that an earlier
193 study would have had 33% power to detect (Lakens et al., 2018)¹. The fNIRS results of
194 Oh et al. (2018) were used as parameters for H_1-H_4 , with a one-tailed test for H_1-H_3 ,
195 and a two-tailed test for H_4 . The SESOI computations were performed using R (the
196 code is available as supplementary material here:
197 <https://doi.org/10.5281/zenodo.6261358>) and the outputs are displayed in Table 1.

198 **Experimental Procedures**

199 The study will consist of four sessions. [There will be a minimum recovery period](#)
200 [of 48 hours between session. Participants will be advised to refrain from engaging in](#)
201 [physical activity the day of the experiment. They also will be advised to avoid intense](#)
202 [physical activity the day before the experiment.](#)

¹ The effect sizes used for the sample size computation and SESOI are two distinct entities. More precisely, the sample size computation serves to ensure that the study is appropriately powered (i.e., good probability that the statistical test will detect an effect that actually exists), while the SESOI serves to ensure that a true effect exists (for further details, see Sullivan & Feinn, 2012).

203 Session 1 will entail screening, administration of questionnaires, and protocol
204 habituation. Sessions 2–4 will be administered in a fully counterbalanced order and
205 comprise cycling (a) with asynchronous music (120–123 beats per minute [bpm]), (b)
206 with an audiobook (audio control), (c) without any extraneous auditory stimuli (i.e.,
207 ambient noise control). The procedure used for the selection of motivational music
208 tracks is presented in Supplementary File 1.

209 During Session 1, the participant will read an information sheet, be afforded an
210 opportunity to ask questions and sign an informed consent form. Participants will
211 perform an incremental $\dot{V}O_{2\max}$ test on a cycle ergometer (Ergomedic 874E, Monark,
212 Vansbro, Sweden) to determine a work rate representative of 5% above the first
213 ventilatory threshold (VT1; for details on its determination, see Supplementary File 2).
214 Five percent above VT1 will be computed for each participant using the heart rate
215 variability index of root mean square of successive differences (see Karapetian et al.,
216 2008). Participants will also be administered several questionnaires relating to (a)
217 socio-demographic and anthropometric details, (b) self-reported physical activity level
218 (International Physical Activity Questionnaire, IPAQ; Craig et al., 2003), (c)
219 motivation to engage in physical activity (Behavioural Regulations in Exercise
220 Questionnaire, BREQ-3; Markland & Tobin, 2004) and (d) tolerance of exercise
221 intensity (Preference for and Tolerance of the Intensity of Exercise Questionnaire,
222 PRETIE-Q; Carlier et al., 2017).

223 During Sessions 2–4, participants will undergo an exercise test on the cycle
224 ergometer. The ambient temperature will be controlled with the use of a climate-control
225 system to maintain 20°C. Participants will cycle at a constant rate of 63 rpm
226 (revolutions per minute) to avoid synchronisation of the pedal revolutions with the
227 tempo of the music tracks (i.e., 120–123 bpm). After a 5-min warm up at 5% below
228 VT1 and a 1-min transition phase performed at VT1, the resistance of the cycle
229 ergometer will be increased so that the participant exercises at 5% above VT1. For the
230 experimental conditions, the auditory stimulus (i.e., asynchronous music or audiobook)
231 will be played to the participant from 1 min before the end of the warm-up session up

232 to the point at which they reach volitional exhaustion. The session will be terminated
233 when the participant is no longer able to maintain the prescribed pedal rate of 63 rpm
234 for a period $> 10 \text{ s}^2$ (see Figure 2). Thereafter, there will be a 3-min active warm down
235 at 63 rpm at an intensity of 5% below VT1.

236 **Data Acquisition and Processing**

237 *Questionnaires*

238 Core affect (Feeling Scale and Felt Arousal Scale; Hardy & Rejeski, 1989; Svebak
239 & Murgatroyd, 1985), perceived exertion (Borg Category Ratio-10 scale, CR10; Borg,
240 1982) and attentional focus (Attention Scale; Tammen, 1996) will be assessed during
241 the cycle ergometer exercise (i.e., at the beginning and end of warm up, every 2.5 min
242 into the 5% above VT1 stage, at the beginning and end of the active recovery stage,
243 and at the end of passive recovery; see Figure 2). Physical activity enjoyment (Physical
244 Activity Enjoyment Scale, PACES; Delignières & Perez, 1998) and remembered
245 pleasure (visual analogue scale developed by Zenko et al., 2016) will be assessed at the
246 end of each experimental session.

247 *Cardiorespiratory Monitoring*

248 Respiratory-rate monitoring will be facilitated by use of TSD201 respiratory
249 effort transducer, connected to a MP150 Biopac device (Biopac Systems, Goleta, USA).
250 This respiratory belt will be placed around the chest wall, at the level of the sternum.
251 The fs will be set to 250 Hz. Data acquisition was facilitated by the AcqKnowledge
252 software that is included in the MP system. Heart rate will be assessed by means of a
253 Polar system (H10 Polar strap) and the HRV Logger app (correction = workout). The
254 fNIRS technique measures cerebral oximetry, which is strongly associated with
255 respiratory and cardiac functioning (Pinti et al., 2019). Using spectral analysis (Welch's

² The duration of the exercise will thus vary in accord with the individual's physiological capacity.

Nonetheless, because the recruited participants will all have similar physical fitness levels (i.e., recreationally active), the 5%-above-VT1 phase should be rather brief and its duration fairly consistent among participants. If outliers are detected, they will be removed prior to the subsequent analyses (see Statistical Analyses subsection).

256 estimation method), both heart and respiratory rates can be identified in the fNIRS
 257 signal. The ability to identify these two frequency components will serve to ensure the
 258 validity of fNIRS measures.

259 *Head Blood-Volume Pulse Assessment*

260 To control for extra-cerebral noise, non-cortical haemodynamic responses will be
 261 monitored by means of a photoplethysmograph sensor (Shimmer3 GSR+ unit; Shimmer,
 262 Dublin, Ireland) that will be attached to the participant’s earlobe. In accord with the
 263 SPA-fNIRS guidelines (Scholkmann et al., 2022), the recorded blood-pulse volume
 264 (frequency of sampling [fs] = 128 Hz) will be regressed from the collected fNIRS signals
 265 to account for non-cortical haemodynamic responses that represent potential confounds.

266 *fNIRS Headset Shift Monitoring*

267 Performing a motor task (e.g., cycling) can cause a shift in the position of the
 268 fNIRS headset. If a headset shift occurs during an experimental session, the exact
 269 source of recorded haemodynamic signals is rather difficult to determine. Thus, a motion
 270 capture technique (Qualisys MoCap, Göteborg, Sweden) will be used to detect shifts in
 271 the fNIRS headset within each experimental session. Specifically, one passive marker
 272 will be taped to the participant’s right temple and two markers to the fNIRS headset.

273 To verify the occurrence of an fNIRS headset shift, the surface of the planar
 274 triangle connecting the 3D markers will be computed over a 30-s timing window (a) at
 275 the beginning of the warm-up phase and (b) 30 s before volitional exhaustion (see
 276 Equation 1; Guérin et al., 2021).

$$\overrightarrow{M_0M_1}(t) \cdot \overrightarrow{M_0M_2}(t) = \begin{pmatrix} x_1(t) - x_0(t) \\ y_1(t) - y_0(t) \\ z_1(t) - z_0(t) \end{pmatrix} \cdot \begin{pmatrix} x_2(t) - x_0(t) \\ y_2(t) - y_0(t) \\ z_2(t) - z_0(t) \end{pmatrix} \quad (1)$$

277 where 0 is the temple marker, 1 is the first headset marker, 2 is the second headset
 278 marker and t is the time point. The percentage of variation between the two values will
 279 be calculated. An fNIRS headset shift will be detected if this value exceeded 15% (i.e.,
 280 10 mm). A participant’s entire data set will be removed prior to further analyses if a

281 fNIRS headset shift is detected in at least one session (see Figure 5). Any excluded
282 participants will be replaced to ensure that $N = 36$.

283 ***fNIRS Data***

284 The fNIRS technique will be used to monitor the brain activity of participants.
285 This technique consists of placing light source and detector optodes on the surface of
286 the scalp. Adjacent sources and detectors of infrared light are ~3 cm apart. The depth
287 of analysis into the cortex is 0.5–2.0 cm with the system that will be used in the
288 proposed study (FOIRE-3000/16; Shimadzu, Kyoto). The system's light beam emanates
289 from three lasers (class 1M) at three wavelengths of 780, 805 and 830 nm. The
290 equipment contains 16 light sources (multicomponent glass bundle fibres) and 16
291 detectors (multi-alkali photomultipliers detectors).

292 The fNIRS headset holding the optodes will be placed on the participant's head
293 in accord with the International 10–20 system guidelines for standard electrode
294 positions (Jasper, 1958). In the proposed study, the brain regions of interest will be the
295 bilateral dlPFC (Brodmann areas [BAs] 9 and 46), medial prefrontal cortex (BAs 10
296 and 11), lateral parietal cortex (BA 39 and 40) and primary visual cortex (BA 17).
297 Thus, a 26-channel model (11 sources and 15 detectors) will be designed in order to
298 cover the brain ROIs over both the left and right hemispheres (see Figure 4). The fOLD
299 toolbox (fNIRS Optodes' Location Decider; Morais et al., 2018) will be used to guide
300 the selection of optimal optode positioning with respect to the brain ROIs³ (see
301 Supplementary File 3).

302 A system calibration will be conducted at the beginning of each experimental
303 session by means of automatic adjustment using LabNIRS to verify that all optodes are
304 emitting correctly. In case that the amount of light detected will be insufficient, the
305 participant's hair will be pushed back beneath each problematic source–detector couple
306 until data can be reliably collected. The sampling frequency will be set at 10 Hz (i.e.,
307 temporal resolution of 100 ms).

³ The obtained optode array will be the same for all participants because the fNIRS headset is rigid and does not facilitate customisation of optode positioning.

308 To control for the quality of acquired *f*NIRS data, the power-spectral density
309 will be computed using Welch’s estimation method for each participant, session and
310 channel. The frequency corresponding to maximal peak in the 100–250 bpm range will
311 be detected in the power-spectral density of the raw *f*NIRS data (for a similar
312 procedure, see Pinti et al., 2019). To guarantee that the identified frequency is the
313 genuine heart-rate frequency, it will be compared to the heart-rate measurements
314 provided by the Polar system, with a tolerance threshold of 10 bpm (Gu erin et al.,
315 2021, 2022). A channel will be excluded if heart rate frequency is not found in the
316 *f*NIRS signals (see Figure 3). The number of excluded channels will be reported in the
317 final manuscript in the interests of transparency. A participant’s entire data set will be
318 removed prior to further analyses if all channels pertaining to at least one region of
319 interest (ROI) are excluded on this basis. Any excluded participants will be replaced to
320 ensure that $N = 36$.

321 The presence of the heart pulse is a necessary but not sufficient condition to
322 ensure the quality of *f*NIRS data (Pollonini et al., 2016). Thus, the QT-NIRS toolbox
323 (Quality Testing of Near-Infrared Scans; Hernandez & Pollonini, 2020) will be used to
324 identify channels with poor optical coupling through the computation of the
325 scalp-coupling index (cardiac filter = 2.5–4 Hz; time window = 5 s; $\lambda = 805$ and 830
326 nm). For a given participant and channel, *f*NIRS signals characterised by a
327 scalp-coupling index < 0.7 for at least 10% of the time segment of interest (i.e.,
328 5%-above-VT1 phase) will be removed prior to further analyses. As for the
329 power-spectral density check, a participant’s entire data set will be removed prior to
330 further analyses, if all channels pertaining to at least one ROI are excluded on this
331 basis. Any excluded participants will be replaced to ensure maintenance of $N = 36$.

332 Correction for motion artefacts will be performed using wavelet filtering
333 (interquartile range = 0.5) in Homer 3 (v1.58.0; Massachusetts General Hospital,
334 Boston, MA). The motion-corrected data will be visually inspected to ensure that the
335 selected interquartile range value is well suited to the *f*NIRS data. For a given
336 participant, channels in which motion artefacts will still be visible (i.e., high-frequency

337 spikes and/or baseline shifts) will be removed prior to further analyses. To reject both
338 cardiac and breathing rates along with parts of Mayer oscillations, a lowpass filter set at
339 0.1 Hz will be applied (see Figure 5).

340 For each participant and condition, the fNIRS data between the beginning and
341 end of the 5%-above-VT1 phase will be extracted and referred to as a trial. The mean
342 haemodynamic response function (HRF) will be computed for each ROI (i.e., mPF,
343 dlPFC, motor cortex, parietal cortex). For each trial i , a polynomial regression will be
344 fitted to the HRF. Thereafter, the decrease in cerebral oxygenation D_i will be defined as
345 the time point at which the polynomial regression reaches its maximal value (see Figure
346 6). To account for possible differences in exercise duration among participants, D_i will
347 not be expressed in absolute time but rather as a percentage of the 5%-above-VT1
348 phase (e.g., if a participant exercises at 5% above VT1 for 10 min and the maximal
349 value of the polynomial regression is reached at 9 min, D_i will correspond with 90%).
350 To estimate the amplitude of changes in oxygenation during a trial, a linear regression
351 will also be fitted to each HRF from the beginning of the 5%-above-VT1 phase to D_i
352 (see Mandrick et al., 2013, for a similar procedure). The amount of cerebral oxygenation
353 will be identified by the slope coefficient of the linear regression, referred to as β_i (see
354 Figure 6).

355 **Statistical Analyses**

356 The statistical analyses will be performed using RStudio (v.1.2.5019). The raw
357 data files and the associated data processing algorithms (pre-processing, statistics and
358 visualisations) will be available as supplementary materials.

359 ***Data Eligible for Analysis***

360 Participants characterised by a duration of the 5%-above-VT1 phase unusually
361 short or long will be removed prior to further statistical analyses. Data will be screened
362 for univariate outliers using standardised scores (i.e., z scores). Participants with z
363 scores $> \pm 3.29$ will be excluded and replaced to ensure that $N = 36$.

364 *Classic Null-Hypothesis Significance Tests*

365 Data from the questionnaires will be analysed by means of one-way
366 repeated-measures (multivariate) analysis of variance (RM [M]ANOVA; audio condition
367 [music, audiobook, control]). [The cardiorespiratory data will also be analysed and](#)
368 [reported in a supplementary file.](#) Because HbO₂ benefits from a better signal-to-noise
369 ratio (see Gervain et al., 2011), only D_{HbO_2} and β_{HbO_2} will be used to support or refute
370 the hypotheses. Nonetheless, HHb indices will also be analysed and the findings
371 reported in the interests of transparency. D_{HbO_2} and β_{HbO_2} will be analysed for each
372 ROI (see Suzuki et al., 2004) by means of RM ANOVAs for H_1 – H_3 . The critical
373 statistical tests used to confirm or disconfirm hypotheses will be the associated pairwise
374 t tests from the post hoc analyses (see Table 1).

375 Normality will be checked in each cell of the analysis using the Shapiro–Wilk
376 test. Where normality is violated, for nonself-reported data, a transformation will be
377 used in accord with the nature of the distribution curve (e.g., log10, square root; see
378 Figure 5). Where Mauchly’s test indicates violations of the sphericity assumption,
379 Greenhouse–Geisser corrections will be applied to the F test. Bonferroni adjustments
380 pairwise/multiple comparisons will be used where necessary to identify where
381 differences lie. In accord with the stipulations of the periodical *Cortex*, the significance
382 level will be set at $p < .020$ for all analyses. Partial eta squared and Cohen’s d effect
383 sizes will be reported alongside each inferential analysis.

384 *Outcome-Neutral Validation Tests*

385 A negative control condition will be included by placing two additional channels
386 over the occipital brain region (Brodmann’s area 17). This region is involved primarily
387 in visual perception and so its activation should not differ in response to the
388 experimental conditions. To confirm that similar haemodynamic responses of the
389 primary visual cortex will be observed regardless of the audio condition (H_4), two
390 one-sided tests (TOSTs) will be used (Lakens et al., 2018). In this procedure, the results
391 of both t tests needed to reach significance in order for equivalence to be claimed.
392 Statistically nonsignificant differences will provide a means by which to confirm that

393 observed mPFC, dlPFC and parietal differences are related to the audio manipulations.
394 If differences are detected over the occipital brain region, the mean occipital HRF will
395 be removed from all other HRFs (for a similar rationale, see Guérin et al., 2021). TOSTs
396 will be computed using the TOSTER R package for paired-samples *t* tests (Lakens,
397 2017).

398 **Anticipated Timeline for Completion of the Proposed Study**

399 If the present contribution were to be accepted for publication, data collection
400 would be conducted within a 6-month timeframe. We estimate the time for data
401 pre-processing and analysis to take a further 2 months. Accordingly, we are likely to
402 submit our Stage 2 manuscript within 9 months of acceptance of the present Stage 1
403 manuscript.

404 **Open Practices**

405 Pilot data and codes are available on a public Zenodo repository
406 (<https://doi.org/10.5281/zenodo.6261358>). All anonymised raw and processed data
407 supporting the reported analyses will be archived in this repository at the point of
408 Stage 2 submission. [Methodological details pertaining to the proposed study were](#)
409 [preregistered using the fNIRS preregistration template developed by Schroeder et al.](#)
410 [\(2023; see Supplementary File 4\).](#)

411 **CRedit Author Statement**

412 First author: Conceptualisation; Methodology; Formal analysis; Data curation;
413 Software; Visualisation; Writing – original draft; Writing – review & editing. Second
414 author: Conceptualisation; Methodology; Formal analysis; Supervision; Writing – review
415 & editing. Third author: Writing – review & editing. Fourth author: Conceptualisation;
416 Methodology; Writing – review & editing. Last author: Conceptualisation; Funding
417 acquisition; Resources; Supervision; Writing – review & editing.

418

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Table 1*Estimated Required Sample and Effect Sizes*

Question	Hypothesis	Sampling plan	Analysis plan	Rationale for deciding the sensitivity of the test for confirming or disconfirming the hypothesis	Interpretation given different outcomes	Theory that could be shown wrong by the outcomes
The decrease in prefrontal oxygenation will be observed earlier under conditions in which participants exercise in silence or with an audiobook, when compared with exposure to asynchronous motivational music.	$D_{\text{HbO}_2, \text{mPFC}}$ will be larger during the music condition vs. the audiobook and silence conditions.	$N = 30$ ($d = 0.64$; $\alpha = .02$; $1-\beta = .90$)	Pairwise t tests	Small telescopes approach ($d_{\text{SESOI}} = 0.28$).	The hypothesis will be accepted if the statistical test is significant ($p < .020$) and the associated	Karageorghis et al.'s (2017) Hypothesis A (see Figure 1) logically extended to mPFC activity.
	$D_{\text{HbO}_2, \text{dlPFC}}$ will be larger during the music condition vs. the audiobook and silence conditions.	$N = 9$ ($d = 1.38$; $\alpha = .02$; $1-\beta = .90$)	Pairwise t tests	Small telescopes approach ($d_{\text{SESOI}} = 0.38$).	Cohen's $d > d_{\text{SESOI}}$.	Karageorghis et al.'s (2017) Hypothesis A (see Figure 1).

Continued

Question	Hypothesis	Sampling plan	Analysis plan	Rationale for deciding the sensitivity of the test for confirming or disconfirming the hypothesis	Interpretation given different outcomes	Theory that could be shown wrong by the outcomes
Less prefrontal activation will be observed when participants exercise in silence or with an audiobook, when compared to when they exercise with music.	$\beta_{\text{HbO}_2, \text{mPFC}}$ will be larger during the music condition vs. the audiobook and silence conditions.	$N = 30$ ($d = 0.64$; $\alpha = .02$; $1-\beta = .90$)	Pairwise t tests	Small telescopes approach ($d_{\text{SESOI}} = 0.28$).	The hypothesis will be accepted if the statistical test is significant ($p < .020$) and the associated	Role of the mPFC in appraisal and expression of negative emotion as proposed by Etkin et al. (2011).
	$\beta_{\text{HbO}_2, \text{dlPFC}}$ will be larger during the music condition vs. the audiobook and silence conditions.	$N = 9$ ($d = 1.38$; $\alpha = .02$; $1-\beta = .90$)	Pairwise t tests	Small telescopes approach ($d_{\text{SESOI}} = 0.38$).	Cohen's $d > d_{\text{SESOI}}$.	Karageorghis et al.'s (2017) Hypothesis B (see Figure 1).
Less parietal activation will be observed under conditions in which participants exercise in silence or with an audiobook, when compared to when they exercise with music.	$\beta_{\text{HbO}_2, \text{IPC}}$ will be larger during the music condition vs. the audiobook and silence conditions.	$N = 9$ ($d = 1.37$; $\alpha = .02$; $1-\beta = .90$)	Pairwise t tests	Small telescopes approach ($d_{\text{SESOI}} = 0.38$).	The hypothesis will be accepted if the statistical test is significant ($p < .020$) and the associated Cohen's $d > d_{\text{SESOI}}$.	Role of the parietal cortex to facilitate the selection of relevant signals proposed by Bigliassi (2021).

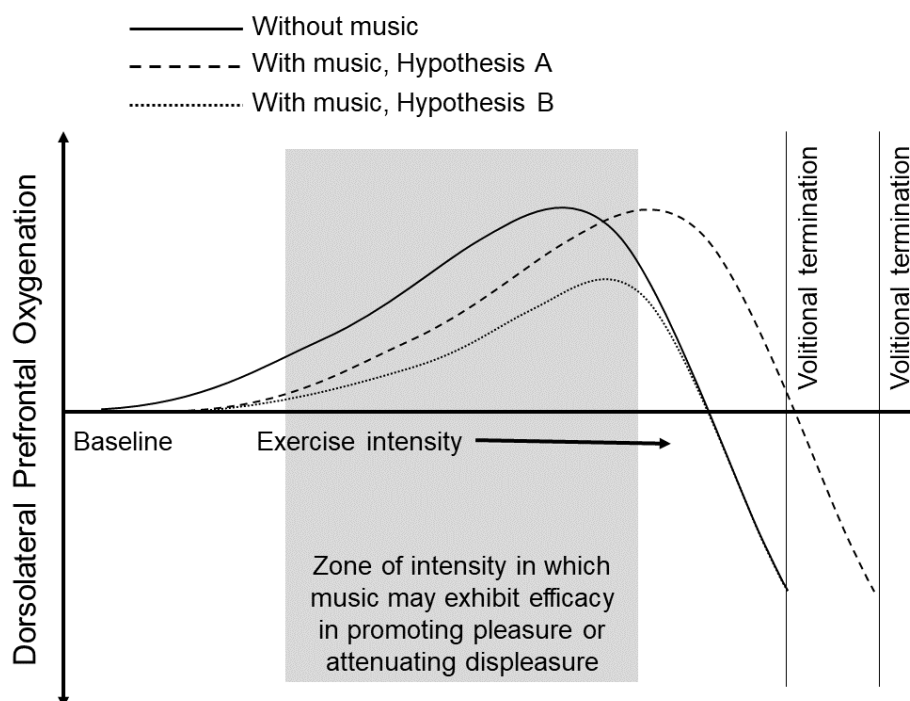
Continued

Question	Hypothesis	Sampling plan	Analysis plan	Rationale for deciding the sensitivity of the test for confirming or disconfirming the hypothesis	Interpretation given different outcomes	Theory that could be shown wrong by the outcomes
Similar haemodynamic responses of the occipital cortex will be observed across conditions.	$\beta_{\text{HbO}_2, \text{motor}}$ will be similar during the music condition, audio-book and silence conditions.	$N = 36$ ($d = 0.62$; $\alpha = .02$; $1-\beta = .90$)	TOSTs	Small telescopes approach ($d_{\text{SESOI}} = 0.62$).	The hypothesis will be confirmed if both t tests are significant.	Not applicable (control condition).

Note. Statistical power, planned analyses and critical statistical tests for each research hypothesis. mPFC = medial prefrontal cortex; dlPFC = dorsolateral prefrontal cortex; IPC = lateral parietal cortex; RM ANOVA = repeated-measures analysis of variance; TOSTs = two one-sided t tests; SESOI = smallest effect size of interest.

Figure 1

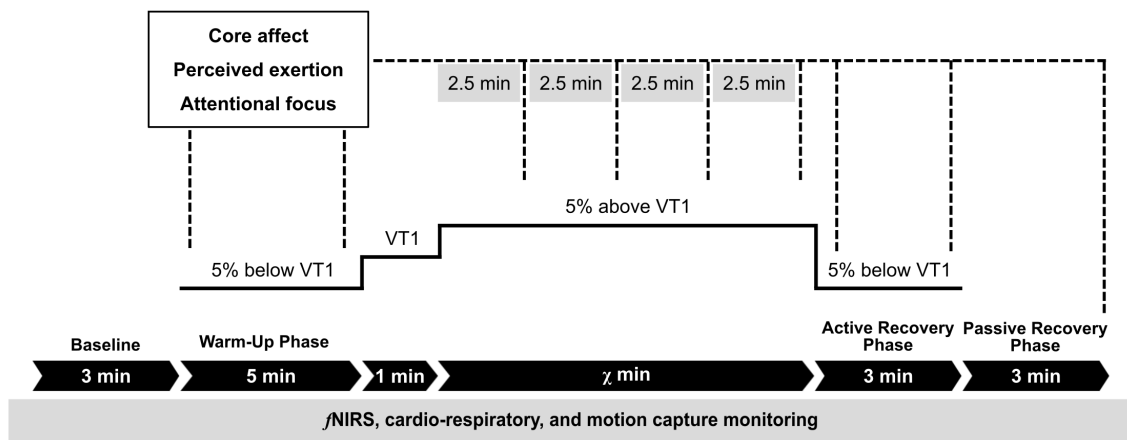
Schematic Representation of the Hypothetical Neurophysiological Mechanisms Underlying the Effect of Music During Exercise



Note. Reproduced from 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.), *The Routledge companion to embodied music interaction*, p. 288. Copyright 2017 by Routledge. Reprinted with permission through PLSclear.

Figure 2

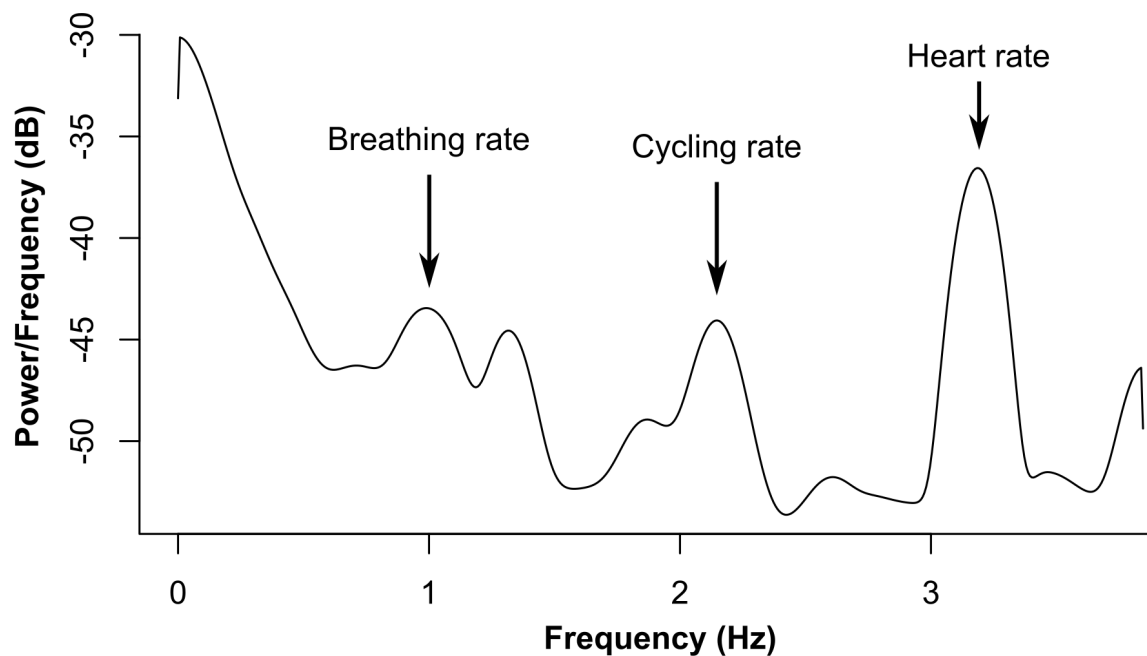
Experimental Protocol for the Proposed Study



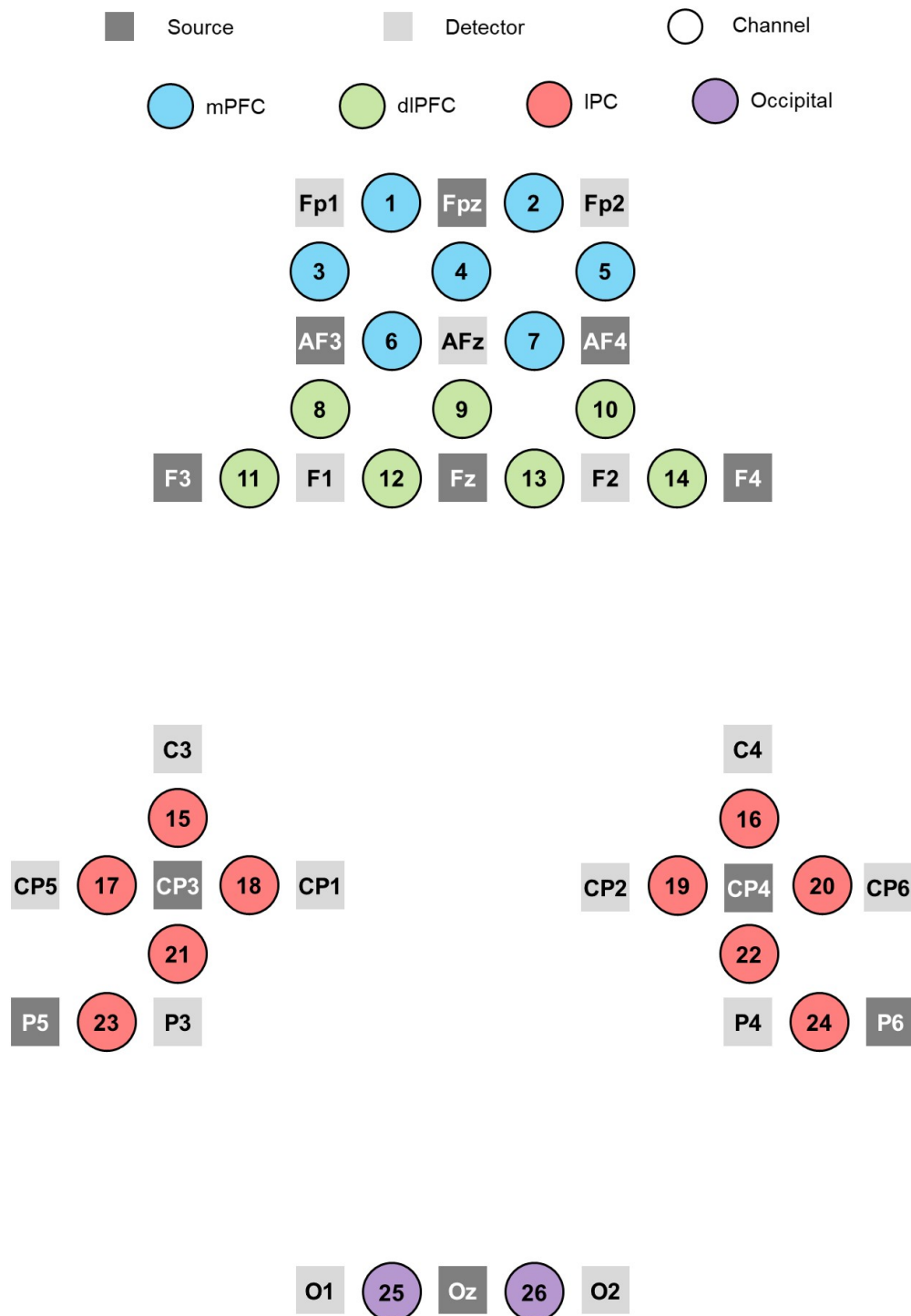
Note. VT1 = first ventilatory threshold.

Figure 3

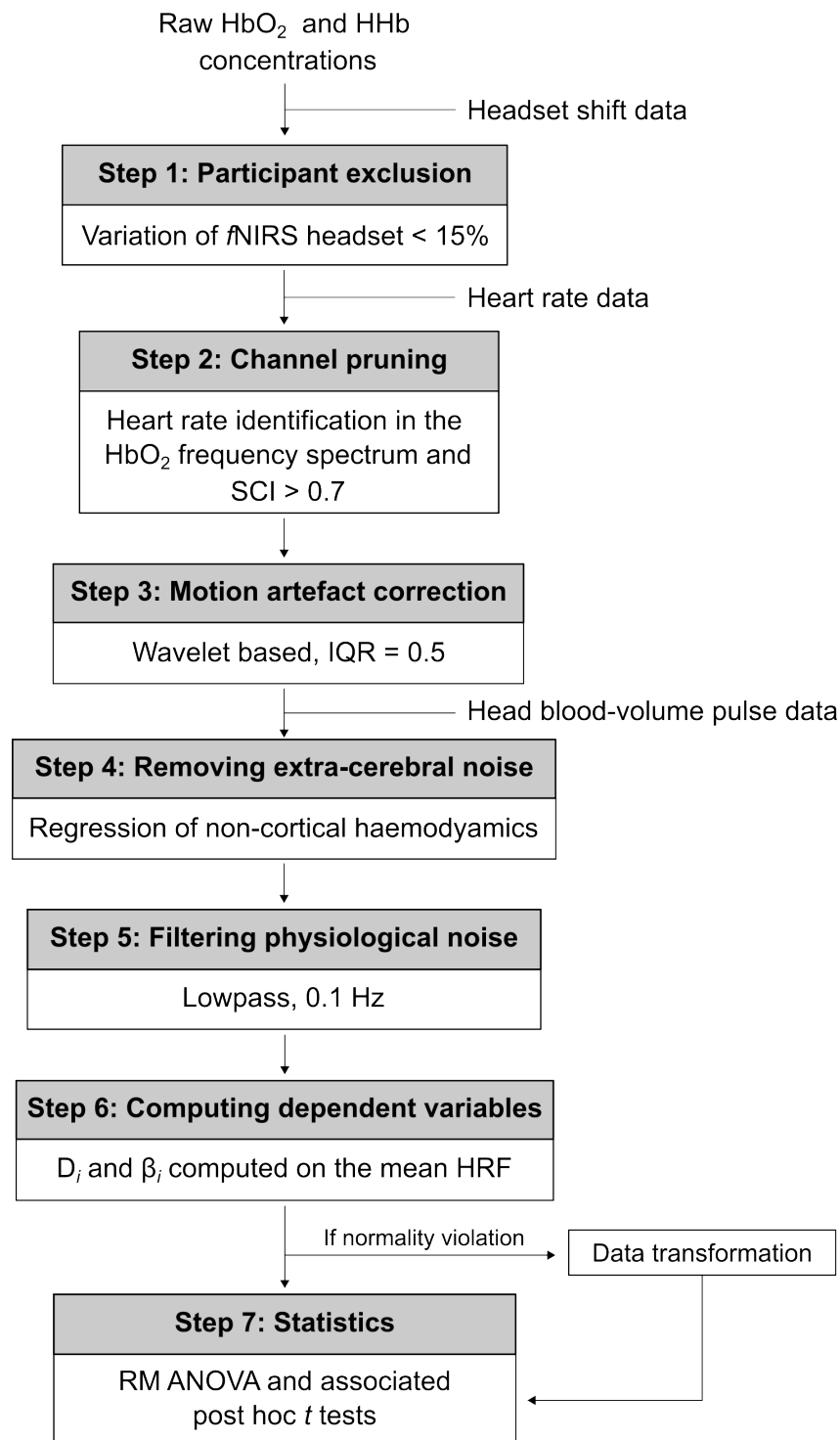
Welch Power-Spectral Density of the raw fNIRS Data



Note. The data were obtained from a pilot test.

Figure 4*Diagrammatic Representation of the fNIRS Sources, Detectors and Channel Layout*

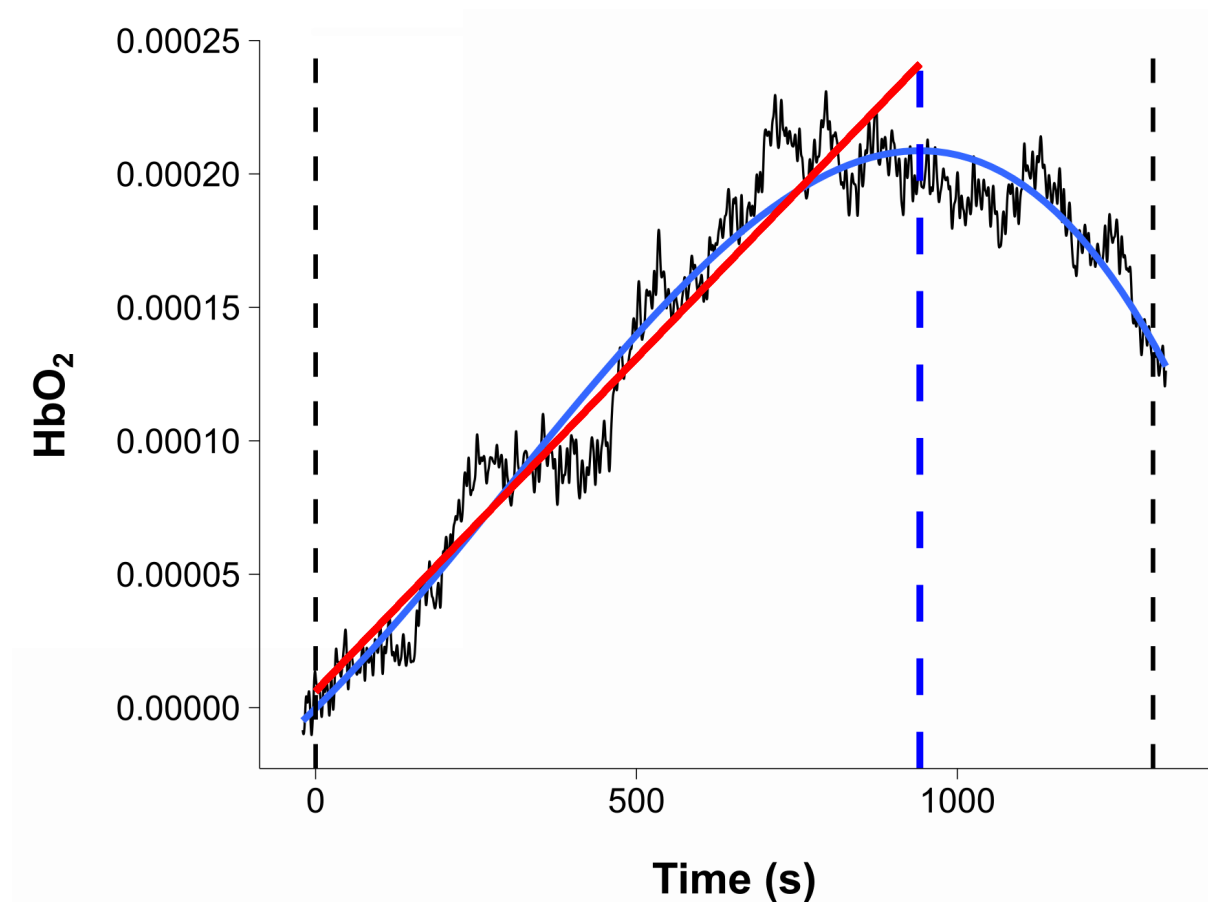
Note. Adjacent sources and detectors will be ~3 cm apart. mPFC = medial prefrontal cortex; dlPFC = dorsolateral prefrontal cortex; IPC = lateral parietal cortex.

Figure 5*Processing Pipeline of the fNIRS Data*

Note. fNIRS = functional near-infrared spectroscopy; SCI = scalp-coupling index; IQR = interquartile range; HRF = haemodynamic response function; RM ANOVA = repeated-measures analysis of variance.

Figure 6

Computation of the Dependent Variables on Orbitofrontal Cortex fNIRS Data



Note. The data were obtained from a pilot test. Dotted lines indicate the beginning and end of the 5%-above-VT1 phase. The polynomial regression is displayed in blue. The dotted blue line indicates the time point at which the maximal value of the polynomial regression is reached. The linear regression is displayed in red. Note that 0 on the x axis corresponds with the beginning of the 5%-above-VT1 phase. HbO₂ = oxygenated haemoglobin.