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4 **The Effects of Congruent and Incongruent Immersive Virtual Reality Modulated Exercise**
5 **Environments in Healthy Individuals: A Pilot Study**

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24 participated in the study.

25 **Conflicts of interest:** Drs Pattinson and Finnegan are named as co-inventors on a provisional
26 U.K. patent titled "Discordant sensory stimulus in VR based exercise" UK Patent office
27 application: 2204698.1 filing date 31/3/2022". This does not alter our adherence to policies
28 on sharing data and materials.

29 **Key words:** Perception, Breathlessness, Physical Activity, Exercise Performance, Perceived
30 Exertion, Virtual Reality,

31

Abstract

32 High-immersive virtual reality (VR) environments can increase enjoyment and
33 frequency of exercise participation. As VR can also be used to manipulate sensory feedback it
34 is possible that specialist environments can modulate exercise performance and ratings of
35 perceived exertion (RPE) and breathlessness. We aimed to (i) assess whether cycling in a
36 'congruent' VR environment (where perceived/virtual exercise intensity and actual pedaling
37 resistance are matched) enhances exercise performance and reduces RPE and breathlessness,
38 and (ii) to assess whether cycling in an 'incongruent' VR environment can further manipulate
39 these perceptions. Following familiarisation, 14 healthy (7 male, 26 ± 2 years) participants
40 repeated a series of four cycling exercise trials on a gradient adjustable ergometer under two
41 conditions: within VR (**VR** condition; comprising of a custom-made VR environment in a head
42 mounted display) and without VR (**nVR** condition). Within **VR**, the hill gradient experienced
43 was either congruent or incongruent with the pedalling resistance. Participants could choose
44 their power output/RPM throughout. During congruent trials participants chose to perform
45 at a higher power output in the **VR** condition ($+11W \pm 14$, $p < 0.05$) with no difference in RPE or
46 breathlessness. There was also a significant interaction between condition (**VR** vs **nVR**) and
47 congruence for RPE and breathlessness. Specifically, when the experienced hill gradient was
48 steeper than pedalling resistance RPE and breathlessness was greater, and when experienced
49 hill gradient was less steep than pedalling resistance RPE and breathlessness was lower. In
50 conclusion, we have shown that congruent VR cycling environments can modulate exercise
51 performance. Furthermore, the novel application of incongruent VR cycling exercise
52 manipulated exercise perceptions in either direction. This technique has potential applications
53 in exercise training or rehabilitation modalities.

54

Introduction

55 Patients with chronic cardiorespiratory disease, such as heart failure (HF) or chronic
56 obstructive pulmonary disease (COPD), often experience severe exercise intolerance and
57 poor quality of life due to enhanced perceptions of breathlessness and physical exertion
58 during exercise (Johnson et al., 2017; Parshall et al., 2012; Scano et al., 2013). This can lead
59 to a 'disease spiral' where exercise is avoided, resulting in physical deconditioning and
60 leading to further exercise intolerance and inactivity (Polkey & Moxham, 2011). Although
61 physical rehabilitation is often prescribed for these patients, the uptake and continuation of
62 exercise programmes is highly variable given the often-distressing nature of exercise for
63 these patients (Keating et al., 2011).

64 The heightened perceptions of exertion and breathlessness during exercise is partly
65 dependent on the underlying pathophysiology, but current opinion considers that it also
66 arises from the brain's integration of sensory feedback and prior expectations (Bruce et al.,
67 2019; Marlow et al., 2019). If this model is accurate, it provides opportunities for new
68 therapies such as the use of virtual reality (VR), that can manipulate sensory feedback and
69 thereby support rehabilitation. VR refers to a computer-simulated environment that aims to
70 induce a sense of being present in another place and allows for the individual to interact
71 with the environment (Baños et al., 2004; Neumann et al., 2018; Sherman & Craig, 2018).
72 This ability to interact with the environment is important for perceptions of immersion and
73 effort (Runswick., 2023) and in the context of exercise, the interaction with the environment
74 can occur through exertion on equipment such as an ergometer (Mueller et al., 2007). The
75 degree of immersion in the virtual environment is partly dependent on factors such as the
76 realism of the visual images and accuracy of physical elements such as interaction with

77 objects and gravity but can be improved with multisensory input such as simulated aural
78 (e.g., ambient sounds), vestibular (e.g., passive physical movements mirroring those in VR)
79 or tactile (e.g., airflow over skin) feedback (Melo et al., 2022). VR environments may be
80 useful in clinical exercise prescription and rehabilitation as they offer the ability to
81 systematically manipulate sensory feedback and exploit patient expectations, and so
82 decrease perceptions of exertion and breathlessness in exercise. Further investigation is
83 needed to establish whether VR cycling can be a useful adjunct to standard therapy (Condon
84 et al., 2020).

85 Previous work has shown that immersive VR increases the enjoyment of exercise
86 (Baños et al., 2004; Mouatt et al., 2020) and may have a positive effect on the frequency of
87 physical activity (Ng et al., 2019). In addition, there is growing evidence that exercise
88 performance (e.g., chosen work rate) can be enhanced in VR compared to non-VR
89 environments despite perceptions of exertion being equal or reduced (Murray et al., 2016;
90 Zeng et al., 2022). For example, Zeng et al. (2022) had college students conduct single bouts
91 of cycling on a VR exercise bike (immersive), and exergaming bike (non-immersive), or
92 traditional exercise bike. Results showed that the commercially available VR bike was able to
93 induce higher levels of physical activity, and importantly, lower levels of perceived effort
94 alongside this. Similarly, McDonough et al. (2020) showed that VR could increase enjoyment
95 and lower perceived exertion compared to an exergame or traditional stationary bike despite
96 no differences in blood pressure across the three exercise types. However, this work has
97 often been conducted without any theoretical basis for examining exercise perception and
98 therefore does not use VR to target any specific function that underpins exercise (Mouatt et
99 al., 2020). It's likely these findings are a result of the basic immersion and distraction that is
100 offered by VR (similar to exercising in nature) rather than the targeting of specific

101 mechanisms of exercise perception such as elements of central command (Slater & Sanchez-
102 Vives, 2016; Williamson, 2010).

103 Mechanisms of perceptions during exercise are a hotly debated topic (Abbiss et al.,
104 2015; Halperin & Emanuel, 2020; Marcora, 2009). Regardless, all models include the input of
105 current sensory information to control exercise performance (Tucker, 2009). This sensory
106 information can be manipulated with various methods, potentially including virtual
107 environments and potentially 'incongruent' VR. There is some limited evidence to support
108 this concept. For example, it has been shown that hypnotised participants have enhanced
109 perceptions of exertion when they perceive they are cycling uphill, despite no change in
110 pedaling resistance (Williamson et al., 2001). Using VR to create incongruence to support
111 exercise performance has generally focused on the use of bodily illusions. For example, Czub
112 and Janeta (2022) manipulated individuals' perception of their own strength by exercising in
113 VR with an avatar that was more muscular (incongruent with) the participant's body. Results
114 showed participants were able to perform more bicep curls than in a non-VR condition.
115 When aiming to support patients with neck pain, Harvie et al. (2020) found no effects of
116 using incongruent VR to overstate a patients range of motion. However, little work has
117 focused on the use of incongruent VR in aerobic exercise.

118 To our knowledge, only one study has used incongruent VR to target specific
119 mechanisms that underpin perceptions of effort during aerobic exercise. Finnegan et al.
120 (2023) noted that breathing responses during exercise seem to be influenced by learning or
121 past experiences of exercise and that changes in visual input have been shown to affect
122 perceptions of breathlessness in cycling exercise. To investigate the use of VR to target these
123 mechanisms, the experimenters used virtual hills of different gradients and congruent or

124 incongruent cycling resistance. In this context, ‘incongruent’ refers to an environment where
125 perceived cycling intensity and actual pedalling resistance do not match. In other words, the
126 pedalling resistance will be lower/higher than that expected by the steepness (gradient) of
127 the VR cycling course. The expectation effort based on gradient was a significant predictor
128 of perceive breathlessness separate from the actual effort exerted during exercise. However,
129 the study only captured perceptions of breathlessness and not overall perceptions of
130 exertion or physiological responses to exercise.

131 Initial evidence suggests that VR may alter patient perceptions, and therefore modify
132 performance, by distraction from the exercise task and enhanced enjoyment of the
133 environment (Baños et al., 2004; Mouatt et al., 2020; Zeng et al., 2022). A separate body of
134 literature has suggested that creating discordance between sensory feedback or input, past
135 experience, and actual performance (Murray et al., 2016) it may be possible to further
136 manipulate perceptions of exercise (e.g., Finnegan et al., 2023). Here the aim was to test
137 both concepts in single study for the first time while also including measures of physiological
138 responses as well as effort perceptions.

139 Young healthy volunteers using ‘congruent’ (exertion matched to VR cycling
140 environment) and “incongruent” (exertion unmatched to VR cycling environment) cycling
141 exercise in a custom-made VR environment The first aim of the current study was to
142 examine whether cycling performance (self-selected power output), enjoyment and
143 perceptions of exertion and breathlessness are altered by a ‘congruent’ VR cycling
144 environment where the VR and the ‘real-world’ are matched as closely as possible. We
145 hypothesise that cycling performance and enjoyment will be enhanced, and perceptions of
146 exertion and breathlessness will be reduced, with congruent VR cycling in comparison to

147 non-VR cycling. Our second aim is to assess whether a theory driven intervention to
148 manipulate perceptions of exertion and breathlessness can be achieved by using an
149 ‘incongruent’ VR cycling environment. We hypothesise that incongruence between actual
150 pedalling resistance and perceived cycling intensity (based on sensory feedback from the VR
151 environment and past experience) will alter perceptions of exertion and breathlessness.

152 **Methods**

153 Participants and Ethical approval

154 Fourteen healthy participants (7 male, 26 ± 2 years of age, 1.70 ± 0.09 metres, $70.4 \pm$
155 13.3 kg) undertook the study (table 1) and gave informed written consent. Participants were
156 required to be over 18 years old with no history of metabolic, respiratory, or cardiovascular
157 disease (e.g., hypertension, asthma, diabetes) or have any condition or injury that would
158 prevent the performance of cycling exercise. All participants were unaware of the nature of
159 the experimental manipulation in the VR environment (see below). All the experimental
160 procedures conformed to the latest revision of the Declaration of Helsinki and were approved
161 by the institutional research ethics committee (LRS/DP-21/22-26409).

162 Participants visited the laboratory on three occasions, with >72 hours between each
163 visit. During visit 1, participants were familiarised to all procedures and underwent a maximal
164 incremental cycling exercise task to assess peak oxygen consumption ($\dot{V}O_{2peak}$). During visit
165 2 and 3, participants performed 4 submaximal cycling exercise tasks with (**VR**) or without
166 (**nVR**) a VR environment. Participants were asked to refrain from consuming food and caffeine
167 within 4 hours and performing strenuous physical activity or consuming alcohol within 12
168 hours of each trial. The study followed a repeated measures design with all participants

169 performing all trials in the **VR** and **nVR** condition (visit 2 and 3) in a randomised order.
 170 Participants were required to always remain in a seated position in the saddle.

171 Equipment

172 Participants VO₂ peak was performed using a cycle ergometer (Lode Excalibur Sport,
 173 Groeningen, The Netherlands) and ventilatory and metabolic variables measured using a
 174 automated metabolic cart system (Metalyzer 3B, Cortex, Leipzig, Germany) which was
 175 calibrated prior to each study per manufacturer instructions. The ramp (Watts/min) of the
 176 incremental exercise task was determined from standard prediction equations (Wasserman et
 177 al., 1987) so that predicted maximum power output (W_{max}) was achieved within 8-12
 178 minutes.

Participant Characteristics	Congruent Trial		Incongruent Trials	
	N=14, M/F = 7/7		N=10, M/F = 5/5	
	Mean	SD	Mean	SD
Age (years)	26	6	26	7
Height (cm)	170	9	170	8
Body Mass (kg)	70.4	13.0	70.7	12.8
Peak $\dot{V}O_2$ (ml/kg/min)	40.6	10.7	39.9	7.3
Peak $\dot{V}O_2$ %pred	110.6	25.6	111.1	22.5

179

180 **Table 1.** Participant characteristics (mean ± standard deviation)

181 The VR and nVR studies were undertaken using an automated cycle ergometer
 182 (Wahoo-Kickr Climb Integrated Cycling system, Wahoo, Atlanta, US) and custom-made VR
 183 environment written in Unity-3D (Finnegan et al., 2023) (Figure 1). The simulation was
 184 rendered in a commercially available VR headset (Vive Pro, HTC, Taiwan), that was physically
 185 tethered with a cable to a VR ready PC (3XS High End Gaming PC with NVIDIA GeForce RTX
 186 3080 and AMD Ryzen 7 5800X). The incline (up/down tilt) of the Wahoo cycle ergometer was

187 automatically adjusted by the VR software to match the gradient of the hill/flat. The use of
188 Wahoo cycle ergometers have been validated previously (Gin et al., 2018). In addition, a fan
189 (Wahoo-Kickr headwind, Wahoo, Atlanta, US) which automatically adjusted its air flow to
190 match estimated cycling speed was used.

191 Protocol

192 Visit 1 – Familiarisation and Peak $\dot{V}O_2$ assessment

193 The incremental cycling exercise task was performed initially to determine peak $\dot{V}O_2$.
194 and then participants were fully familiarised with all experimental procedures of visit 2 and 3.
195 During this familiarisation session, participants performed a short cycling course in the VR
196 environment which consisted of a straight road with 3 stages: (i) 200m flat (0% incline), (ii)
197 100m hill (X% incline and (iii) 200m flat (0% incline). Pedalling resistance was congruent with
198 the visual gradient of the flats/hill (i.e., the perceived cycling intensity) and the VR software
199 automatically adjusted both the incline on the Wahoo bike to match the gradient of the virtual
200 road, and the fan airspeed to match estimated cycling speed. The changes to bike incline and
201 fan windspeed acted to enhance the immersion of the participants into the VR environment.
202 As motion sickness is a recognised side-effect of VR, any participants experiencing such
203 symptoms were asked to verbally report this at any time during familiarisation. No participants
204 experienced any adverse effects, and none were excluded from the study at this stage.

205 Visit 2 and 3

206 During visit 2 and visit 3, participants performed 4 cycling exercise trials with and
207 without VR. During VR trials the incline of the bike, and fan airspeed were adjusted
208 automatically by the VR software. Identical exercise trials were performed during the **nVR**

209 condition, but no VR headset was worn, and no adjustment was made to the incline on the
210 Wahoo bike. While the fan was used, no adjustment to fan speed was performed **VR** and **nVR**
211 testing days were performed in a randomised order.



212
213 **Figure 1.** Top. An example of the VR set up in the lab showing the wind simulation fan (left)
214 and viewing the environment (right). Bottom. First person view of the VR environment when
215 approaching the hill from the first flat section, this image was captured during live testing.

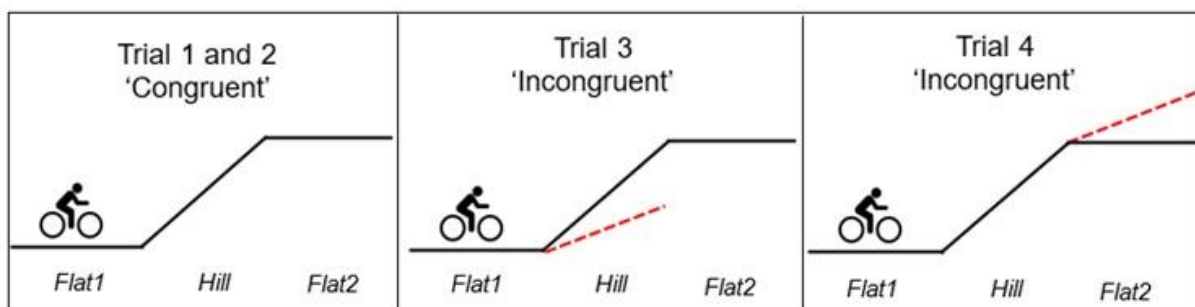
216 The four cycling trials are shown in figure 2. Each trial consisted of a straight road, with
217 a set distance and was visually identical in all trials. As in the familiarisation trial, the course
218 consisted of 3 stages: (i) a flat at 0% visual gradient (*Flat1*), (ii) a hill at 5% visual gradient (*Hill*),
219 (iii) followed by another flat at 0% visual gradient (*Flat2*). The length of the flat segments was
220 constant at 1000m, while the length of the hill segment was variable. As it was difficult for
221 participants to change gear on the Wahoo ergometer when going uphill in the VR environment
222 while wearing a VR headset, gearing remained fixed throughout the trials. Instead, the length
223 of the hill segment was adjusted depending on the fitness (W_{max}) of each participant: W_{max}
224 $< 175W = 375m$; $175W-225W = 500m$; $> 225W = 750m$. Pilot testing revealed these categories
225 resulted in a similar time of hill completion. But any variability between participants was
226 controlled for by the repeated measures study design.

227

228 Trial 1 and 2 were ‘congruent’ with pedalling resistance matched to the visual gradient
229 (the perceived cycling intensity). Trial 3 and Trial 4 were ‘incongruent’; during one stage in
230 each trial the pedalling resistance did not match the visual gradient. In trial 3, the pedalling
231 resistance during the *Hill* was set lower than the visual gradient of 5%, and in trial 4 the
232 resistance during *Flat2* was set to be higher than the visual gradient of 0%. Importantly, the
233 pedalling resistance during these incongruent stages (*Hill* (Trial 3) and *Flat2* (trial 4)) was
234 identical (i.e. equivalent of a 2.5% gradient hill). Trial 1 and 2 were always performed first, to
235 set expectations that the VR cycling will match past experience. This might enhance the effects
236 of the incongruent manipulation (as discussed in the introduction) and trial 3 and 4 were
237 performed in a random order. Each individual participant performed trial 3 and 4 in the same

238 order in the **VR** and **nVR** conditions. During each visit, participants rested for 15 minutes
239 between trials.

240 In the **nVR** condition, participants still completed the same course as in the **VR**
241 condition, but they had no visual information or information from the bike gradient or fan
242 speed. For all trials participants were given instructions to complete the course at whatever
243 'speed' (RPM) they choose.



245 **Figure 2.** A schematic representation of the 4 trials used on **VR** and **nVR** test days. Black lines
246 represent the visual gradient. When not accompanied by a broken red line, the pedalling
247 resistance is matched to the visual gradient. Therefore Trial 1 and 2 are entirely 'congruent'.
248 Broken red line represent a stage where pedalling resistance does not match the visual grade.
249 Therefore Trial 3 and 4 have 'incongruent' stages. Note that the pedalling the resistance on
250 the *Hill* (Trial 3) and *Flat2* (Trial 4) are identical, as denoted by the identical slope of the broken
251 red line.

252 Physiological and psychological measures

253 During the four trials, heart rate (HR), respiratory rate (RR) were recorded continuously
254 with an ECG and respiratory belt respectively (Equivital EQ02, Cambridge, UK) using LabChart
255 version 8 (AD instruments, Oxford UK). Immediately before each trial, heart rate and
256 respiratory rate was collected for 1 minute while participants rested on the bike.
257 Measurements of distance, watts, and cadence (RPM) were recorded each second using the
258 Wahoo fitness app. Overall ratings of perceived exertion (RPE), as well as sensations of

259 breathlessness and leg fatigue, were measured using a CR10 Borg scale (Borg, 1982) during
260 the final 30 seconds of each stage of each trial. Participants were familiar with the measure
261 before testing and then verbalised their ratings when prompted. The scale could not be used
262 visually given the VR headset.

263 Following each trial participants completed 3 questionnaires. The Comfort Affective
264 Labelled Magnitude (CALM) scale (Cardello et al., 2003). A revisited version of the NASA Task
265 Load Index (Hart & Staveland, 1988) specifically developed for simulations: the Simulation
266 Task Load Index (Sim-TLX; (Harris et al., 2020). The 8-item Physical Activity Enjoyment Scale
267 (PACES) (Kendzierski & DeCarlo, 1991; Mullen et al., 2011) was also completed. Following the
268 trial 1 in the **VR** condition, the presence questionnaire (Witmer et al., 2005; Witmer & Singer,
269 1998) was completed by all participants to evaluate their presence in the virtual environment.

270 Data analysis

271 Mean HR and RR were recorded during the final 30 seconds of each stage of the trials.
272 HR and RR is presented as change (Δ) from baseline (recorded during the rest period
273 immediately before the start of each trial). A repeated measures two-way ANOVA, and where
274 appropriate multiple comparison *post hoc* analysis with Bonferroni correction, was used to
275 examine differences in Δ HR, Δ RR, power output, RPM, RPE, leg fatigue and breathlessness
276 between trial stages and between condition (**VR** vs **nVR**). Before ANOVA, if Mauchly's test of
277 sphericity was violated, degrees of freedom were adjusted in accordance to the Greenhouse-
278 Geisser test. A student's paired t-test was used to examine differences between the data
279 recorded by PACES, Sim-TLX and CALM between the **VR** and **nVR** condition (within the same
280 trial).

281 Both 'congruent' trials (1 and 2) are identical, but when presenting 'congruent' data
282 we have analysed data from trial 2 alone. This is to remove any variability encountered in the
283 first trial the participant performed. When performing the analysis, it was noticed that
284 incorrect resistances were applied during some stages of the incongruent trials of four
285 participants due to an error in the software. These participants have been removed from the
286 incongruent analysis but remain in congruent analysis as these trials were not affected. Data
287 are expressed as mean \pm SD (unless otherwise stated) and statistical significance was taken as
288 ($P < 0.05$). Statistical analysis was conducted using a standard statistical package (SPSS, Chicago,
289 IL, USA) and figures produced through GraphPad (Prism). We performed a sample size
290 calculation using G*Power (3.1.9.7) based upon pilot data collected. Average power output
291 was +10W (± 14 W) greater in the **VR** condition vs **nVR** condition. With an α of 0.05, and Power
292 of 0.8, we calculated a required sample size of 14.

293

294

295

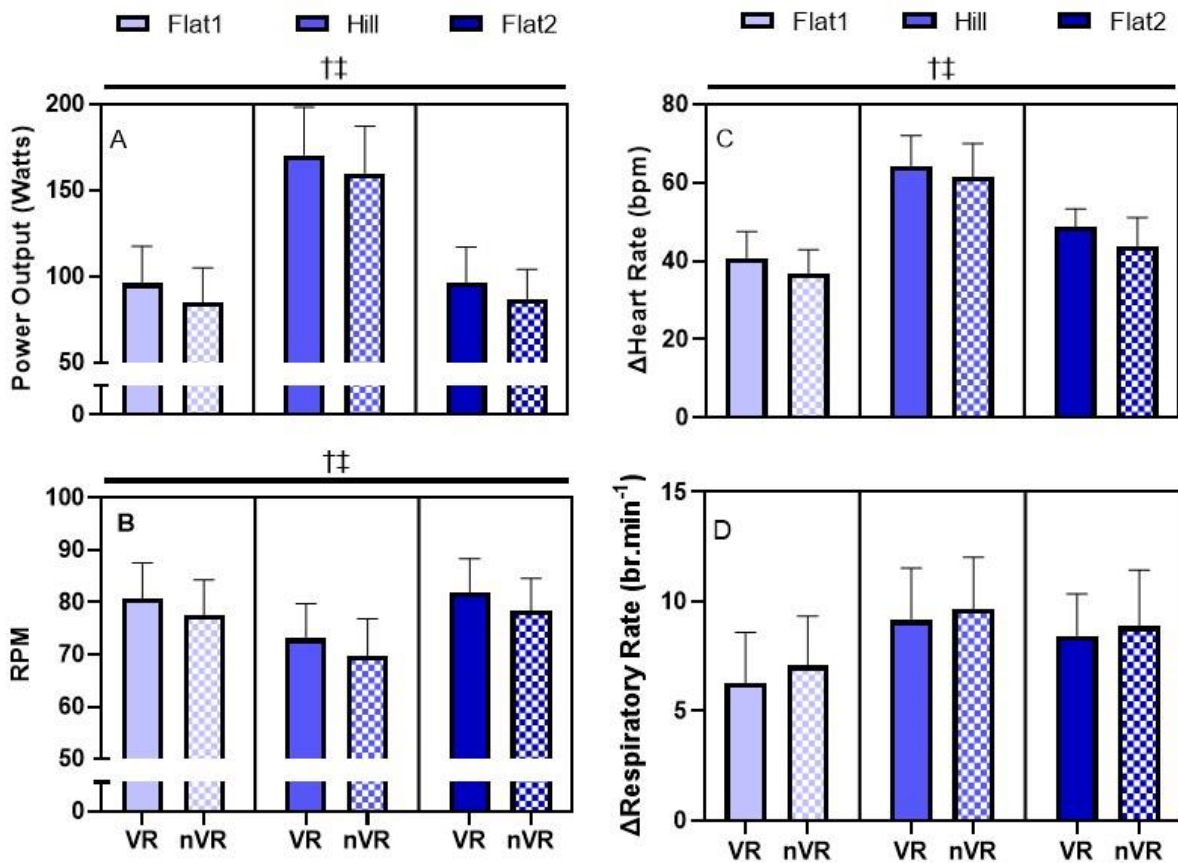
296

Results

297 Participant Characteristics

298 In total, 14 participants (7 male) were studied (Table 1). Due to an error in the VR
 299 software (see above), 4 participants were removed in the analysis of the incongruent trials
 300 data. No participants experienced any motion sickness during familiarisation and so continued
 301 on to visit 2 and 3.

302



303

304 **Figure 3.** Mean (±SD) power output (A), RPM (B), ΔHR (C) and ΔRR (D) during the final 30
 305 seconds of each trial stage (*Flat1*, *Hill*, *Flat2*) in the **VR** (solid) and **nVR** (chequered)
 306 condition. † = significant main effect of trial stage ($p < 0.05$). ‡ = significant main effect of
 307 condition (**VR** vs **nVR**; $p < 0.05$).

308

309 Congruent Trials

310 Figure 3 presents the mean power output, RPM, Δ HR and Δ RR during each stage of the
311 congruent trial in both **VR** and **nVR** conditions. For power output (figure 3A) there was a
312 significant main effect of trial stage ($F(2, 26) = 135.3, p < 0.001, \eta_p^2 = 0.901$) and **VR/nVR**
313 condition ($F(1,13) = 13.4, p < 0.05, \eta_p^2 = 0.508$), but there was no significant interaction.
314 Power output chosen by participants was greater in the **VR** condition during *Flat1* (+11W \pm
315 14), *Hill* (+10W \pm 14) and *Flat2* (+10W \pm 13) stages ($p < 0.05$). For RPM (figure 3B) there was
316 also a significant main effect of trial stage ($F(2, 26) = 25.2, p < 0.001, \eta_p^2 = 0.66$) and **VR/nVR**
317 condition ($F(1,13) = 11.3, p < 0.05, \eta_p^2 = 0.44$), but there was no significant interaction.

318 For Δ HR (figure 3C) there was a significant main effect of trial stage ($F(2, 26) = 96.7,$
319 $p < 0.001, \eta_p^2 = 0.963$) and **VR/nVR** condition ($F(1,13) = 8.2, p < 0.05, \eta_p^2 = 0.388$), but there
320 was no significant interaction. Heart rate was greater in the **VR** condition during *Flat1*
321 (+4bpm \pm 3), *Hill* (+4 bpm \pm 2) and *Flat2* (5bpm \pm 3) stages ($p < 0.05$). For Δ RR there was a
322 significant main effect of trial stage ($F(2, 26) = 9.02, p = 0.001, \eta_p^2 = 0.401$) but no significant
323 main effect for **VR/nVR** condition or interaction (figure 3D).

324 Figure 4 (A-C) presents mean ratings of perceived exertion (RPE), leg fatigue and
325 breathlessness during each stage of the congruent trial in both **VR** and **nVR** conditions.
326 There was no significant main effect (Trial stage or **VR/nVR** condition) or interaction effect
327 for any of these variables.

328 The Sim-TLX records perceived workload of the task in regard to its specific demands (i.e.
329 mental, physical, temporal, frustration, complexity, stress, distraction, strain, control and
330 performance). In the congruent trial, the only significant difference between the **VR** and **nVR**

331 conditions was 'distraction', which was higher in the VR condition (5.6 ± 4.8) in comparison
 332 to the nVR condition (1.9 ± 1.7 ; $p < 0.05$, Cohen's $d = 0.76$).

333 There was no significant difference in comfort (CALM) between **VR** vs **nVR** conditions (-
 334 5.5 ± 39.9 vs. -2.6 ± 37.9). The presence questionnaire was completed immediately following
 335 the congruent **VR** trial. Questions 20-22 were not used as there were no sounds elements
 336 within our virtual environment. The environment was highly immersive, where mean total
 337 presence was 76.1 ± 15.8 , realism was 29.2 ± 9 , possibility to act was 15.6 ± 5.1 , quality of
 338 interface was 15.1 ± 2.4 and self-evaluation of performance was 10.6 ± 2.1 . VR was rated more
 339 enjoyable than nVR across all questions in PACES (p 's < 0.05 ; Figure 5).

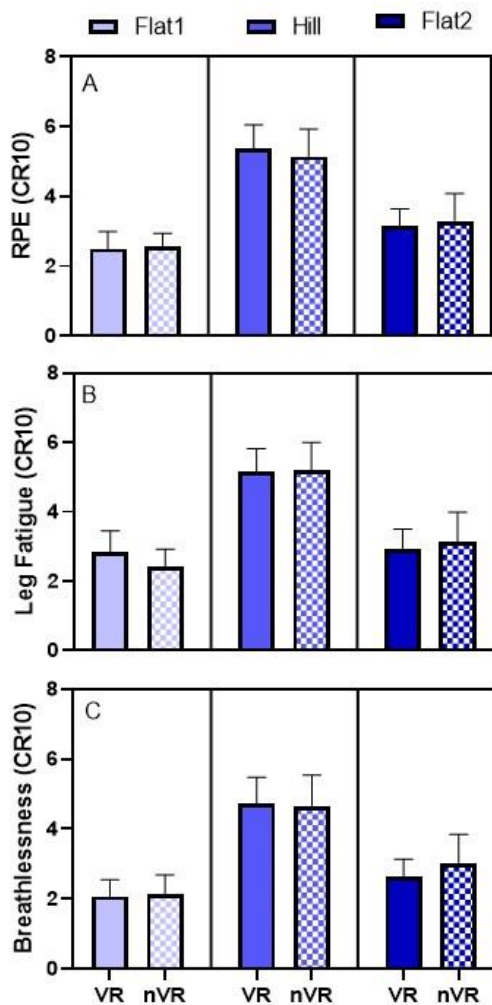
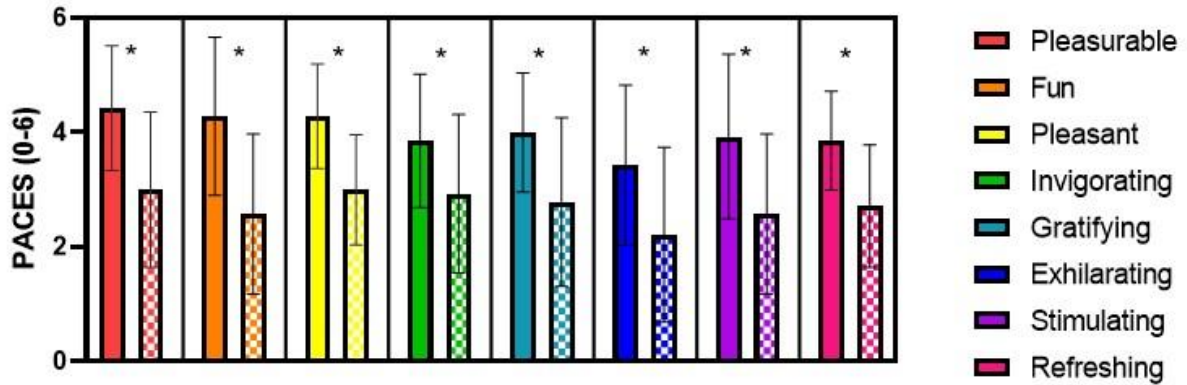


Figure 4. Mean (\pm SD) ratings of perceived exertion (RPE, A), Leg Fatigue (B) and Breathlessness (C) during the final 30 seconds of each trial stage (*Flat1*, *Hill*, *Flat2*) in the **VR** (solid) and **nVR** (chequered) condition.

340



341

342 **Figure 5.** Mean (\pm SD) values from each category of the physical activity enjoyment scale
 343 (PACES). Solid = VR, chequered = nVR. * = significant difference between condition (**VR** vs
 344 **nVR**; $p < 0.05$).

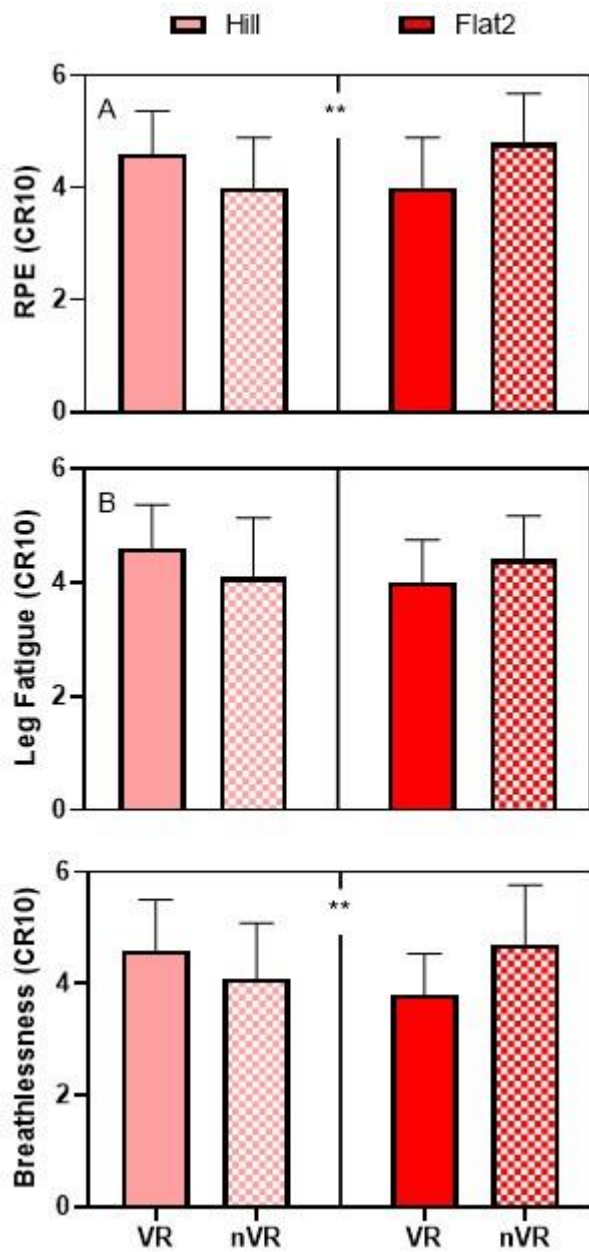
345 Incongruent Trials

346 Figure 6 (A-C) presents mean ratings of perceived exertion (RPE), leg fatigue and
 347 breathlessness during each incongruent trial stage in both **VR** and **nVR** conditions. There was
 348 no significant main effect (Trial stage or **VR/nVR** condition) for RPE, leg fatigue or
 349 breathlessness. There was a significant interaction effect for RPE ($F(1,9) = 5.8, p < 0.05, \eta_p^2 =$
 350 0.377) and for breathlessness ($F(1,9) = 5.6, p < 0.05, \eta_p^2 = 0.392$) but not for leg fatigue. RPE
 351 and breathlessness was greater in the VR condition when on the *Hill* stage, and they were
 352 greater in the nVR condition when on the *Flat2* stage.

353 Figure 7 (A-D) presents mean power output, RPM, Δ HR and Δ RR during each incongruent
 354 trial stage in both **VR** and **nVR** conditions. Although power output, RPM and Δ HR tended to
 355 be higher in the **VR** condition, there was no significant main effect or interaction effect for
 356 any variable.

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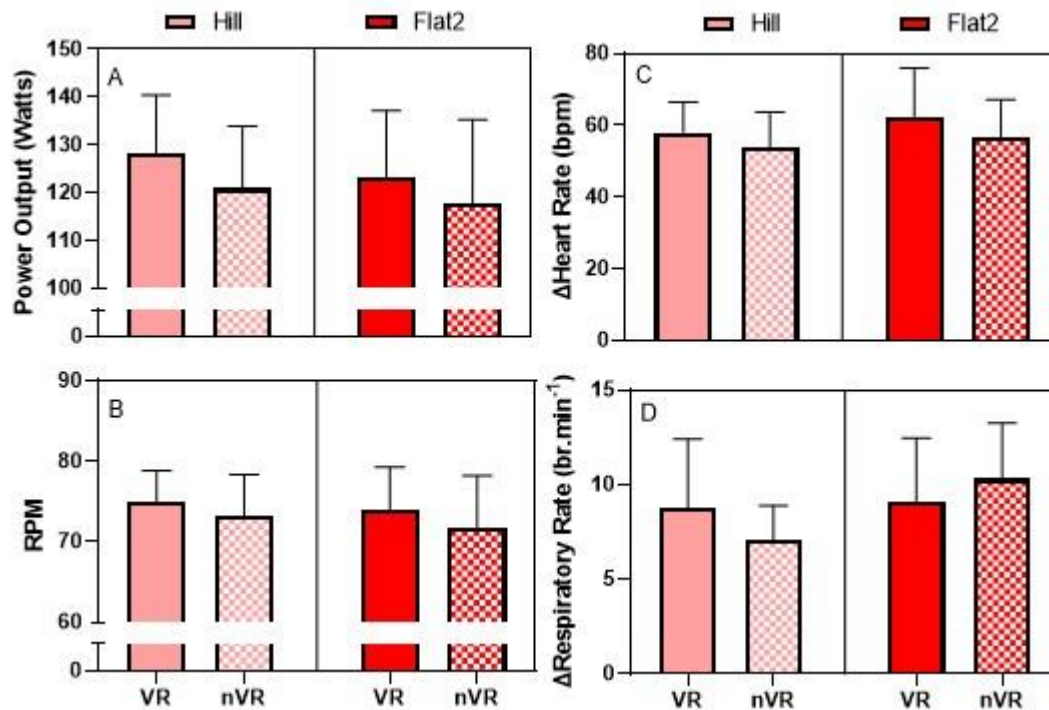


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360

361 **Figure 6.** Mean (\pm SD) ratings of perceived exertion (RPE, A), Leg Fatigue (B) and
 362 Breathlessness (C) during the *Hill* stage of trial 3 and *flat2* stage of trial 4. Note, these two
 363 stages were performed with the same pedalling resistance, but different visual gradients (5%
 364 and 0% respectively). ** = significant interaction effect between trial stage (Hill vs Flat2) and
 365 condition (VR vs nVR; $p < 0.05$)

366



367

368 **Figure 7.** Mean (\pm SD) power output, RPM, Δ HR and Δ RR during the final 30 seconds of
 369 congruent trial stages (*Hill* in Trial 3 and *Flat2* in Trial 4) in the **VR** (solid) and **nVR**
 370 (*chequered*) condition.

371

Discussion

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We aimed to capture the effect of a congruent and incongruent virtual reality (VR)

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cycling protocol on exercise performance and perceptions of exertion and breathlessness in

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healthy individuals. The presence questionnaire and SIM-TLX measures showed an

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immersive and potentially distracting exercise environment that had no difference in

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reported comfort compared to a matched non-VR equivalent. Cycling with VR increased all

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measures of enjoyment and showed that participants chose to work at a higher work rate

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for the same perceived of exertion. When analysing incongruent trials where visual gradient

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and pedalling resistance were mismatched, these data showed an interaction effect on

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perceptions of exertion and breathlessness. This interaction indicated successful

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manipulation of participant perceptions, despite an identical pedalling resistance.

382 The current findings support a developing body of literature that demonstrate
383 undertaking exercise using VR, without any intentional manipulation of visual input and
384 pedalling resistance, is more enjoyable and beneficially altered the relationship between
385 workload and exertion (Ng et al., 2019; Qian et al., 2020). There has been limited work
386 investigating the underlying mechanism of this finding (Mouatt et al., 2020). Our use of the
387 SIM-TLX suggests distraction may play a key role, whereby a more engaging visual
388 environment takes attention away from physical discomfort. An ability to deliberately
389 manipulate visual environments to not simply change perceived exertion but to alter it in a
390 desired direction offers the biggest potential for VR exercise in training or rehabilitation
391 settings (Mouatt et al., 2020).

392 We applied theoretical understanding of exercise perceptions to design a protocol where
393 an incongruence is created between sensory inputs (e.g., vision) and pedalling resistance.
394 Perceived exertion was reported to be higher than the matched non-VR equivalent in trials
395 where participants were visually cycling uphill but working at a lower resistance than was
396 expected from the visual incline, However, when participants were visually cycling on the
397 flat, but working at a resistance that was higher than expected, participants reported a lower
398 perceived exertion in comparison to the non-VR equivalent. This supports the initial work of
399 Runswick et al., (2021) who showed perception of speed was dictated by the steepness of
400 virtual slopes, and particularly the work of Finnegan et al. (2023) where expectation of effort
401 based on visual input of the gradient of the slope was an independent predictor of
402 perceptions of breathlessness and actual effort. It is clear that a new direction in
403 manipulating, rather than distracting, individuals' effort perceptions could be practically
404 achieved using VR.

405 The findings suggest that that manipulating perceptions of exercise with VR can offer
406 numerous practical applications both in clinical settings and athletic populations. However,
407 these methods also provide new avenues for testing theoretical accounts of the mechanisms
408 that underpin exercise perceptions. For example, manipulation of sensory input allows for
409 comparison of feedback (exertion) and feedforward (effort) control (Abbiss et al., 2015;
410 Halperin & Emanuel, 2020; Marcora, 2009). While we did not directly test one theoretical
411 approach, our data does suggest perceptions during exercise likely arise from a complex
412 interaction between expectations and sensory inputs. In incongruent trials we saw a
413 manipulation of RPE and breathlessness, which was potentially driven by a relationship
414 between various sensory inputs (i.e., visual, vestibular, tactile, muscle sensory feedback) and
415 past-experiences. This new incongruent VR method offers researchers opportunities to
416 adopt more targeted manipulations in theoretically driven research (Abbiss et al., 2015;
417 Bubic et al., 2010; Marcora, 2009; Tucker, 2009).

418 While these findings offer initial encouragement for the use of VR to manipulate exercise
419 perceptions, there were some novel findings that are difficult to explain. For example,
420 participants chose to perform a similar power output in the incongruent VR and non-VR
421 conditions, but higher power-output in the congruent VR conditions. This is potentially due
422 to the unfamiliar nature of the incongruent trials meaning participants were more aware of
423 the resistance on the bike. Although leg fatigue did follow a similar trend to RPE and
424 breathlessness in the incongruent trials, it did not reach statistical significance. It is possible
425 that leg fatigue, in comparison to RPE and breathlessness, is more closely associated with
426 afferent feedback from the exercising muscle which was presumably very similar between
427 the VR and non-VR incongruent conditions as the pedalling resistance was identical.

428 There are some limitations to consider in this work. Changing the incline of the bike to
429 match the visual gradient itself could have altered the seated position of the cyclist and
430 hence the workload and physiological responses to the exercise. However, despite the likely
431 change in vestibular activity associated with this change in incline, pilot testing (without VR)
432 revealed no difference in $\dot{V}O_2$, heart rate or chosen RPM when cycling with a gradient of 0%
433 and 5% with the same pedalling resistance. So apart from changes in vestibular projections
434 to the CNS, the bike incline is unlikely to have had a direct effect on exercise workload and
435 the physiological response.

436 The development of this method offers significant scope for future work in this area. We
437 have shown participants may choose to work at higher rates in VR. Future studies that use
438 VR might control the workload and make comparisons between congruent and incongruent
439 environments more straightforward. Work is also required to assess the elements of
440 immersion that are most effective and causing the incongruence effect. Here we applied not
441 only virtual visual stimuli, but this was matched with vestibular manipulation through the
442 tilting of the bike and with a speed matched wind fan. While the bike incline adds to the
443 immersion of the simulation, the environment did not include sound effects of wind (aside
444 from the fan) or the bike on the road. Adding these elements to the simulation could
445 increase levels of immersion and potentially enhance both the VR and congruence effects.
446 These are issues related to the use of a custom-made application, which was chosen
447 because existing applications do not allow researchers to create incongruence between
448 visual stimuli and pedalling resistance.

449 The initial proof of concept here alongside the work of Finnegan (Finnegan et al., 2023)
450 leaves potential for systematic investigation of the optimum conditions to maximise

451 separation of perceptions of exertion from actual work rate. This could be through use of
452 elements such as levels of incline, size of incongruence, setting expectations through prior
453 experience of congruent trials, and the autonomy offered to participants on elements such
454 as RPM and use of gearing. The custom made set up here required a specialised bike,
455 premium VR headset, and high-end VR ready PC. The total cost of this research set up may
456 be a barrier for clinical applications. Future research should aim to investigate effects of
457 existing popular applications, the level of immersion needed to create effects (e.g., is sound
458 or bike tilt really required), the use of more comfortable bikes, and how these additions
459 affect cost and the levels of acceptability and accessibility for different clinical populations
460 (Creed et al., 2023, Xu et a., 2022).

461 In summary, we have used a multi-sensory VR cycling experience to show that exercise in
462 VR is not only more enjoyable and efficient than a non-VR equivalent, but that perceptions
463 of exertion and breathlessness can be altered by manipulating sensory inputs from an
464 immersive virtual environment. Findings offer implications for clinical practice and training,
465 as well as offering new approaches for understanding perceptions of exercise.

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624 **Biographies**

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650 **Dr Sarah Finnegan** completed her PhD and Postdoctoral research work at the University of
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652 chronic lung disease. In particular, using computational techniques to stratify patient
653 populations and predict treatment outcomes.

654 **Dr Martin Sargeant** obtained his PhD at Liverpool University in molecular microbiology and
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658 **Professor Kyle Pattinson** is a Senior Clinical Research Fellow and Associate Professor at the
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662 **Dr Richard Bruce** is a Senior Lecturer in Cardiorespiratory Physiology at King's College
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