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

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

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

Abstract

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

Introduction

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

The heightened perceptions of exertion and breathlessness during exercise is partly dependent on the underlying pathophysiology, but current opinion considers that it also arises from the brain's integration of sensory feedback and prior expectations (Bruce et al., 2019; Marlow et al., 2019). If this model is accurate, it provides opportunities for new therapies such as the use of virtual reality (VR), that can manipulate sensory feedback and thereby support rehabilitation. VR refers to a computer-simulated environment that aims to induce a sense of being present in another place and allows for the individual to interact with the environment (Baños et al., 2004; Neumann et al., 2018; Sherman & Craig, 2018). This ability to interact with the environment is important for perceptions of immersion and effort (Runswick., 2023) and in the context of exercise, the interaction with the environment can occur through exertion on equipment such as an ergometer (Mueller et al., 2007). The degree of immersion in the virtual environment is partly dependent on factors such as the realism of the visual images and accuracy of physical elements such as interaction with objects and gravity but can be improved with multisensory input such as simulated aural (e.g., ambient sounds), vestibular (e.g., passive physical movements mirroring those in VR) or tactile (e.g., airflow over skin) feedback (Melo et al., 2022). VR environments may be useful in clinical exercise prescription and rehabilitation as they offer the ability to systematically manipulate sensory feedback and exploit patient expectations, and so decrease perceptions of exertion and breathlessness in exercise. Further investigation is needed to establish whether VR cycling can be a useful adjunct to standard therapy (Condon et al., 2020).

Previous work has shown that immersive VR increases the enjoyment of exercise (Baños et al., 2004; Mouatt et al., 2020) and may have a positive effect on the frequency of physical activity (Ng et al., 2019). In addition, there is growing evidence that exercise performance (e.g., chosen work rate) can be enhanced in VR compared to non-VR environments despite perceptions of exertion being equal or reduced (Murray et al., 2016; Zeng et al., 2022). For example, Zeng et al. (2022) had college students conduct single bouts of cycling on a VR exercise bike (immersive), and exergaming bike (non-immersive), or traditional exercise bike. Results showed that the commercially available VR bike was able to induce higher levels of physical activity, and importantly, lower levels of perceived effort alongside this. Similarly, McDonough et al. (2020) showed that VR could increase enjoyment and lower perceived exertion compared to an exergame or traditional stationary bike despite no differences in blood pressure across the three exercise types. However, this work has often been conducted without any theoretical basis for examining exercise perception and therefore does not use VR to target any specific function that underpins exercise (Mouatt et al., 2020). It’s likely these findings are a result of the basic immersion and distraction that is offered by VR (similar to exercising in nature) rather than the targeting of specific mechanisms of exercise perception such as elements of central command (Slater & Sanchez-Vives, 2016; Williamson, 2010).

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

To our knowledge, only one study has used incongruent VR to target specific mechanisms that underpin perceptions of effort during aerobic exercise. Finnegan et al. (2023) noted that breathing responses during exercise seem to be influenced by learning or past experiences of exercise and that changes in visual input have been shown to affect perceptions of breathlessness in cycling exercise. To investigate the use of VR to target these mechanisms, the experimenters used virtual hills of different gradients and congruent or incongruent cycling resistance. In this context, ‘incongruent’ refers to an environment where perceived cycling intensity and actual pedalling resistance do not match. In other words, the pedalling resistance will be lower/higher than that expected by the steepness (gradient) of the VR cycling course. The expectation effort based on gradient was a significant predictor of perceive breathlessness separate from the actual effort exerted during exercise. However, the study only captured perceptions of breathlessness and not overall perceptions of exertion or physiological responses to exercise.

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

Young healthy volunteers using ‘congruent’ (exertion matched to VR cycling environment) and “incongruent” (exertion unmatched to VR cycling environment) cycling exercise in a custom-made VR environment The first aim of the current study was to examine whether cycling performance (self-selected power output), enjoyment and perceptions of exertion and breathlessness are altered by a ‘congruent’ VR cycling environment where the VR and the ‘real-world’ are matched as closely as possible. We hypothesise that cycling performance and enjoyment will be enhanced, and perceptions of exertion and breathlessness will be reduced, with congruent VR cycling in comparison to non-VR cycling. Our second aim is to assess whether a theory driven intervention to manipulate perceptions of exertion and breathlessness can be achieved by using an ‘incongruent’ VR cycling environment. We hypothesise that incongruence between actual pedalling resistance and perceived cycling intensity (based on sensory feedback from the VR environment and past experience) will alter perceptions of exertion and breathlessness.

Methods

Participants and Ethical approval

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

Participants visited the laboratory on three occasions, with >72 hours between each visit. During visit 1, participants were familiarised to all procedures and underwent a maximal incremental cycling exercise task to assess peak oxygen consumption ($\dot{V}O_2$peak). During visit 2 and 3, participants performed 4 submaximal cycling exercise tasks with (**VR**) or without (**nVR**) a VR environment. Participants were asked to refrain from consuming food and caffeine within 4 hours and performing strenuous physical activity or consuming alcohol within 12 hours of each trial. The study followed a repeated measures design with all participants performing all trials in the **VR** and **nVR** condition (visit 2 and 3) in a randomised order. Participants were required to always remain in a seated position in the saddle.

Equipment

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

Table 1. Participant characteristics (mean ± standard deviation)

The VR and nVR studies were undertaken using an automated cycle ergometer (Wahoo-Kickr Climb Integrated Cycling system, Wahoo, Atlanta, US) and custom-made VR environment written in Unity-3D (Finnegan et al., 2023) (Figure 1). The simulation was rendered in a commercially available VR headset (Vive Pro, HTC, Taiwan), that was physically tethered with a cable to a VR ready PC (3XS High End Gaming PC with NVIDIA GeForce RTX 3080 and AMD Ryzen 7 5800X). The incline (up/down tilt) of the Wahoo cycle ergometer was automatically adjusted by the VR software to match the gradient of the hill/flat. The use of Wahoo cycle ergometers have been validated previously (Gin et al., 2018). In addition, a fan (Wahoo-Kickr headwind, Wahoo, Atlanta, US) which automatically adjusted its air flow to match estimated cycling speed was used.

Protocol

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

The incremental cycling exercise task was performed initially to determine peak $\dot{V}O_2$.

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

Visit 2 and 3

During visit 2 and visit 3, participants performed 4 cycling exercise trials with and without VR. During VR trials the incline of the bike, and fan airspeed were adjusted automatically by the VR software. Identical exercise trials were performed during the **nVR** condition, but no VR headset was worn, and no adjustment was made to the incline on the Wahoo bike. While the fan was used, no adjustment to fan speed was performed **VR** and **nVR** testing days were performed in a randomised order.

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

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

Trial 1 and 2 were 'congruent' with pedalling resistance matched to the visual gradient (the perceived cycling intensity). Trial 3 and Trial 4 were 'incongruent'; during one stage in each trial the pedalling resistance did not match the visual gradient. In trial 3, the pedalling resistance during the *Hill* was set lower than the visual gradient of 5%, and in trial 4 the resistance during *Flat2* was set to be higher than the visual gradient of 0%. Importantly, the pedalling resistance during these incongruent stages (*Hill* (Trial 3) *and Flat2* (trial 4)) was identical (i.e. equivalent of a 2.5% gradient hill). Trial 1 and 2 were always performed first, to set expectations that the VR cycling will match past experience. This might enhance the effects of the incongruent manipulation (as discussed in the introduction) and trial 3 and 4 were performed in a random order. Each individual participant performed trial 3 and 4 in the same order in the **VR** and **nVR** conditions. During each visit, participants rested for 15 minutes between trials.

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

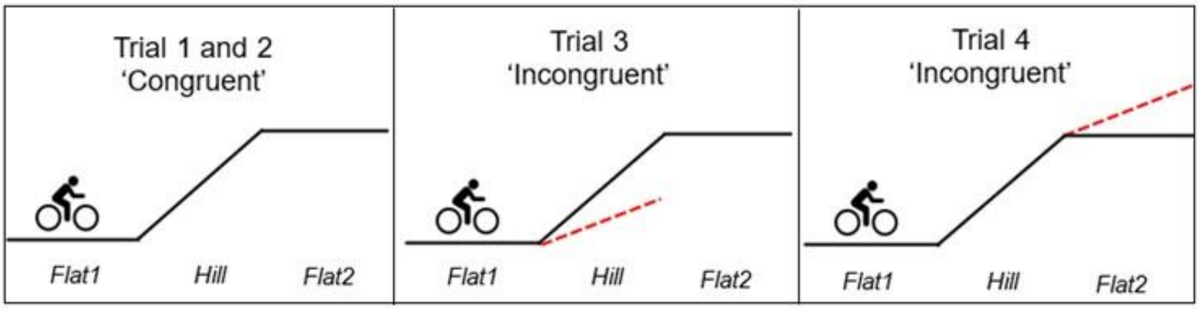

Figure 2. A schematic representation of the 4 trials used on **VR** and **nVR** test days. Black lines represent the visual gradient. When not accompanied by a broken red line, the pedalling resistance is matched to the visual gradient. Therefore Trial 1 and 2 are entirely 'congruent'. Broken red line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

<u>Physiological and psychological measures</u>

During the four trials, heart rate (HR), respiratory rate (RR) were recorded continuously with an ECG and respiratory belt respectively (Equivital EQ02, Cambridge, UK) using LabChart version 8 (AD instruments, Oxford UK). Immediately before each trial, heart rate and respiratory rate was collected for 1 minute while participants rested on the bike. Measurements of distance, watts, and cadence (RPM) were recorded each second using the Wahoo fitness app. Overall ratings of perceived exertion (RPE), as well as sensations of breathlessness and leg fatigue, were measured using a CR10 Borg scale (Borg, 1982) during the final 30 seconds of each stage of each trial. Participants were familiar with the measure before testing and then verbalised their ratings when prompted. The scale could not be used visually given the VR headset.

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

Data analysis

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

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

Results

Participant Characteristics

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

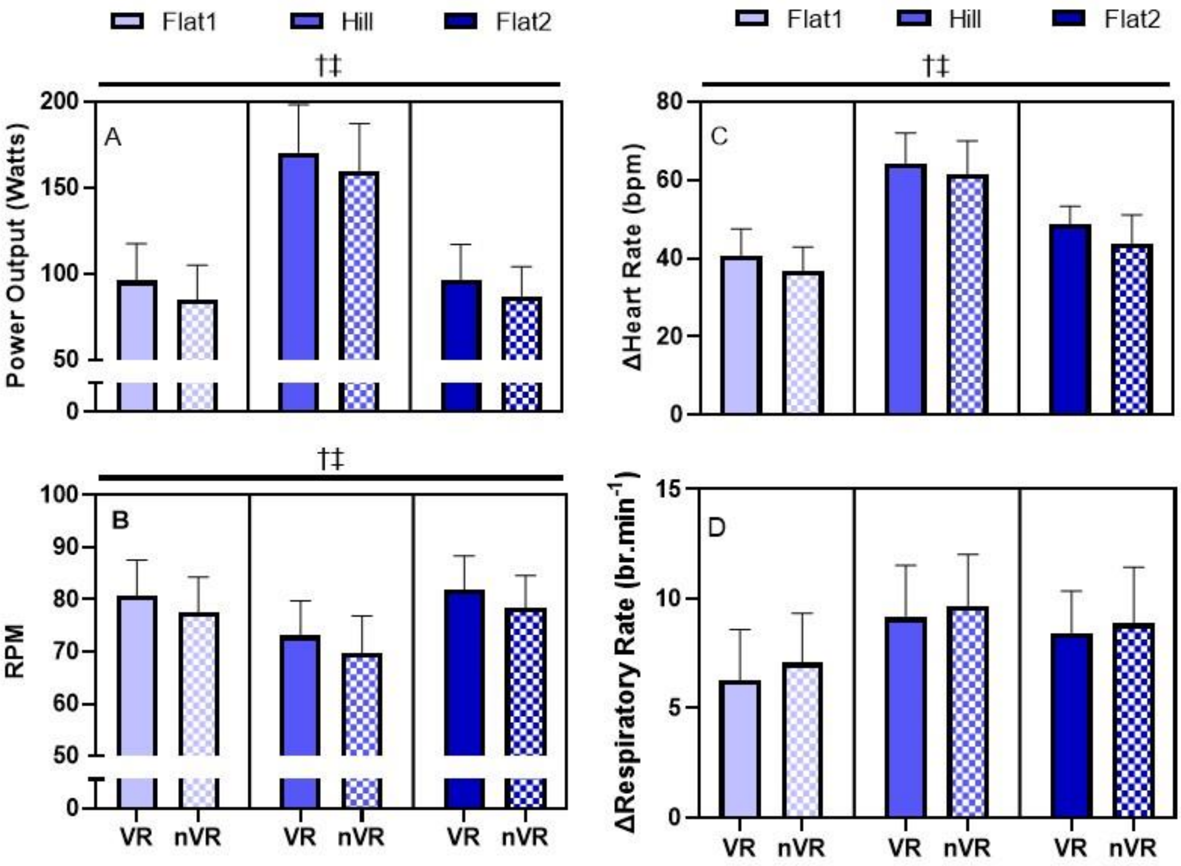

Figure 3. Mean (±SD) power output (A), RPM (B), ΔHR (C) and ΔRR (D) during the final 30 seconds of each trial stage (*Flat1, Hill, Flat2*) in the **VR** (solid) and **nVR** (chequered) condition. † = significant main effect of trial stage ($p<0.05$). ‡ = significant main effect of condition (**VR** vs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

Congruent Trials

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

For ΔHR (figure 3C) there was a significant main effect of trial stage ($F(2, 26) = 96.7$, $p<0.001$, $\eta_p^2 = 0.963$) and **VR/nVR** condition ($F(1,13) = 8.2$, $p<0.05$, $\eta_p^2 = 0.388$), but there was no significant interaction. Heart rate was greater in the **VR** condition during *Flat1* (+4bpm ± 3), *Hill* (+4 bpm ± 2) and *Flat2* (5bpm ± 3) stages ($p<0.05$). For ΔRR there was a significant main effect of trial stage ($F(2, 26) = 9.02$, $p0=.001$, $\eta_p^2 = 0.401$) but no significant main effect for **VR/nVR** condition or interaction (figure 3D).

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

The Sim-TLX records perceived workload of the task in regard to its specific demands (i.e. mental, physical, temporal, frustration, complexity, stress, distraction, strain, control and performance). In the congruent trial, the only significant difference between the **VR** and **nVR** conditions was ‘distraction’, which was higher in the VR condition (5.6 ± 4.8) in comparison to the nVR condition (1.9 ± 1.7; $p<0.05$, Cohen’s d = 0.76).

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

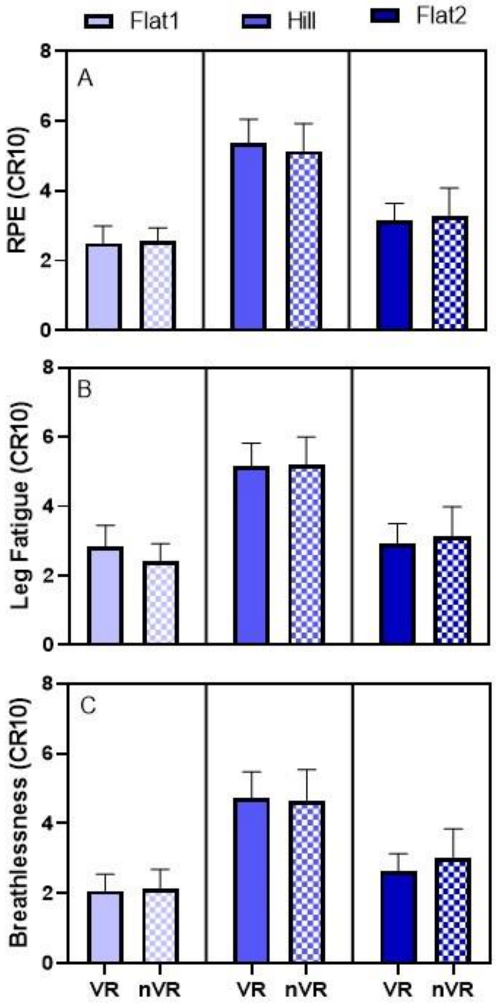

Figure 4. Mean (±SD) ratings of perceived exertion (RPE, A), Leg Fatigue (B) and Breathlessness (C) during the final 30 seconds of each trial stage (*Flat1, Hill, Flat2*) in the **VR** (solid) and **nVR** (chequered) condition.

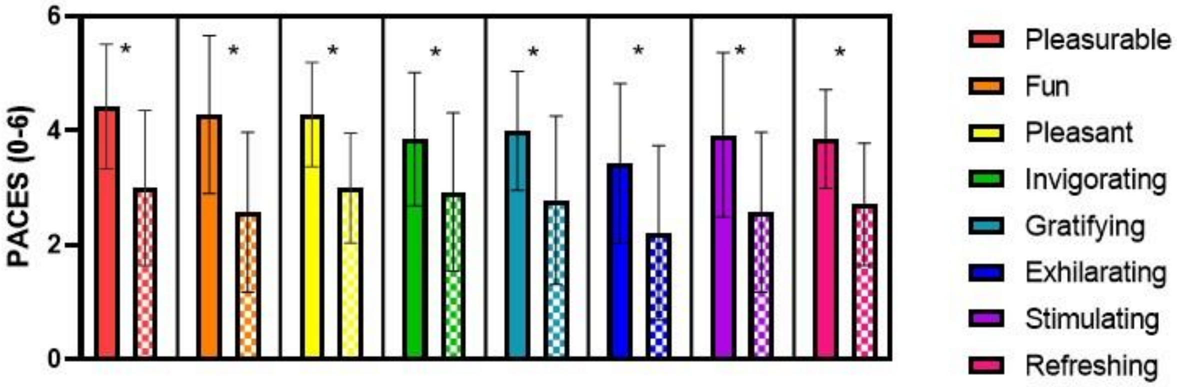

Figure 5. Mean (±SD) values from each category of the physical activity enjoyment scale (PACES). Solid = VR, chequered = nVR. * = significant difference between condition (**VR** vs **nVR**; p<0.05).

Incongruent Trials

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

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

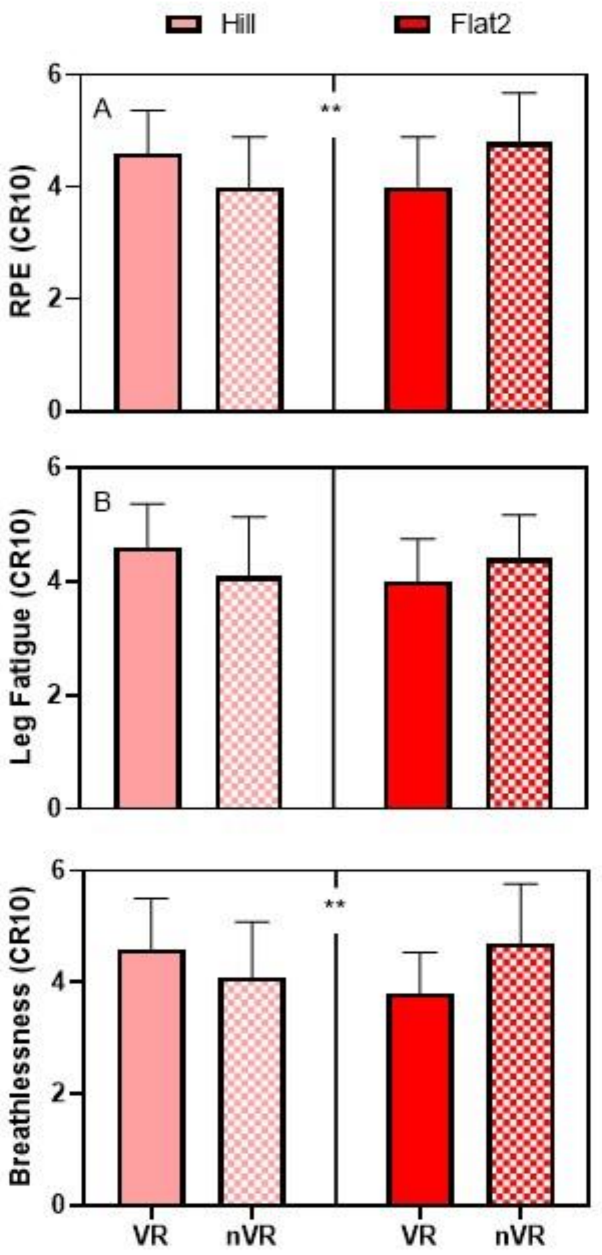

Figure 6. Mean (±SD) ratings of perceived exertion (RPE, A), Leg Fatigue (B) and Breathlessness (C) during the *Hill* stage of trial 3 and *flat2* stage of trial 4. Note, these two stages were performed with the same pedalling resistance, but different visual gradients (5% and 0% respectively). ** =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

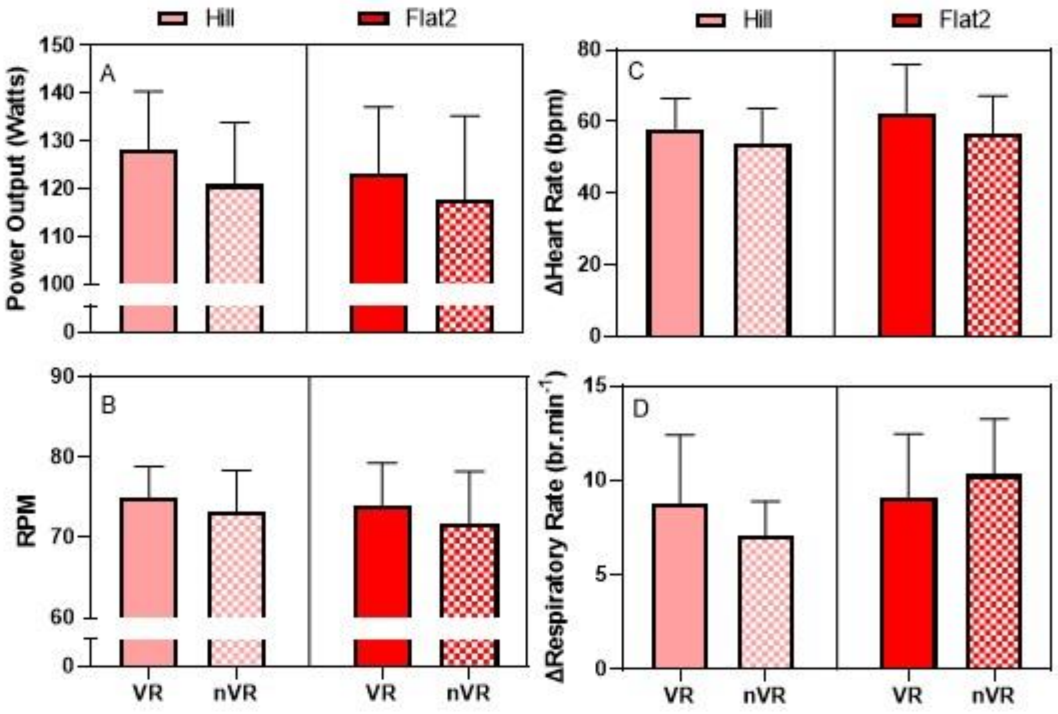

Figure 7. Mean (±SD) power output, RPM, ΔHR and ΔRR during the final 30 seconds of congruent trial stages (*Hill* in Trial 3 and *Flat2* in Trial 4) in the **VR** (solid) and **nVR** (chequered) condition.

Discussion

We aimed to capture the effect of a congruent and incongruent virtual reality (VR) cycling protocol on exercise performance and perceptions of exertion and breathlessness in healthy individuals. The presence questionnaire and SIM-TLX measures showed an immersive and potentially distracting exercise environment that had no difference in reported comfort compared to a matched non-VR equivalent. Cycling with VR increased all measures of enjoyment and showed that participants chose to work at a higher work rate for the same perceived of exertion. When analysing incongruent trials where visual gradient and pedalling resistance were mismatched, these data showed an interaction effect on perceptions of exertion and breathlessness. This interaction indicated successful manipulation of participant perceptions, despite an identical pedalling resistance.

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

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

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

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

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

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

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

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

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