Ger J Exerc Sport Res
https://doi.org/10.1007/s12662-024-00964-4
Received: 2 November 2023
Accepted: 9 April 2024

Carla Luttmann[1] · Manuel Mayer[2] · Markus Siebertz[1] · Leonardo Jost[1] · Niels Henze[2] · Petra Jansen[1]
[1] Faculty of Human Sciences, University of Regensburg, Regensburg, Germany
[2] Faculty of Language, Literature, and Cultural Sciences, University of Regensburg, Regensburg, Germany

Effects of visual flow velocity on cycling experience in virtual reality

Supplementary Information

The online version of this article (https://doi.org/10.1007/s12662-024-00964-4) contains supplementary material, which is available to authorized users.

Introduction

Virtual reality (VR) has recently gained significant attention in sports and exercise sciences. It can impact subjective experience and behavior during exercise, similar to how video games (Lyons et al., 2014) or music (Jones, Karageorghis, & Ekkekakis, 2014) increase enjoyment compared to exercising without media. The use of VR as a highly immersive medium enables the diversion of attention from internal stimuli towards external stimuli within the virtual environment (Neumann & Moffitt, 2018). Users can embody virtual avatars, leading to bodily illusions (Yee, Bailenson, & Ducheneaut, 2009). Both virtual scene and avatar design have impacted enjoyment (Mouatt et al., 2020) and behavior (Banakou, Kishore, & Slater, 2018) in various tasks. While the effects of avatar characteristics have received recent attention, the influence of other VR properties requires further investigation. It remains indistinct whether scene configurations can induce similar effects as avatar design. Considering the role of interoceptive sensitivity in the susceptibility to bodily illusions (Tsakiris, Tajadura-Jiménez, & Costantini, 2011), interoception could be a moderating factor in this process. Furthermore, interoceptive abilities are essential for the subjective experience of effort and affective states (Herbert, Ulbrich, & Schandry, 2007), which majorly affect exercise behavior.

Understanding the effects of specific virtual scene configurations on exercise experience could improve exercising in VR, with implications for health promotion and professional sports. Given its widespread use in endurance training, stationary constant load cycling was chosen as a physical exercise. As for every locomotive action, performance evaluation during cycling relies highly on the perception of movement speed. The speed of the virtual scene moving toward the user (*visual flow*) provides visual information about cycling performance. In the manner of false feedback experiments (Hutchinson, Sherman, Martinovic, & Tenenbaum, 2008) and visualization of athleticism through avatar design (Kocur et al., 2021), ineptly slow or fast visual flow is hypothesized to affect physiological and psychological reactions to exercise. This has rarely been investigated (Parry, Chinnasamy, & Micklewright, 2012). Clarifying the role of interoception in the relation of internally formed affective states or perception of effort and external cues of performance may aid in distinguishing the appropriate target group for such applications.

Embodiment and visual feedback in virtual reality

Exercising in VR has enhanced self-efficacy, enjoyment, arousal, performance, affective attitude towards exercise, and exercise frequency (Cao, Peng, & Dong, 2021; Plante, Aldridge, Bogden, & Hanelin, 2003; Rhodes, Warburton, & Bredin, 2009; Zeng, Pope, & Gao, 2017). However, these results are not found consistently (Ng, Ma, Ho, Ip, & Fu, 2019). These effects can be attributed to several factors, including the gamification of exercise, the immersion into a different environment, or the novelty of exercising in a virtual world. Comparing the effectiveness of different VR configurations, avatar design emerges as a relevant component. Embodying the virtual avatar can induce behavioral and attitudinal changes in the user (Yee et al., 2009), as the outer appearance of the avatar triggers inferences about its personality traits (e.g., taller avatars are perceived as more assertive in arguments). Acting in accordance with these assumed personality traits (e.g., being more assertive when the avatar is taller than a counterpart) is termed the *Proteus effect* (Yee & Bailenson, 2007). Kocur et al. (2021), for instance, demonstrated differences in perceived exertion and heart rate during short incremental cycling exercises depending on the appearance of the virtual avatar. A muscular avatar coincided with lower heart rates and perceived effort compared to medium or nonathletic avatars. Similarly, participants completed more repetitions in a weightlifting exercise when embodying a muscular avatar in VR than when exercising in front of a mirror (Czub & Janeta, 2021). These effects may be explained by the theory

Published online: 21 May 2024

of the *minimal self* (Gallagher, 2000), which consists of a sense of body ownership and a sense of agency. Embodying a particular body (i.e., the virtual avatar) presumably induces a sense of ownership for this body, leading the user to adopt competencies associated with the embodied avatar. Existing research (Banakou et al., 2018) supports the idea that the avatar's appearance affects the user's self-perception and behavior.

Complementary to the sense of body ownership, the sense of agency refers to the feeling of authorship for one's actions and their outcomes (Pyasik, Furlanetto, & Pia, 2019). Manipulating sensory action outcomes realistically, combined with a feeling of body ownership for the avatar, has previously induced agency illusions for speech (Banakou & Slater, 2017) and movements (Burin et al., 2018) in VR. In exercise contexts, however, most studies focus on effects of avatar design. Specific scene configurations providing altered performance output may induce an illusionary sense of agency, impacting perceptions of the actual movement (e.g., effort). This could affect self-efficacy, enjoyment, and user experience like body ownership illusions without needing a (wholly visible) virtual avatar. Given that higher self-efficacy coincides with lower effort ratings (Hutchinson et al., 2008) and more positive affect (Wienke & Jekauc, 2016) during exercise, manipulated performance output may influence various subjective aspects of physical activity.

Visual feedback in locomotion

In locomotion, movement speed is a central performance parameter and a sensory outcome directly linked to the expended physical effort. It holds the potential to manipulate the user's sense of competence and can be utilized for inducing an agency illusion. Movement speed during locomotion is primarily assessed through the perception of visual flow speed, a parameter crucial for the control of motor parameters such as speed or balance. Conflicting visual flow that contradicts actual movement speed usually prompts compensational movements in order to keep a constant visual flow rate (Ludwig et al., 2018). Although most visual flow studies focus on preferred walking speed (Janeh et al., 2017) or driving simulations (Pretto & Chatziastros, 2006), their findings support the notion that visual flow in VR affects locomotion parameters and speed perception. However, these studies do not provide insights into the relation of visual flow speed and physical performance parameters. Parry et al. (2012) investigated the effects of visual flow speed on performance parameters during cycling in VR. They observed a significantly higher power output, decreased perception of effort, and unaltered heart rate during time-trials with slow visual flow compared to normal (matching) or fast visual flow. The authors attribute these outcomes to the role of visual flow speed in distance estimation, assuming that participants inferred a larger distance to completion during slow visual flow and, therefore, increased their power output. It is noteworthy that the study's statistical power is limited, reducing the conclusiveness of the results. To our knowledge, the impact of visual flow speed on objective and subjective effort during aerobic exercise in VR has not been investigated outside of time trials (Parry et al., 2012).

Psychological components of exercise

Aside from physiological parameters (e.g., heart rate, oxygen consumption, or lactate accumulation) and objective indicators of physical load (e.g., power output, speed, resistance), exercise can be evaluated by subjective parameters like perceived effort or affective states.

In general, exercise tends to elevate mood (Ligeza, Nowak, Maciejczyk, Szygula, & Wyczesany, 2021), especially in combination with VR (Privitera, Antonelli, & Szal, 2014). By inducing a more dissociative attentional focus (Mestre, Ewald, & Maiano, 2011) and distracting users from the perception of internal strain (Lyons et al., 2014), VR enhances positive psychological responses to exercise. This effect can be explained by the Dual-Mode Theory (DMT, Ekkekakis, 2003, 2009), which posits that affective states during physical activity are shaped by cognitive processes such as intentions or self-efficacy and interoceptive cues. Perceived effort is also rooted in the integration of internal and external cues, combining information from muscles, joints, cardiovascular and respiratory systems, the central nervous system (Borg, 1982), and several cognitive and emotional processes (Rejeski, 1985), including self-efficacy (Hutchinson et al., 2008). DMT suggests that internal and external cues compete for attentional focus during exercise (Ekkekakis, 2009). A more associative (internal) focus thus often leads to an increased perception of fatigue and exertion (Pennebaker & Lightner, 1980).

The subjective appraisal of physical activity can influence acute behavior, perceived exertion (Di Fronso et al., 2020), and affective attitudes towards exercise (Williams, 2008). Positive feelings during sport often induce an increased sense of competence (Wienke & Jekauc, 2016), while the perception of effort is crucial for exercise adherence (Perri et al., 2002). Therefore, it seems sensible to organize physical activities accordingly. This can be achieved, among other methods, by enhancing the sense of competence through specific avatar or scene configurations. Manipulated movement feedback has the potential to create an illusionary sense of agency, even if it is incongruent with actual effort. The perceived agency could then impact the subjective assessment of the activity and physical competence, similar to how cycling with an athletic avatar was perceived as less strenuous than cycling with a nonathletic avatar (Kocur et al., 2021). Yasukawa et al. (2021) report that faster visual flow during cycling coincided with significantly higher ratings of *vitality* and *pleasure* on a two-dimensional mood scale, while other performance parameters remained unchanged. Although their results are limited by a small sample size of 18 participants, they give reason to investigate the relation of visual flow speed and affect further. A study on rollercoaster simulations confirms that higher visual flow speed can enhance enjoyment (Stephens & Smith, 2022). However, these findings refer to passive movement and may not apply to locomotion. Once again, existing research focuses on avatar configuration (Czub & Janeta, 2021; Kocur et al., 2021; Kocur, Kloss, Schwind, Wolff, & Henze, 2020).

The relation between the configuration of external stimuli (i.e., the virtual scene) and subjective appraisals might further be influenced by the individual ability to accurately perceive internal signals, as suggested by findings that high interoceptive sensitivity protects against bodily illusions (Tsakiris et al., 2011). Interoception includes proprioceptive cues from the skin and the musculoskeletal apparatus, and visceroceptive signals from the inner organs. Interoceptive sensitivity is typically assessed by objective heartbeat detection tasks measuring a person's ability to correctly count their heartbeats. Greater interoceptive sensitivity manifests in increased cortical processing of cardiac signals (Pollatos, Kirsch, & Schandry, 2005). Another facet of interoception is interoceptive awareness, a metacognitive quality describing the correlation between interoceptive sensitivity and subjective confidence judgments. Despite recent criticism of the heartbeat detection task for its low correlations with other interoceptive measures (Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015; Ponzo, Morelli, Suksasilp, Cairo, & Plans, 2021), it was considered the best available implicit measure of interoceptive abilities. Due to the importance of heart rate in forming effort evaluations during aerobic exercise (Borg, 1982), measuring the ability to perceive cardiac signals appeared appropriate.

Hypotheses

Avatar design has impacted user behavior and performance in VR (Kocur et al., 2021; Yee et al., 2009), and manipulated action output has evoked agency illusions (Banakou & Slater, 2017). Consequently, it was hypothesized that altered visual flow speed induces an illusionary sense of agency for the virtual movement speed. Visual flow speed is directly related to the expended physical effort and can be interpreted as a visualization of athletic competence. Thus, manipulated visual flow speed should impact perceived effort and heart rate similarly to avatar configuration (Kocur et al., 2021).

The embodiment of an athletic avatar has previously led to lower heart rate and perceived effort during incremental cycling (Kocur et al., 2021). With faster visual flow representing greater athletic competence, we hypothesize that:

H1: Heart rate is lower during faster visual flow conditions.

H2: Perceived exertion is lower during faster visual flow conditions.

Affective states are partly based on the perception of bodily signals (e.g., heart rate). Arousal should thus change in accordance with heart rate:

H3a: Arousal is lower during faster visual flow conditions.

Yasukawa et al. (2021) demonstrated higher levels of vitality and pleasure during cycling with fast visual flow. We therefore expect that:

H3b: Affective valence is more positive during faster visual flow conditions.

These hypotheses are grounded in the relation between the perception of physical strain and performance (visual flow speed) realized under a specific effort. The susceptibility to the visual flow illusion is likely influenced by interoception, which has been shown to diminish bodily illusions (Tsakiris et al., 2011). Lower interoception may lead to a more dissociative attentional focus. Consequently, participants with low interoceptive abilities may rely more on external than internal sensory cues to evaluate effort and affect. Interoceptive awareness is thus anticipated to affect the susceptibility to the virtual movement illusion and moderate the differences in all outcome measures between varying visual flow speed conditions:

H4: The effect of visual flow speed on all outcome measures is reduced with higher interoceptive awareness.

Abstract

Ger J Exerc Sport Res
https://doi.org/10.1007/s12662-024-00964-4

C. Luttmann · M. Mayer · M. Siebertz · L. Jost · N. Henze · P. Jansen

Effects of visual flow velocity on cycling experience in virtual reality

Abstract
Applying virtual reality to exercise has revealed mood- and performance-enhancing properties of immersive media. Social–cognitive theory and the Proteus effect suggest that avatar appearance contributes to this relation by eliciting behavioral changes. Attempting to influence exercise parameters without modifying the virtual avatar, the present study investigated the effects of differing visual flow speeds on physiological and perceived effort during aerobic exercise. Eighty-two university students participated in three separate experimental trials. During each trial, a virtual cycling track was presented at one of three velocities (16, 20, 24 km/h) in counterbalanced order, while participants cycled at a moderate intensity for 20 min. Objective and subjective measures of effort and affective states were recorded every five minutes. With increasing visual flow speed, a linear decrease of heart rate, perceived effort, and arousal and a linear increase of valence were expected. Mixed linear model analyses revealed no significant main effect of visual flow speed on any dependent variable. A nonlinear relation between visual flow speed and heart rate was identified through pairwise comparisons between visual flow conditions.

Keywords
Aerobic exercise · Agency · Interoception · Action feedback · Self-motion illusion

Method

Design

In a repeated measure within-subject design, each participant completed three experimental trials, each 1 week apart. During each trial, participants cycled on an ergometer for 20 min. A virtual cycling track was presented through a head-mounted display (HMD), creating the impression of moving forward. The speed of the virtual scene varied across three conditions: medium speed at 20 km/h,

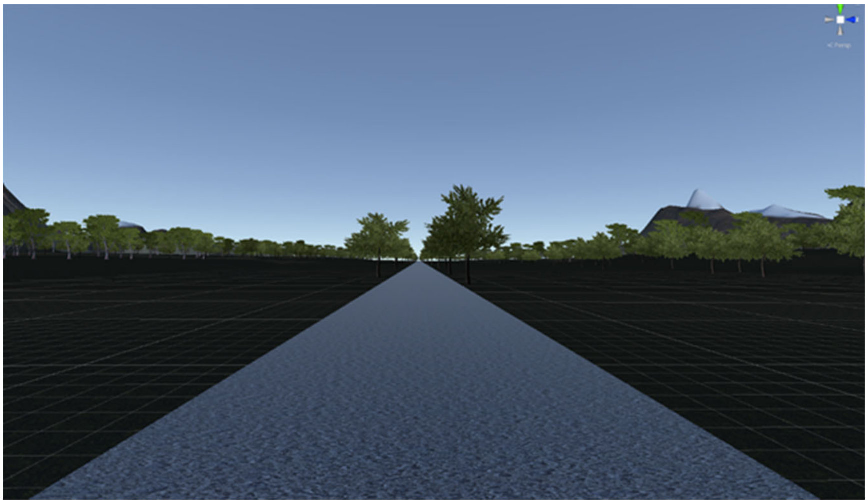

Fig. 1 ▲ Virtual reality scene

slow speed at 16 km/h (–20%), and fast speed at 24 km/h (+20%). The order of trials was randomized and counterbalanced between participants. All experimental procedures were in accordance with the Declaration of Helsinki, and all participants provided informed consent.

Participants

A power analysis was conducted using G*Power software (Faul, Erdfelder, Buchner, & Lang, 2009), to determine the required sample size. Based on the effect size found by Kocur et al. (2021) for avatar effects on average heart rate (f = 0.19), the analysis for a repeated measure ANOVA (analysis of variance; within factors, $\alpha = 0.05$, $f = 0.15$, $\beta = 0.8$) yielded a required sample size of $N = 73$. The target sample size was increased by 10% (N = 80) to enhance statistical power. University students aged 18–35 years enrolled in the "movement science" degree course were recruited via an online newsletter. Exclusion criteria for participants were acute or chronic cardiovascular or muscular diseases, sensitivity to motion and cybersickness, and anxiety triggered by a heightened interoceptive focus during the heartbeat detection task. In all, 82 students participated in three experimental trials to receive study credits. Two participants could not complete all three trials and were excluded from all analyses. The final sample size for the main analyses was $N = 80$ (35 women). One subject had to terminate an experimental trial prematurely due to dizziness caused by VR, but the trial was analyzed as planned. For two participants, one postexperimental questionnaire was not recorded due to technical errors, resulting in sample sizes of $N = 79$ for slow visual flow, $N = 80$ for medium visual flow, and $N = 79$ for fast visual flow for the questionnaire analyses.

Materials

Virtual reality

For the VR system, an HTC Vive HMD (HTC Vive, Taoyuan, Taiwan) was combined with two HTC Vive trackers attached to the pedals of the ergometer. The VR system ran on a desktop PC with an NVIDIA GeForce® RTX™ 3060 Ti 8 GB GDDR6 graphic card. The virtual scene consisted of a straight street surrounded by trees and mountains (**Fig. 1**), providing a simple but realistic environment. The simplicity was essential to avoid excessive distraction from the task, which could have impeded steady cycling and maintaining a forward gaze. Because visual flow arises from the surroundings moving towards the actor in an expanding circle, consistent gaze direction is crucial to ensure constant visual flow speed (Pretto & Chatziastros, 2006). The scene was programmed in Unity (Version 2020.3.38 f1) and presented in VR by Unity and SteamVR (Valve Corporation, Kirkland, WA, USA). The avatars were created in Daz Studio 3D (DAZ Productions, Salt Lake City, UT, USA) and imported into Unity as rigged models. The Final IK Unity Asset (RootMotion, Tartu, Estonia) was used to synchronize the avatar's and the participant's movements.

Outcome measures

During cycling, heart rate, ratings of perceived exertion (RPE), arousal, and valence were recorded every 5 minutes, resulting in five measures for each variable. Heart rate was measured by a chest strap heartrate sensor (Polar H10, Polar Electro Oy, Kempele, Finland) measuring continuously and transferring data to a smartphone app (PolarBeat, Polar Electro Oy) via Bluetooth. RPE was assessed by the *Anstrengungsskala Sport* (ASS, Büsch, Utesch, & Marschall, 2022) ranging from "1" ("not strenuous") to "10" ("so strenuous that I have to stop"). The ASS is a task-unspecific scale and a reliable German adaptation of the CR10-Scale (Borg, 1982) with numeric and semantic labels of each scale step that shows consistent matching of the respective label pairs (Büsch et al., 2022). Arousal and valence were assessed by a German adaptation of the Affect Grid (Russell, Weiss, & Mendelsohn, 1989). Participants reported a value between "1" and "9" for each dimension, indicating low or high arousal and negative or positive feelings. The Affect Grid is based on theoretical assumptions that all emotions can be described by their qualities on the dimensions "arousal" and "affective valence" (Russell et al., 1989). Because of its fast and easy use, it was considered an adequate tool to measure affect during physical activity. This seemed necessary because subsequent measures of affect often capture feelings about the activity ending more than about those occurring during exercise (Wininger, 2007). Pedaling cadence was recorded every 5 minutes to ensure it was kept over 50 rpm.

Measuring interoception

A six-interval heartbeat detection task (HDT) including confidence judgments was conducted at the beginning of every experimental trial. It was programmed in and presented by PsychoPy (Peirce et al., 2019, Version 2021.2.3). Interval length ranged from 25 to 50 s in steps of 5 s, presented in a random order. A custom-built optical heartbeat sensor (SE050, Iduino) was attached to the participant's earlobe, transmitting data via USB to PsychoPy through an Arduino-compatible microcontroller (DFR0282 Beetle, DFRobot). To ensure that the sensor correctly measures heartbeats, its recordings were validated before data collection by comparing it with electrocardiogram (ECG) data recorded simultaneously. ECG data was recorded with BrainVision Recorder (Brain Products, Gilching, Germany) and analyzed with BrainVision Analyzer (Brain Products, Gilching, Germany) to identify individual heartbeats. During the experiment, participants were instructed to count their heartbeats without feeling their pulse. A short sound indicated the start and finish of the respective intervals. Participants could initiate the next interval by pressing a key that started a 5-second countdown. After each interval, participants typed in their counted heartbeats and rated their confidence about their counting on a continuous scale from "0" (no heartbeats were counted) to "100" (all heartbeats were counted). For each interval, interoceptive sensitivity was calculated as follows:

$$1-\left(\frac{\left|\begin{array}{c}number\ of\ heartbeats\\ -counted\ heartbeats\end{array}\right|}{number\ of\ heartbeats}\right)$$

Sensitivity was then correlated with the confidence judgments to calculate awareness for each trial. Mean sensitivity and awareness for each participant were used for further analyses. Participants that counted zero heartbeats in more than two intervals automatically received a "0" for awareness to avoid contradictory scores.

Postexperimental questionnaire

After cycling, participants completed a computerized questionnaire consisting of the I-group presence questionnaire (IPQ, Schubert, Friedmann, & Regenbrecht, 2001), the items "body ownership" and "agency" of the body representation questionnaire (BRQ, Banakou et al., 2018), and the scales "endurance" and "strength" of the Physisches Selbstkonzeptskalen (PSK, Stiller, Würth, & Alfermann, 2004). The questionnaire was programmed in and presented by PsychoPy.

The IPQ consists of the scales "spatial presence", "involvement", "experienced realism", and a general item and aims to measure these constructs for virtual environments. Each scale consists of four to five statements that are rated on a 7-point scale between −3 and 3, with different semantic anchors on either end. The general item is rated in the same way. The questionnaire aims to assess the subjective experience of feeling present in the virtual environment (Schubert et al., 2001), which affects the effectiveness of VR (Ijaz, Ahmadpour, Wang, & Calvo, 2020). It was applied to check for possible differences in presence ratings that may subsequently explain differences in the outcome measures between the conditions and among participants reporting different degrees of presence. The questionnaire has demonstrated acceptable validity, internal consistency, and sensitivity (Berkman & Catak, 2021; Hartmann et al., 2016). However, it is noteworthy that the items have been collected from existing questionnaires and that not all of them measure spatial presence (Hartmann et al., 2016).

The BRQ contains five statements on a 7-point scale between −3 and 3. The statements "I felt that the virtual body I saw when looking down at myself was my own body" and "I felt that the movements of the virtual body were caused by my own movements" were chosen to assess body ownership and agency (Banakou et al., 2018). They were translated into German. The main aim was to determine differences between the conditions. Body ownership was expected to remain stable across conditions as the avatar did not change. Visual flow speed differences could manifest in differing agency scores, which could then explain differences in the outcome measures.

The two subscales "strength" and "endurance" from the PSK were included to assess self-perception of fitness. They each contain five statements rated on a 4-point scale between 1 and 4 that are averaged to calculate the scale score (Stiller et al., 2004). These scales were chosen because they are crucial abilities for cycling performance. The items assessed whether visual flow speed affects postexercise self-perception, as has been found before (Kocur et al., 2021). An effect of visual flow on self-perceived fitness could underscore the impact on self-perception, even in the absence of changes in the outcome measures.

Table 1 provides an overview over all measures, material, and measurement times.

Procedure

Participants completed a 20-min cycling exercise on an ergometer (Cyclus2, RBM elektronik-automation GmbH, Leipzig, Germany). Resistance on the ergometer was kept constant at 60% of the estimated maximum power output throughout all three trials. Maximum power output was estimated from sex and body weight. For male participants, body weight (kg) was multiplied by 3, and for female participants by 2.5 to calculate the maximum power output in watts (from Fünten, Faude, Skorski, & Meyer, 2013). The pedaling cadence had to be kept above 50 rpm to ensure consistent workload while allowing individually comfortable pedaling frequencies.

All experimental trials were organized equally. First, participants completed the HDT on a desktop PC. Then, participants read through the instructions about the cycling task and were familiarized with the ASS and the Affect Grid. They were seated on the cycling ergometer at a comfortable saddle height and put on the HMD. The experimenter manually adjusted the virtual avatar's position so that the body moved realistically on the virtual bicycle. Visual flow speed was adjusted to the appropriate speed of the condition. When participants were ready to start, the virtual scene was initiated, and the first measures of heart rate, RPE, arousal, and valence were recorded. After completing the cycling exercise, participants removed the HMD and filled in the computerized questionnaire.

Table 1 Overview of all measurements		
Measure	**Material**	**Time**
Heartbeats & counted heartbeats (interoceptive sensitivity), confidence judgments (interoceptive awareness)	Custom-built optic heartbeat sensor, HDT (keyboard and continuous rating scale)	Before cycling
Heart rate	Chest strap sensor (Polar H10)	During cycling, at 0, 5, 10, 15, 20 min
Subjective effort	ASS (Büsch et al., 2022)	During cycling, at 0, 5, 10, 15, 20 min
Affect (arousal and affective valence)	German version of Affect Grid (Russell et al., 1989)	During cycling, at 0, 5, 10, 15, 20 min
Cadence	Ergometer (Cyclus2)	During cycling, at 5, 10, 15, 20 min
Presence	IPQ (Schubert et al., 2001)	After cycling
Body ownership and agency	"Body ownership" and "agency" scales of BRQ (Banakou et al., 2018)	After cycling
Self-perceived strength and endurance	"Strength" and "endurance" scales of PSK (Stiller et al., 2004)	After cycling

Analysis

The four outcome measures heart rate, RPE, arousal, and valence were analyzed regarding their differences between flow conditions. All independent variables were normalized to their mean before statistical analyses. Visual flow speed was scaled so that estimates correspond to 1 km/h speed differences. Interoceptive awareness and sensitivity were scaled to a range of 1 between their minimum and maximum, respectively. The first measure of every outcome variable was omitted from the dataset as it represented premanipulation data.

For statistical analyses, the lme4 package (Bates, Mächler, Bolker, & Walker, 2015) was used in R (R Core Team, 2012) to perform linear mixed effects analyses. The maximal models for each outcome measure included visual flow speed (condition), measurement time (measure), and trial time (trial) as fixed effects[1]. As random effects, intercepts for participants and random slopes for all within-subjects effects[2] were included. Random slopes were reduced stepwise following the procedure of Matuschek, Kliegl, Vasishth, Baayen, and Bates (2017). Complexity reductions were stopped when a likelihood ratio test with $p < 0.2$ indicated a loss in goodness of fit. Absolute estimates (including standard errors and 95% confidence intervals) were calculated for each model. Assumptions of normality, linearity, and homoscedasticity were checked visually. Subsequently, nonsignificant fixed effects, indicated by a likelihood ratio test with $p < 0.05$, were removed from the model. χ^2 and p-values for each fixed effect of interest were calculated by comparing a model containing the fixed effect of interest with a second model without this effect. In addition to the preregistered analyses, pairwise comparisons were calculated when visual inspection suggested a nonlinear effect of condition. For pairwise comparisons of conditions, no random slope for trial was included to avoid overparameterization and because the effect of trial would represent the randomized order of conditions. An exploratory analysis was executed for each outcome measure when a significant effect of condition was found. In these models, the interaction terms condition × interoceptive awareness or condition × sensitivity, respectively, replaced trial as a fixed effect. The procedure was analogous to the preregistered procedure.

To analyze the postexperimental questionnaires, mean scores of every scale were calculated for each trial. Mean values for each scale were then compared between conditions and trials by mixed linear models with fixed effects for condition and trial. A random intercept for participant and a random slope for condition were included. Awareness and sensitivity replaced trial as fixed effects to analyze their effects on presence scores by comparing the respective models with each other. All variables were centered and scaled in the same way as for the analysis of the outcome measures. Complexity reductions followed the previously described procedure.

For each model, absolute effect sizes, χ^2–, and p-values for significant effects are reported. Complete estimates, standard errors, confidence intervals, χ^2, and p-values are provided in tabular form as supplementary material.

[1] The preregistration stated that awareness and the interaction of awareness and condition would be included as fixed effects but the models were adapted to avoid overparameterization.

[2] In the preregistration, it was stated that random slopes would be used for all predictors but they can only be entered for within-subject effects.

Results

Heart rate

The model for heart rate analysis included fixed effects for measure, condition, and trial, random slopes for measure, condition and trial, and a random intercept for participants. The estimated intercept was 145.91 ± 1.70 beats per minute (bpm). Measure had a significant main effect on heart rate (5.50 ± 0.23 bpm, $\chi^2_{(1)} = 164.98$, $p < 0.001$), indicating an increase of heart rate between the individual recordings within a trial. Trial and condition had no significant main effect on heart rate. The absence of an effect of trial confirmed that objective effort was consistent in the three trials. The absence of an effect of condition was unexpected. However, visual inspection of heart rate in the different conditions (**Fig. 2**) suggested a nonlinear relationship of visual flow speed and heart rate. So, we repeated the analyses for split datasets containing only two conditions. Heart rate differed significantly between slow and medium flow conditions (−0.40 ± 0.16 bpm, $\chi^2_{(1)} = 5.90$, $p = 0.015$), underlining the nonlinear course of heart rate. The remaining pairwise comparisons (slow vs fast; medium vs fast) showed no significant differences. Because of the significant differences between slow and medium flow, explorative analyses were executed for this portion

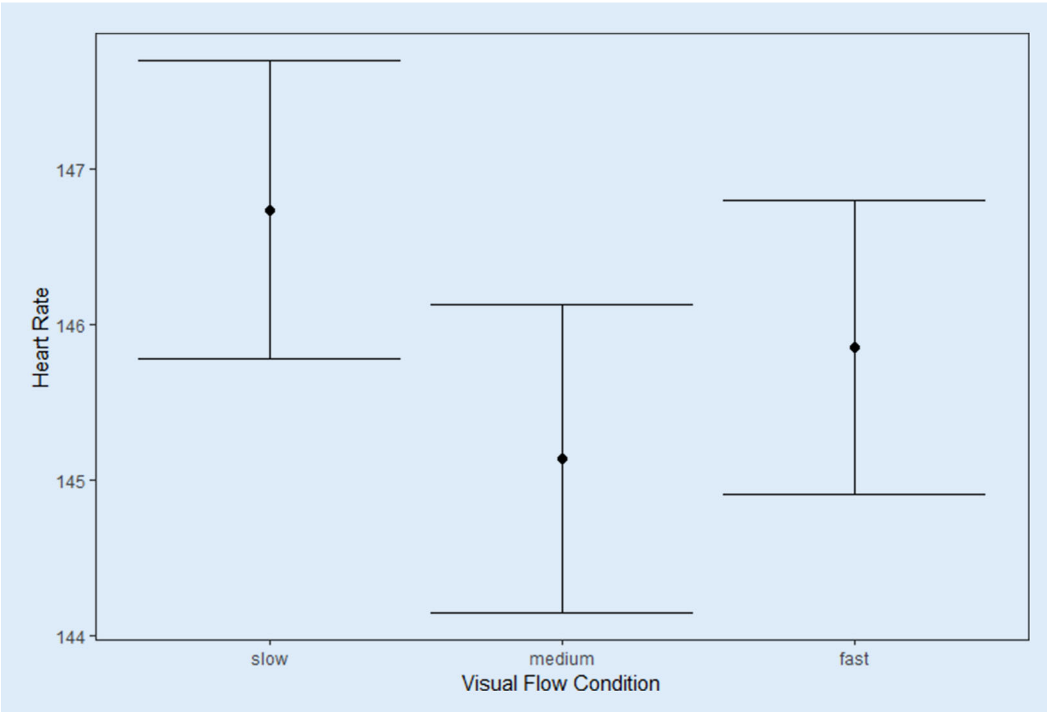

Fig. 2 ◀ Mean heart rate in the three visual flow conditions

of the data. Neither interaction term (condition × awareness; condition × sensitivity) had a significant effect on heart rate.

Subjective effort

The model for ratings of perceived exertion (RPE) analysis included fixed effects for measure, condition, and trial, random slopes for measure and condition, and a random intercept for participants. The estimated intercept was 5.17 ± 0.12. Measure had a significant main effect on RPE (0.67 ± 0.03, $\chi^2_{(1)} = 148.87$, $p < 0.001$), indicating an increase in subjective effort within trials. Trial had a significant main effect (-0.20 ± 0.05, $\chi^2_{(1)} = 14.10$, $p < 0.001$), suggesting a small training effect from trial to trial. Condition had no main effect on RPE, and visual inspection did not suggest a nonlinear relationship. Pairwise comparisons or exploratory analyses of the effect of interoceptive abilities were thus not calculated.

Affective states

Valence

The model for valence analysis included fixed effects for measure, condition, and trial, random slopes for measure and condition, and a random intercept for participants. The estimated intercept was 5.31 ± 0.13. Measure had a significant main effect on valence (-0.09 ± 0.04, $\chi^2_{(1)} = 4.53$, $p = 0.033$), indicating a decrease in pleasure within trials. Trial and condition had no significant main effects on valence. Visual inspection (**Fig. 3**) suggested a nonlinear relationship of visual flow speed and valence, so we repeated the analyses for split datasets containing only two conditions. Condition had no significant effect in either analysis. Explorative analyses were not calculated.

Arousal

The model for arousal analysis included fixed effects for measure, condition, and trial, random slopes for measure and condition, and a random intercept for participant. The estimated intercept was 5.95 ± 0.11. Measure had a significant main effect on arousal (0.20 ± 0.04, $\chi^2_{(1)} = 25.68$, $p < 0.001$), indicating an increase in arousal within trials. Trial had a significant main effect (-0.17 ± 0.08, $\chi^2_{(1)} = 5.39$, $p = 0.020$), suggesting a reduction of arousal from trial to trial. Condition had no significant main effect on arousal. Visual inspection (see **Fig. 4**) suggested a nonlinear relationship of visual flow speed and arousal, so we repeated the analyses for split datasets containing only two conditions. Condition had no significant effect in either analysis. Explorative analyses were not calculated.

Interoception

Because condition had no significant effect on most variables, the impact of interoception on this relation was investigated only for heart rate during slow and medium visual flow. However, neither interaction term (condition × interoceptive awareness; condition × sensitivity) was significant.

Postexperimental questionnaires

Physical self-concept

Both scale scores of the PSK were calculated by averaging all answers of the respective scale. Condition had no significant effect on either scale. Both scale scores increased over the three trials (strength: 0.05 ± 0.02, $\chi^2_{(1)} = 10.33$, $p = 0.001$; endurance: 0.07 ± 0.02, $\chi^2_{(1)} = 15.63$, $p < 0.001$), suggesting a training effect on self-perceived fitness. However, the estimates are of small absolute value regarding the scale steps of the PSK.

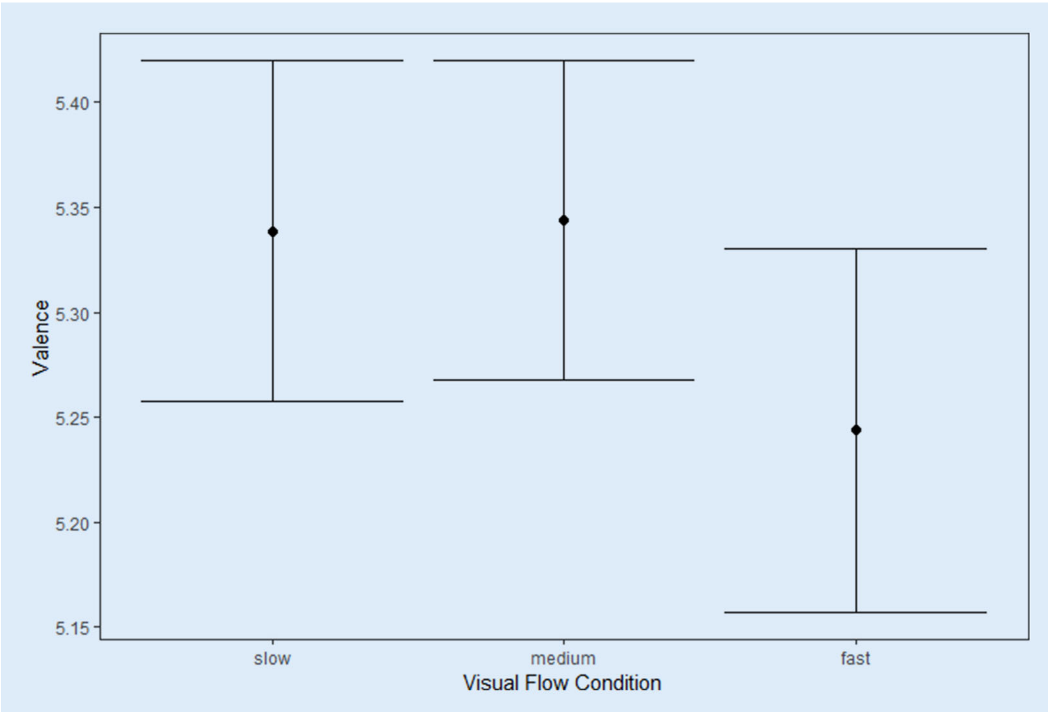

Fig. 3 ◀ Mean valence in the three visual flow conditions

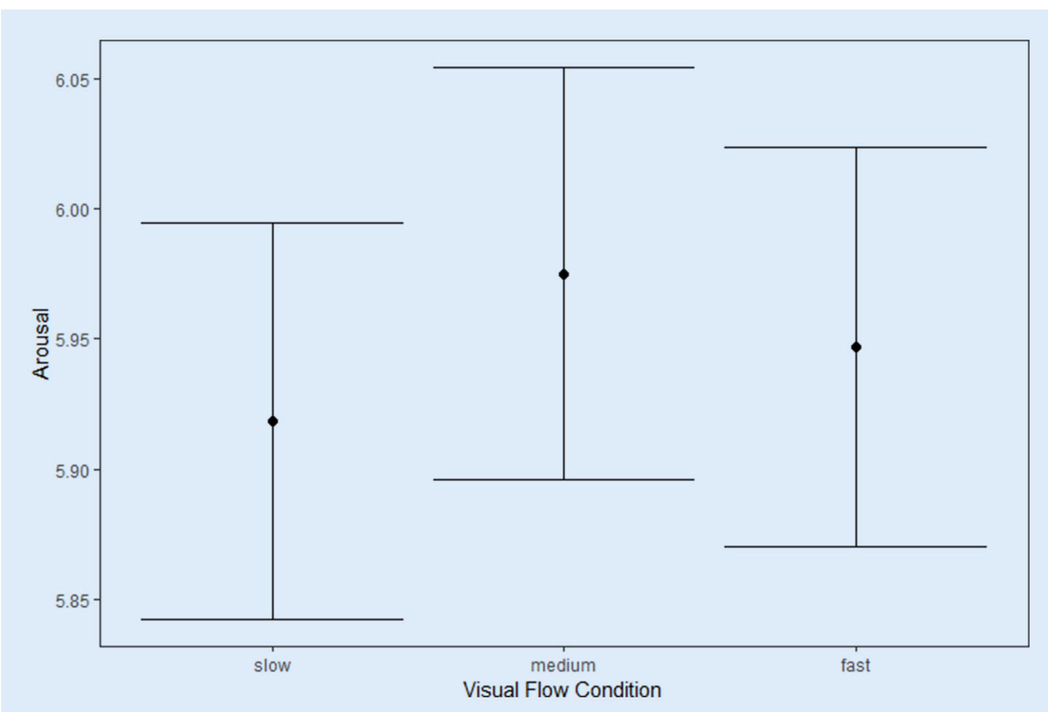

Fig. 4 ◀ Mean arousal in the three visual flow conditions

Presence

The score for the presence scale of the IPQ was calculated by averaging the items of the spatial presence scale and the general item. Condition, awareness, and sensitivity had no significant effect on presence, but presence decreased over the three trials (-0.20 ± 0.04, $\chi^2_{(1)} = 21.70$, $p < 0.001$).

Body ownership and agency

Analysis of agency revealed no significant effects of condition or trial. Trial had a significant main effect on body ownership (-0.20 ± 0.10, $\chi^2_{(1)} = 4.17$, $p = 0.041$), suggesting a reduction over time.

Discussion

Statistical analyses revealed no significant effect of visual flow speed on the measured variables except for heart rate between slow and medium visual flow. Descriptively, no difference or a bidirectional change from medium to fast or slow visual flow was observed, contradicting our hypotheses. Further, interoception did not significantly affect differences evoked by visual flow speed. As the subjective measures and postexperimental questionnaires indicate, the three experimental trials were not perceived as substantially different experiences. Heightened self-perception of fitness induced by avatar manipulations (Kocur et al., 2021) could not be evoked by visual flow speed. Theories on body ownership illusions suggest that the embodiment of the avatar affects self-perception (Yee et al., 2009) and that body ownership and agency are closely related concepts (Braun et al., 2018). Nonetheless, the present agency illusion did not evoke similar effects as avatar manipulations.

Visual flow and heart rate

The primary statistical model for heart rate revealed a significant effect of measure, indicating an increasing heart rate throughout a trial, which corresponds to a usual increase in heart rate during prolonged exercise, the cardiovascular drift (Coyle & González-Alonso, 2001). The expected decrease in heart rate with increasing visual flow speed was not visible in the present data. Visual inspection revealed a nonlinear relationship between visual flow speed and heart rate, meaning that heart rate was higher in both diverging conditions compared to medium speed. This difference was only significant for medium and slow speeds, partly confirming our hypothesis but contradicting our assumption of a linear decrease with increasing visual flow speed. It suggests that any visual input deviating from medium speed elevates heart rate. This result is similar to findings in walking studies showing bidirectional changes of gait parameters for isometric and nonisometric visual flow speed mappings (Janeh et al., 2017). However, visual flow speed in the present study was not matched to the actual cycling. In contrast to walking, cycling speed is not easily transferred from ergometer to outdoor cycling. Although resistance differed between participants, intensity was comparable. The main aim was to investigate the influence of different speeds, not the influence of nonisometric speed gains. Thus, 20 km/h was considered a moderate speed matching the moderate resistance. The estimated differences in heart rate were only significant for slow and medium speeds and very small. Due to the different resistances, participants may have perceived different visual flow speeds as matching. This should have been assessed in the postexperimental questionnaire. Although a 20% difference between conditions was considered adequate (Kocur et al., 2021), more significant speed differences should be applied in future studies to investigate the context further.

Visual flow and subjective effort

Perceived effort increased over the course of a trial, corresponding to the physiological effort depicted by increasing heart rate. The significant effect of trial indicates a small but practically meaningless training effect for subjective effort, considering the scale steps of the ASS. Visual flow speed did not significantly affect subjective effort, contradicting our hypothesis and previous findings (Parry et al., 2012). This might be due to the small speed differences, as mentioned above. Furthermore, it remains unclear whether the participants detected the speed differences. It can be argued that the manipulation has to be more pronounced to find effects like Kocur et al. (2021) or Parry et al. (2012), who compared the effects of different configurations in one trial. The comparison with avatar effects may also lack substance because the athleticism of the avatar is far more explicit than the visual flow speed differences.

Although differently expected, the observed steady subjective effort can be interpreted as facilitating exercise, considering the altered heart rate. Assuming a more significant effect for larger speed differences, a heart rate elevation without increased subjective effort during slower visual flow would enable greater training effects without changing objective exercise intensity.

Visual flow and affective states

Valence significantly decreased throughout a trial. However, the absolute estimate is of irrelevant practical value, considering the scale steps of the Affect Grid. Our hypothesis that valence was more positive during fast flow and more negative during slow flow could not be confirmed. Valence was generally rated as medium, implying that the task was neither pleasurable nor unpleasurable. Flow velocity did not impact this perception, contradicting previous findings about greater pleasure during fast flow (Yasukawa et al., 2021). However, the present exercise had a much longer duration, possibly affecting feeling states differently. Other impressions might have overlapped with flow-induced pleasure, eventually evening each other out. These could be physical strain, boredom, or superordinate emotions.

Arousal significantly increased throughout a trial, which matches increasing effort. Trial time had a significant effect, suggesting a small time-effect for arousal. Visual flow speed did not affect arousal ratings. Similar to valence, arousal ratings may be based on very diverse perceptions.

Although our primary hypotheses could not be confirmed, the present results indicate that objective exercise parameters (heart rate) can be altered by manipulating visual flow speed without affecting subjective experience, which may be helpful in exercise contexts. Similar to perceived effort, maintaining valence and arousal levels while reaching higher heart rates during slower visual flow could help achieve training goals without producing more unpleasant affective states.

The role of interoception

Interoceptive abilities have not been found to impact the effect of visual flow velocity on the outcome measures in the present sample. This could imply that interoception does not shield from such illusions, as was expected following research about bodily illusions (Tsakiris et al., 2011). On the other hand, no main effect of visual flow speed was found in the first place. Interoception was expected to moderate the effects of visual flow speed, which is associated with smaller effect sizes. Consequently, the present sample size may have failed to reach sufficient power to detect these effects.

Although the heartbeat detection task is a commonly used task to investigate interoceptive abilities, the calculated measures have come under criticism for their lack of correlation with qualitative measures of interoception (Garfinkel et al., 2015). Further, it remains unequivocal whether proprioception falls into the concept of interoception (Herbert, Pollatos, & Klusmann, 2020). As leg muscle exhaustion is one factor predicting performance during cycling (Abbiss & Laursen, 2005), the perception of muscular tension may be more critical than heartbeat perception during such exercise. Furthermore, the ability to perceive internal signals does not necessarily imply a more internal focus during exercise. As of the importance of attentional focus for subjective ratings during exercise (Emad, Neumann, & Abel, 2017), it may be a more suitable moderator of virtual illusion effects.

Limitations

The present results are limited chiefly by their low absolute values. Further, oral reports from participants suggest that the virtual scene was boring and too monotonous. The scene was programmed to seem realistic without being too exciting, to prevent participants from looking around too much. Although this was achieved, boredom induced by the monotony of the scene could have affected the outcome measures. The simplicity of the scene may have also impeded immersion into the virtual reality. However, due to the within-subject design, the impact of low immersion should be balanced out between the conditions. Furthermore, visual flow speed was independent of pedaling cadence. Participants with a greater variance in cadence throughout a trial possibly noticed this independence and likely felt low agency for the virtual movement speed. A restriction of cadence may resolve this issue. It remains unclear whether medium visual flow speed was perceived as such and whether speed differences were large enough. Future studies should include more significant differences and an assessment of speed perception.

Conclusion

The present study identified hints to a relation between visual flow speed and physiological effort when cycling at a constant load in virtual reality. Larger and more explicit speed differences could evoke significant effects. Furthermore, albeit contradictory to our expectations, the present results suggest that virtual movement speed impacted objective exertion without affecting subjective exercise experience. The diverging effects on heart rate and the subjective measures allow for assumptions that visual flow speed manipulations may be useful in exercise management and facilitation.

The relation between interoception and the effects of manipulated performance output remains unclear. A more thorough differentiation of the different interoceptive abilities and their relation to attentional focus seems relevant for resolving this uncertainty.

The present study is one of few studies investigating visual flow speed in aerobic exercise, which made comparing and discussing the results an intricate process. However, first steps were made to identify the usability of visual flow speed manipulations in virtual reality-based exercise contexts. Subsequent experiments should take methodological limitations into account.

Corresponding address

Carla Luttmann
Faculty of Human Sciences, University of Regensburg
Universitätsstraße 31, 93053 Regensburg, Germany
carla.luttmann@ur.de

Funding. Manuel Mayer was supported by the UR Fellows program.

Author Contribution. Carla Luttmann: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing—Original Draft, Writing—Review & Editing. Manuel Mayer: Software, Writing—Review & Editing. Markus Siebertz: Software, Formal analysis, Resources. Leonardo Jost: Conceptualization, Formal analysis, Writing—Review & Editing. Niels Henze: Software, Resources, Writing—Review & Editing. Petra Jansen: Conceptualization, Writing—Review & Editing, Supervision.

Funding. Open Access funding enabled and organized by Projekt DEAL.

Declarations

Conflict of interest. C. Luttmann, M. Mayer, M. Siebertz, L. Jost, N. Henze and P. Jansen declare that they have no competing interests.

All experimental procedures were in accordance with the Declaration of Helsinki, and all participants provided informed consent. For this article no studies with animals were performed by any of the authors. All studies mentioned were in accordance with the ethical standards indicated in each case.

References

Abbiss, C. R., & Laursen, P. B. (2005). Models to explain fatigue during prolonged endurance cycling. *Sports Medicine*, *35*(10), 865–898. https://doi.org/10.2165/00007256-200535100-00004.

Banakou, D., & Slater, M. (2017). Embodiment in a virtual body that speaks produces agency over the speaking but does not necessarily influence subsequent real speaking. *Scientific Reports*, *7*(1), 14227. https://doi.org/10.1038/s41598-017-14620-5.

Banakou, D., Kishore, S., & Slater, M. (2018). Virtually being einstein results in an improvement in cognitive task performance and a decrease in age bias. *Frontiers in Psychology*, *9*, 917. https://doi.org/10.3389/fpsyg.2018.00917.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*. https://doi.org/10.18637/jss.v067.i01.

Berkman, M. I., & Catak, G. (2021). I-group presence questionnaire: psychometrically revised english version. *Mugla Journal of Science and Technology*, *7*(0), 1–10. https://doi.org/10.22531/muglajsci.882271.

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

14(5), 377–381. https://doi.org/10.1249/00005768-198205000-00012.
Braun, N., Debener, S., Spychala, N., Bongartz, E., Sörös, P., Müller, H. H. O., & Philipsen, A. (2018). The senses of agency and ownership: a review. *Frontiers in Psychology*, *9*, 535. https://doi.org/10.3389/fpsyg.2018.00535.
Burin, D., Pyasik, M., Ronga, I., Cavallo, M., Salatino, A., & Pia, L. (2018). "as long as that is my hand, that willed action is mine": timing of agency triggered by body ownership. *Consciousness and Cognition*, *58*, 186–192. https://doi.org/10.1016/j.concog.2017.12.005.
Büsch, D., Utesch, T., & Marschall, F. (2022). Entwicklung und Evaluation der Anstrengungsskala Sport. *German Journal of Exercise and Sport Research*, *52*(1), 173–178. https://doi.org/10.1007/s12662-021-00757-z.
Cao, L., Peng, C., & Dong, Y. (2021). Ellic's Exercise Class: promoting physical activities during exergaming with immersive virtual reality. *Virtual Reality*, *25*(3), 597–612. https://doi.org/10.1007/s10055-020-00477-z.
Coyle, E. F., & González-Alonso, J. (2001). Cardiovascular drift during prolonged exercise: new perspectives. *Exercise and Sport Sciences Reviews*, *29*(2), 88–92. https://doi.org/10.1097/00003677-200104000-00009.
Czub, M., & Janeta, P. (2021). Exercise in virtual reality with a muscular avatar influences performance on a weightlifting exercise. *Cyberpsychology: Journal of Psychosocial Research on Cyberspace*. https://doi.org/10.5817/CP2021-3-10.
Di Fronso, S., Aquino, A., Bondár, R. Z., Montesano, C., Robazza, C., & Bertollo, M. (2020). The influence of core affect on cyclo-ergometer endurance performance: Effects on performance outcomes and perceived exertion. *Journal of Sport and Health Science*, *9*(6), 578–586. https://doi.org/10.1016/j.jshs.2019.12.004.
Ekkekakis, P. (2003). Pleasure and displeasure from the body: perspectives from exercise. *Cognition & Emotion*, *17*(2), 213–239. https://doi.org/10.1080/02699930302292.
Ekkekakis, P. (2009). The Dual-Mode Theory of affective responses to exercise in metatheoretical context: I. Initial impetus, basic postulates, and philosophical framework. *International Review of Sport and Exercise Psychology*, *2*(1), 73–94. https://doi.org/10.1080/17509840802705920.
Emad, M., Neumann, D. L., & Abel, L. (2017). Attentional focus strategies used by regular exercisers and their relationship with perceived exertion, enjoyment, and satisfaction. *Journal of Human Sport and Exercise*. https://doi.org/10.14198/jhse.2017.121.09.
Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*power 3.1: tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149.
aus der Fünten, K., Faude, O., Skorski, S., & Meyer, T. (2013). Sportmedizin. In A. Güllich & M. Krüger (Eds.), *Sport* (pp. 171–210). Springer. https://doi.org/10.1007/978-3-642-37546-0_7.
Gallagher, S. (2000). Philosophical conceptions of the self: implications for cognitive science. *Trends in Cognitive Sciences*, *4*(1), 14–21. https://doi.org/10.1016/S1364-6613(99)01417-5.
Garfinkel, S. N., Seth, A. K., Barrett, A. B., Suzuki, K., & Critchley, H. D. (2015). Knowing your own heart: distinguishing interoceptive accuracy from interoceptive awareness. *Biological Psychology*, *104*, 65–74. https://doi.org/10.1016/j.biopsycho.2014.11.004.
Hartmann, T., Wirth, W., Schramm, H., Klimmt, C., Vorderer, P., Gysbers, A., Böcking, S., Ravaja, N., Laarni, J., Saari, T., Gouveia, F., & Sacau, M. A. (2016). The Spatial Presence Experience Scale (SPES). *Journal of Media Psychology*, *28*(1), 1–15. https://doi.org/10.1027/1864-1105/a000137.
Herbert, B. M., Ulbrich, P., & Schandry, R. (2007). Interoceptive sensitivity and physical effort: Implications for the self-control of physical load in everyday life. *Psychophysiology*, *44*(2), 194–202. https://doi.org/10.1111/j.1469-8986.2007.00493.x.
Herbert, B. M., Pollatos, O., & Klusmann, V. (2020). Interoception and Health. *European Journal of Health Psychology*, *27*(4), 127–131. https://doi.org/10.1027/2512-8442/a000064.
Hutchinson, J. C., Sherman, T., Martinovic, N., & Tenenbaum, G. (2008). The effect of manipulated self-efficacy on perceived and sustained effort. *Journal of Applied Sport Psychology*, *20*(4), 457–472. https://doi.org/10.1080/10413200802351151.
Ijaz, K., Ahmadpour, N., Wang, Y., & Calvo, R. A. (2020). Player Experience of Needs Satisfaction (PENS) in an Immersive Virtual Reality Exercise Platform Describes Motivation and Enjoyment. *International Journal of Human–Computer Interaction*, *36*(13), 1195–1204. https://doi.org/10.1080/10447318.2020.1726107.
Janeh, O., Langbehn, E., Steinicke, F., Bruder, G., Gulberti, A., & Poetter-Nerger, M. (2017). Walking in virtual reality: effects of manipulated visual self-motion on walking biomechanics. *ACM Transactions on Applied Perception*, *14*(2), 1–15. https://doi.org/10.1145/3022731.
Jones, L., Karageorghis, C. I., & Ekkekakis, P. (2014). Can high-intensity exercise be more pleasant? Attentional dissociation using music and video. *Journal of Sport and Exercise Psychology*, *36*(5), 528–541. https://doi.org/10.1123/jsep.2013-0251.
Kocur, M., Kloss, M., Schwind, V., Wolff, C., & Henze, N. (2020). Flexing muscles in virtual reality: effects of avatars' muscular appearance on physical performance. In P. Mirza-Babaei, V. McArthur, V. Vanden Abeele & M. Birk (Eds.), *Proceedings of the annual symposium on computer-human interaction in play* (pp. 193–205). ACM. https://doi.org/10.1145/3410404.3414261.
Kocur, M., Habler, F., Schwind, V., Woźniak, P. W., Wolff, C., & Henze, N. (2021). Physiological and perceptual responses to athletic avatars while cycling in virtual reality. In Y. Kitamura, A. Quigley, K. Isbister, T. Igarashi, P. Bjørn & S. Drucker (Eds.), *Proceedings of the 2021 CHI conference on human factors in computing systems* (pp. 1–18). ACM. https://doi.org/10.1145/3411764.3445160.
Ligeza, T. S., Nowak, I., Maciejczyk, M., Szygula, Z., & Wyczesany, M. (2021). Acute aerobic exercise enhances cortical connectivity between structures involved in shaping mood and improves self-reported mood: an EEG effective-connectivity study in young male adults. *International Journal of Psychophysiology*, *162*, 22–33. https://doi.org/10.1016/j.ijpsycho.2021.01.016.
Ludwig, C. J. H., Alexander, N., Howard, K. L., Jedrzejewska, A. A., Mundkur, I., & Redmill, D. (2018). The influence of visual flow and perceptual load on locomotion speed. *Attention, Perception & Psychophysics*, *80*(1), 69–81. https://doi.org/10.3758/s13414-017-1417-3.
Lyons, E. J., Tate, D. F., Ward, D. S., Ribisl, K. M., Bowling, J. M., & Kalyanaraman, S. (2014). Engagement, enjoyment, and energy expenditure during active video game play. *Health Psychology*, *33*(2), 174–181. https://doi.org/10.1037/a0031947.
Matuschek, H., Kliegl, R., Vasishth, S., Baayen, H., & Bates, D. (2017). Balancing Type I error and power in linear mixed models. *Journal of Memory and Language*, *94*, 305–315. https://doi.org/10.1016/j.jml.2017.01.001.
Mestre, D. R., Ewald, M., & Maiano, C. (2011). Virtual reality and exercise: behavioral and psychological effects of visual feedback. *Studies in Health Technology and Informatics*, *167*, 122–127.
Mouatt, B., Smith, A. E., Mellow, M. L., Parfitt, G., Smith, R. T., & Stanton, T. R. (2020). The use of virtual reality to influence motivation, affect, enjoyment, and engagement during exercise: a scoping review. *Frontiers in Virtual Reality*, *1*, 564664. https://doi.org/10.3389/frvir.2020.564664.
Neumann, D. L., & Moffitt, R. L. (2018). Affective and attentional states when running in a virtual reality environment. *Sports*. https://doi.org/10.3390/sports6030071.
Ng, Y.-L., Ma, F., Ho, F. K., Ip, P., & Fu, K. (2019). Effectiveness of virtual and augmented reality-enhanced exercise on physical activity, psychological outcomes, and physical performance: a systematic review and meta-analysis of randomized controlled trials. *Computers in Human Behavior*, *99*, 278–291. https://doi.org/10.1016/j.chb.2019.05.026.
Parry, D., Chinnasamy, C., & Micklewright, D. (2012). Optic flow influences perceived exertion during cycling. *Journal of Sport and Exercise Psychology*, *34*(4), 444–456. https://doi.org/10.1123/jsep.34.4.444.
Peirce, J. W., Gray, J. R., Simpson, S., MacAskill, M. R., Höchenberger, R., Sogo, H., Kastman, E., Lindeløv, J. (2019). PsychoPy2: experiments in behavior made easy. *Behavior Research Methods*. https://doi.org/10.3758/s13428-018-01193-y.
Pennebaker, J. W., & Lightner, J. M. (1980). Competition of internal and external information in an exercise setting. *Journal of Personality and Social Psychology*, *39*(1), 165–174. https://doi.org/10.1037/0022-3514.39.1.165.
Perri, M. G., Anton, S. D., Durning, P. E., Ketterson, T. U., Sydeman, S. J., Berlant, N. E., Kanasky, W. F., Newton, R. L., Limacher, M. C., & Martin, A. D. (2002). Adherence to exercise prescriptions: Effects of prescribing moderate versus higher levels of intensity and frequency. *Health Psychology*, *21*(5), 452–458. https://doi.org/10.1037/0278-6133.21.5.452.
Plante, T. G., Aldridge, A., Bogden, R., & Hanelin, C. (2003). Might virtual reality promote the mood benefits of exercise? *Computers in Human Behavior*, *19*(4), 495–509. https://doi.org/10.1016/S0747-5632(02)00074-2.
Pollatos, O., Kirsch, W., & Schandry, R. (2005). Brain structures involved in interoceptive awareness and cardioafferent signal processing: a dipole source localization study. *Human Brain Mapping*, *26*(1), 54–64. https://doi.org/10.1002/hbm.20121.
Ponzo, S., Morelli, D., Suksasilp, C., Cairo, M., & Plans, D. (2021). Measuring Interoception: the CARdiac Elevation Detection Task. *Frontiers in Psychology*, *12*, 712896. https://doi.org/10.3389/fpsyg.2021.712896.

Pretto, P., & Chatziastros, A. (2006). Changes in optic flow and scene contrast affect the driving speed. In *Driving simulation conference europe (DSC europe 2006)* (pp. 263–272).

Privitera, G. J., Antonelli, D. E., & Szal, A. L. (2014). An enjoyable distraction during exercise augments the positive effects of exercise on mood. *Journal of Sports Science & Medicine*, *13*(2), 266–270.

Pyasik, M., Furlanetto, T., & Pia, L. (2019). The role of body-related afferent signals in human sense of agency. *Journal of Experimental Neuroscience*. https://doi.org/10.1177/1179069519849907.

Rejeski, W. J. (1985). Perceived exertion: an active or passive process? *Journal of Sport Psychology*, *7*(4), 371–378. https://doi.org/10.1123/jsp.7.4.371.

Rhodes, R. E., Warburton, D. E. R., & Bredin, S. S. D. (2009). Predicting the effect of interactive video bikes on exercise adherence: an efficacy trial. *Psychology, Health & Medicine*, *14*(6), 631–640. https://doi.org/10.1080/13548500903281088.

Russell, J. A., Weiss, A., & Mendelsohn, G. A. (1989). Affect grid: a single-item scale of pleasure and arousal. *Journal of Personality and Social Psychology*, *57*(3), 493–502. https://doi.org/10.1037/0022-3514.57.3.493.

Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The experience of presence: factor analytic insights. *Presence: Teleoperators and Virtual Environments*, *10*(3), 266–281. https://doi.org/10.1162/105474601300343603.

Stephens, R., & Smith, M. (2022). Effect of speed on flow and enjoyment for driving and rollercoasters. *Transportation Research Part F: Traffic Psychology and Behaviour,*, *85*, 276–286. https://doi.org/10.1016/j.trf.2022.02.001.

Stiller, J., Würth, S., & Alfermann, D. (2004). Die Messung des physischen Selbstkonzepts (PSK). *Zeitschrift für Differentielle und Diagnostische Psychologie*, *25*(4), 239–257. https://doi.org/10.1024/0170-1789.25.4.239.

Tsakiris, M., Tajadura-Jiménez, A., & Costantini, M. (2011). Just a heartbeat away from one's body: Interoceptive sensitivity predicts malleability of body-representations. *Proceedings. Biological Sciences*, *278*(1717), 2470–2476. https://doi.org/10.1098/rspb.2010.2547.

Wienke, B., & Jekauc, D. (2016). A qualitative analysis of emotional facilitators in exercise. *Frontiers in Psychology*, *7*, 1296. https://doi.org/10.3389/fpsyg.2016.01296.

Williams, D. M. (2008). Exercise Affect and Adherence: An Integrated Model and a Case for Self-Paced Exercise. *Journal of Sport and Exercise Psychology*, *30*(5), 471–496. https://doi.org/10.1123/jsep.30.5.471.

Wininger, S. R. (2007). Improvement of affect following exercise: methodological artifact or real finding? *Anxiety, Stress, and Coping*, *20*(1), 93–102. https://doi.org/10.1080/10615800601170540.

Yasukawa, K., Koike, Y., Konno, T., Sudo, M., Ohkawara, K., & Ando, S. (2021). Effects of visual flow alterations on Psychophysiological responses to virtual reality exercise. *Perceptual and Motor Skills*, *128*(3), 1169–1182. https://doi.org/10.1177/00315125211000861.

Yee, N., & Bailenson, J. (2007). The proteus effect: the effect of transformed self-representation on behavior. *Human Communication Research*, *33*(3), 271–290. https://doi.org/10.1111/j.1468-2958.2007.00299.x.

Yee, N., Bailenson, J. N., & Ducheneaut, N. (2009). The proteus effect: implications of transformed digital self-representation on online and offline behavior. *Communication Research*, *36*(2), 285–312. https://doi.org/10.1177/0093650208330254.

Zeng, N., Pope, Z., & Gao, Z. (2017). Acute effect of virtual reality exercise bike games on college students' physiological and psychological outcomes. *Cyberpsychology, Behavior and Social Networking*, *20*(7), 453–457. https://doi.org/10.1089/cyber.2017.0042.

Publisher's Note. Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.