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Heart rate changes with visual flow speed in virtual reality cycling

Carla Luttmann *, Petra Jansen

Faculty of Human Sciences, University of Regensburg, Regensburg, Germany

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ABSTRACT

Virtual reality has emerged as a helpful tool in exercise facilitation and performance enhancement. As a highly immersive medium, it enables diversion of attention, embodiment of virtual avatars, and display of false performance feedback. These mechanisms can reduce strain, improve affective responses, and influence behaviour or performance. While the role of avatar design in these relations has been extensively studied, other areas of virtual reality require further investigation. Especially scene configurations bear the potential to enable realistic first-person scenarios of exercise, for instance, by showing action feedback such as visual flow during locomotion. The present study aims to investigate the impact of unmatching visual flow speed on heart rate and subjective effort during moderate intensity cycling in virtual reality. Both were expected to decrease with increasing visual flow speed. Eighty university sports students cycled at a self-chosen cadence for ten minutes, viewing a virtual cycling track at one of two velocities (0.5*actual speed or 1.5*actual speed). Each participant experienced both velocity conditions in counterbalanced order. Heart rate and perceived exertion were recorded continuously. Linear mixed model analyses revealed a significant main effect of visual flow speed on heart rate but not on perceived exertion. This suggests a dissociation between physiological and perceived effort, which calls for future research to identify the specific sources of effort ratings.

1. Introduction

Research increasingly shows that exercise performed in virtual reality (VR) or game-based settings can enhance the overall workout experience. Compared to conventional exercise, participants often report greater enjoyment, engagement, and even improved performance when exercising with video games or immersive technologies (Cao et al., 2021; Dębska et al., 2019; Kraft et al., 2011; Lyons et al., 2014; Mestre et al., 2011; Warburton et al., 2009; Yao and Kim, 2019). These benefits are frequently linked to the distractive qualities of interactive environments, gamification elements, or the motivational impact of avatar design (Li et al., 2014; Peña et al., 2016) and make VR attractive for applications in recreational and professional exercise, physical therapy, and injury rehabilitation. To determine VR's practical usability, various mechanisms—ranging from perceptual illusions to avatar design—have been investigated. One key element in this context is action feedback, which can shape the sense of agency, self-efficacy, and perceived exertion during exercise.

Recent work extends beyond visual feedback and avatars to active augmentation of exertion through sensor-based systems. For instance, Andres et al. (2018) introduced body-controlled e-bike acceleration with sound augmentation as a playful medium to enhance speed sensations and exertion experiences. Similarly, Andres et al. (2020) developed Ena: the EEG-eBike, which monitors peripheral awareness via EEG to dynamically regulate engine support in exertion contexts. Additionally, recent proposals highlight the importance of further studying Proteus effects in VR as a means of facilitating exertion engagement through embodiment (Czub and Janeta, 2021).

1.1. Related work

1.1.1. Exercise in VR

Numerous studies have explored VR as a tool to improve exercise experiences. Plante et al. (2003) demonstrated that VR-enhanced workouts were perceived as more enjoyable compared to traditional exercise. A unique strength of VR is its capacity to draw attention away from internal bodily sensations, fostering a dissociative focus that can lessen the perception of effort. For instance, in cycling contexts, VR immersion has been shown to positively influence subjective strain and persistence (Mestre et al., 2011; Wender et al., 2022). Beyond reducing discomfort, VR has also been applied to skill learning and pacing strategy development, with evidence suggesting it can help participants

* Corresponding author at: Faculty of Human Sciences, University of Regensburg, Universitätsstraße 31 93053 Regensburg, Germany.
E-mail address: carla.luttmann@ur.de (C. Luttmann).

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acquire motor skills (Kilteni et al., 2013; Pastel et al., 2023), manage pacing (Hoffmann et al., 2014), and increase physical output (McClure and Schofield, 2020).

Several studies demonstrate that virtual representations of training partners, coaches, or opponents can meaningfully influence both subjective and physiological outcomes. For example, displaying virtual coaches or competitors has been linked to changes in effort regulation and motivation (Mestre et al., 2011; Mouatt et al., 2020). Manipulated action feedback provides another powerful tool: Parry et al. (2012) showed that altering visual flow during cycling time trials influenced both performance and perceived exertion. Likewise, Matsangidou et al. (2017) manipulated virtual weight in a strength task, finding extended endurance and reduced pain when the displayed weights appeared lighter than reality. Wender et al. (2022) further reported that VR environments can support higher exercise intensities despite increased muscle pain, especially when perceptual load is kept low.

Such findings highlight VR's versatility: it not only offers engaging and enjoyable exercise contexts but also enables controlled manipulations of perception and feedback that directly affect physical performance. This capacity makes VR a promising tool for both enhancing recreational exercise and informing applied research on the psychology and physiology of effort.

Parallel work outside VR has similarly leveraged augmentation to improve exertion experiences. For example, the body-controlled eBike project showed how combining whole-body control with sound feedback amplified perceived acceleration and enjoyment during cycling (Andres et al., 2018). Although not VR-based, such findings highlight the potential of multimodal feedback mechanisms to shape effort perception.

1.1.2. Embodiment of virtual avatars

Until now, a lot of research on VR-based exercise has focused on the effects of avatar design. As a graphical representation of the user (O'Connor, 2019), the avatar's appearance can affect user behaviour and attitude (Yee et al., 2009). When the avatar is perceived as the representation of the user, the virtual body is embodied, and the user adopts its inferred abilities (*Proteus Effect,* Yee et al., 2009).

The Proteus Effect describes how avatar characteristics can alter users' behaviour and self-perceptions (Yee et al., 2009). For instance, athletic-looking avatars can enhance perceived physical ability and performance (Kocur et al., 2021). In their study, participants cycling with more athletic avatars exhibited higher heart rates and lower perceived exertion. Similarly, congruent avatar movements improve spatial judgments, such as distance estimation (Mohler et al., 2010).

Embodiment is not limited to body ownership but extends to the sense of agency (Gallagher, 2000), i.e., the feeling of authorship over one's actions and their consequences. Agency illusions can be induced by altering sensory outcomes (Burin et al., 2018), which in turn can influence self-efficacy and task appraisal. For example, Hutchinson et al. (2008) showed that manipulated action feedback in an isometric task increased self-efficacy, leading to lower perceived effort and greater enjoyment. This highlights how VR-induced agency illusions may be harnessed to influence exercise experiences. Recent perspectives suggest that Proteus effects should be studied more deeply in the context of exertion engagement in VR (Czub and Janeta, 2021).

1.1.3. Action feedback in VR

Action feedback during locomotion can not only be induced through the avatar design but also by manipulating the *visual* or *optic flow* (Pretto and Chatziastros, 2006). Visual flow is the visible speed of the environment moving toward the actor during self-motion (Warren and Hannon, 1988). Due to its circular expansion from where the movement is headed (the focus of expansion, FOE) towards the periphery, visual flow close to the FOE is slower. In comparison, lamellar (peripheral) visual flow is faster (Bornstein and Gibson, 1980). Consequently, gaze direction substantially affects speed perception based on visual flow. In fact, speed estimations based on lamellar flow are more accurate (Banton et al., 2005; Campos et al., 2007).

Visual flow also directly relates to the devoted effort and enables immediate speed and balance control. For instance, the presentation of visual flow that does not match actual walking speed typically elicits compensational movements, such as adaptations of stride length or frequency (Ludwig et al., 2018). Furthermore, Zadra and Proffitt (2016) demonstrated the relation between effort (the energy to walk) and visual flow, showing that the effort and not the walking speed influences the visual-motor calibration between locomotion and visual flow.

Research on walking in VR has confirmed these principles. Janeh et al. (2017) manipulated optic flow during treadmill walking and found that changes in visual flow velocity influenced gait speed and locomotor adjustments, underlining the importance of visual flow for speed control. Similarly, Pretto and Chatziastros (2006) used driving simulations to examine optic flow and showed that discrepancies between actual speed and perceived flow led participants to adapt their driving behavior, highlighting the central role of visual feedback in dynamic movement regulation. Further, visual speed information was shown to influence the gait transition speed and the preferred walking speed (Mohler et al., 2007).Some research has looked into cycling performance in VR, investigating the effects of visual flow velocity on power output and subjective effort during time-trials (Parry et al., 2012). In their study, visual flow slower than actual cycling speed led to higher power output and lower subjective effort than matching or faster visual flow. The visual flow speed is crucial for estimating the time or distance to completion, so the power output is likely adapted to ensure task fulfilment (i.e., completing a certain distance as fast as possible).

The effect of visual flow on continuous cycling at moderate intensities has rarely been looked into. Without a distance goal, distance estimation loses importance, diminishing the role of visual flow speed in cycling performance or behaviour. In preceding studies on constant load cycling behaviour, no effects of visual flow speed on heart rate or subjective effort were seen (Luttmann et al., 2024). Nonetheless, all visual flow speed research areas demonstrate its important role in speed perception during locomotion (Janeh et al., 2017; Parry et al., 2012; Pretto and Chatziastros, 2006).

1.1.4. Measures of exercise intensity

To quantify VR's effects on exercise, both objective and subjective measures are required.. Objective effort is often captured through heart rate, which reflects cardiovascular load. While avatar design and VR immersion can modulate heart rate (Kocur et al., 2021; Warburton et al., 2009), visual flow manipulations typically affect arousal in passive tasks (Pretto and Chatziastros, 2006; Stephens and Smith, 2022) rather than active exercise. Even in cycling, heart rate sometimes remains stable despite changes in power output (Parry et al., 2012). These effects can be based on physiological or psychological activation, arousal, or mood changes. In a study on time-trial cycling in VR, heart rate remained unchanged between two visual flow speeds. However, self-chosen power output differed significantly between visual flow conditions, suggesting an effect on physiological effort through increased performance (Parry et al., 2012). Such an effect could not be reproduced in continuous moderate-intensity cycling (Luttmann et al., 2024), which is likely rooted in the task not requiring visual flow for distance estimation. In addition, visual flow speed in this study was independent of actual cycling cadence, reducing the reliability of the action feedback. In general, affecting heart rate during exercise without changing objective load (resistance, speed, etc.) seems rather difficult. Nonetheless, heart rate is a relevant exercise parameter, especially given its easy and common assessment through smart watches and the like.

Using rating scales, exercise-induced strain can also be measured by subjective perceptions of effort (RPE) (Borg, 1982; Büsch et al., 2022). RPE is a major factor for regulating physical load (Herbert and Pollatos, 2012) and exercise adherence (Perri et al., 2002) and it interacts with affective appraisal of exercise (Di Fronso et al., 2020). Various information is integrated to form these ratings, including bodily signals from muscles or the cardiovascular system (Borg, 1982) and cognitive aspects like emotions (Rejeski, 1985) or self-efficacy (Hutchinson et al., 2008). Dual-Mode Theory (DMT, Ekkekakis, 2003, 2009) posits that there is a competition for attentional focus between internal and external cues. A more associative (internal) focus is associated with an increased perception of fatigue (Pennebaker and Lightner, 1980) and the ability to dissociate from internal cues becomes increasingly difficult at higher intensities (Jones et al., 2014). By diverting attention towards external stimuli, VR can induce a more dissociative attentional focus (Mestre et al., 2011), distracting users from the perception of internal strain (Lyons et al., 2014) and, therefore, possibly reducing RPE. Because RPE impacts affective evaluations of physical activity, achieving adequate subjective exhaustion is crucial for sustaining motivation. Such effects could potentially be evoked by creating agency illusions through manipulated action output (Banakou and Slater, 2017). As has been discussed before, false feedback can affect the subjective perception of effort by suggesting a much better performance, for instance, systems such as the EEG-eBike (Andres et al., 2020) and sound-augmented eBike (Andres et al., 2018) further demonstrate that multimodal feedback can affect perceived exertion without altering mechanical load. However, such effects have not been found consistently, demonstrating low affectability or bidirectional changes of RPE. For example, providing participants with false cardiac feedback during exercise created an illusion of increased exertion, despite no change in actual physiological responses (Iodice et al., 2019). Similarly, inaccurate distance feedback during a 6 km treadmill time trial—delivering either premature, delayed, or absent distance cues—did not significantly alter pacing or RPE, although participants exercised at lower metabolic intensity when no feedback was provided (Faulkner et al., 2011). Collectively, these findings suggest that false action feedback can modulate subjective perceptions of effort, but the magnitude and direction of this effect depend on the type of feedback, timing, and individual interpretation.

1.2. Objective

The primary aim of this study is to investigate the role of action feedback, specifically the manipulation of visual flow speed, on cycling performance in VR. By synchronizing flow speed with actual cadence, the study builds on prior work where visual feedback lacked agency congruence. The research seeks to clarify whether manipulated visual feedback can influence objective (power output, heart rate) and subjective (RPE, enjoyment) exercise parameters.

Beyond the immediate context, this work contributes to a broader understanding of how perceptual manipulations in VR affect motivation, adherence, and performance in exercise. Insights may inform public health strategies to counter sedentary lifestyles, support rehabilitation programs, and optimize athletic training by reducing perceived exertion and enhancing exercise experiences.

1.3. Hypotheses

According to the assumption that action feedback can not only be induced by avatar design but also through visual flow speed, which is directly related to the devoted physical effort; unmatching visual flow speeds were expected to affect the subjective appraisal of effort (RPE). Following findings that the display of increased athleticism leads to lower heart rates (Kocur et al., 2021; Yee et al., 2009), higher visual flow speeds were expected to evoke lower heart rates at the same objective intensity. The following hypotheses were investigated:

H1: Heart rate is lower during faster visual flow than during slower visual flow.

H2: RPE is lower during faster visual flow than during slower visual flow.

2. Method

2.1. Design

In a repeated measures within-subject design, each participant completed two experimental trials of ten-minute cycling. The cycling ergometer was set to a fixed incline of 0 %, so that power output (and cycling speed) increased with cadence. Visual flow speed of the virtual scene was set to one of two different levels, respectively (0.5*cycling speed, 1.5*cycling speed). The order of the visual flow speed conditions was randomized and counterbalanced between participants.

All experimental procedures were conducted in accordance with the Declaration of Helsinki. All participants provided informed consent.

2.2. Participants

Aiming to detect a small effect size, a power analysis was conducted using G*Power (Faul et al., 2009). The analysis yielded a required sample size of $N = 72$ for a repeated measures ANOVA with $\alpha = 0.05, f = 0.15$, and $\beta = 0.8$. The sample size was increased by 10 % ($N = 80$) to account for subject exclusion. Exclusion criteria were acute or chronic cardiovascular or muscular diseases and sensitivity to motion- or cybersickness. University sports students were recruited via an online newsletter. Eighty students participated for study credits. Seven participants were excluded from all analyses because of technical errors. The final sample size was $N = 73$ (38 male, 22.63 ± 2.28 years).

2.3. Material

2.3.1. VR

The VR system consisted of an HTC Vive head mounted display (HTC Vive, Taoyuan, Taiwan), two HTC Vive basestations, and two HTC Vive trackers attached to the ankles. The VR system ran on a desktop PC with an NVIDIA GeForce® RTX™ 3060 Ti 8 GB GDDR6 graphic card. The virtual scene was programmed in Unity (Version 2020.3.38f1) and presented in VR by Unity and SteamVR (Valve Corporation, Washington, USA). It displayed a straight street surrounded by trees and mountains (Fig. 1). The scene was kept simple to avoid extensive head movements that would affect visual flow speed perception due to the differences between lamellar and central visual flow (Banton et al., 2005; Campos et al., 2007). Nonetheless, the scene provided a naturalistic view of a cycling environment.

The two avatars (male and female) were created in Daz Studio 3D (DAZ Productions, Utah, USA) and imported into Unity as rigged models. Fig. 2 shows the female avatar and bicycle from the side. The Final IK Unity Asset (RootMotion, Tartu, Estonia) was used to synchronize the participant's and the avatar's movements. Participants were instructed to look forward during the exercise, but it was deemed necessary to provide a graphical representation of the bicycle and the user, in case participants looked down. This increased the realism of the scene and the immersion into the VR. The position of the HMD as well as the interpupillary distance were adapted individually to provide a sharp image of the virtual scene.

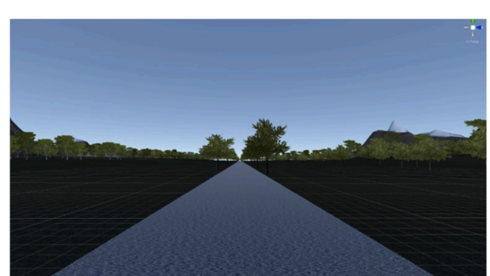

Fig. 1. VR scene.

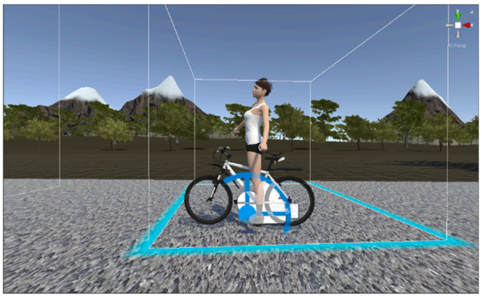

Fig. 2. The female avatar and the bike from a lateral view.

Fig. 3. RPE scale from participant view.

2.3.2. Outcome measures

Heart rate was measured by a chest strap heartbeat sensor (Polar H10, Polar Electro Oy, Kempele, Finland) measuring continuously and transferring data to a smartphone app (PolarBeat, Polar Electro Oy, Kempele, Finland) via Bluetooth. A baseline heart rate was recorded in a seated position after participants read the instructions about the experiment. This measure does not represent the resting heart rate but serves as a reference for the break between the two trials. During cycling, heart rate was recorded in the last ten seconds of every minute. In the present study, heart rate (HR) rather than heart rate variability (HRV) was chosen as the primary physiological indicator of exercise intensity. HR is a robust and widely accepted parameter that scales reliably with oxygen uptake across a wide submaximal range and is therefore well suited to quantify physiological strain during cycling tasks (Canário-Lemos et al., 2020; Olsson et al., 2022; Schantz et al., 2019). In contrast, HRV requires high-fidelity beat-to-beat data, extended artifact-free windows, and elaborate preprocessing procedures to ensure reliable indices (Laborde et al., 2017; Shaffer and Ginsberg, 2017). Moreover, HRV is particularly sensitive to movement artifacts, which are difficult to avoid in cycling protocols, and current wearable devices show variable accuracy in R–R detection during exercise, limiting HRV's practical value in such contexts (Georgiou et al., 2018; Wang et al., 2017). By contrast, mean HR can be robustly captured with validated chest-strap monitors and is less affected by small inaccuracies in beat detection (Etiwy et al., 2019; Gillinov et al., 2017). For these reasons, HR was deemed the most reliable and interpretable measure of exercise intensity in the present VR cycling paradigm.

To derive consistent HR values, the last 10 s of each minute were averaged rather than using the full minute. This approach offers several advantages: (1) it aligns the physiological recording with concurrent subjective assessments such as ratings of perceived exertion, which were also taken at minute marks, thereby ensuring temporal precision; (2) it avoids contamination from transient fluctuations at the beginning of each minute, allowing HR to stabilize before sampling; and (3) it reduces data volume while maintaining sufficient sensitivity to detect minute-by-minute physiological changes. Although averaging longer periods (e.g., 30–60 s) is often recommended to reduce random variability (Buchheit, 2014; Scott et al., 2018), short epochs can be justified when high temporal alignment with behavioral events is required, provided that HR is derived from validated chest-strap sensors and checked for artifacts (Gillinov et al., 2017). The last-10-second method thus represents a practical compromise between methodological rigor and experimental feasibility, ensuring reliable tracking of exercise intensity while maintaining precise synchronization with VR task events.

RPE was assessed every three minutes by the *Anstrengungsskala Sport* (ASS, Büsch et al., 2022) ranging from "1″ ("not strenuous") to "10″ ("so strenuous that I have to stop"). It was presented as a transparent image in the middle of the virtual scene (Fig. 3). The ASS is a reliable German adaptation of the CR10-Scale (Borg, 1982). It is task-unspecific and the numeric and semantic label pairs of each scale step show consistent matching (Büsch et al., 2022). Cadence was recorded by the VR-system and then averaged for every minute. The current cycling speed was calculated from cadence as follows:

$$speed\ [km/h] = 0.152 + (0.417 * cadence\ [rpm])$$

2.3.3. Post-experimental questionnaire

Because the manipulation of the visual flow is related to the sense of body ownership and the sense of agency, and to enjoyment, the items "body ownership" and "agency" of the body representation questionnaire (BRQ, Banakou et al., 2018) and the Physical Activity Enjoyment Scale (PACES, Jekauc et al., 2020) were used.

The BRQ contains five statements on 7-point scales between −3 ("does not apply at all") and 3 ("applies completely"). 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). The statements were translated into German. No changes in body ownership were expected because the avatar remained the same in both conditions. Visual flow speed may elicit different levels of agency because of the different transformations from cadence (*0.5 vs *1.5). Differences in agency ratings between the conditions could moderate the effects of visual flow speed on heart rate or RPE.

The 16 statements of the PACES are rated on 5-point scales between 1 ("disagree entirely") and 5 ("agree entirely"). Although the short version of the PACES bears the advantage of containing only positively worded items, the long version offered some relevant items while also displaying better internal consistency (Fritsch et al., 2022; Jekauc et al., 2020). The statements are worded generally but are to be rated regarding the present exercise (e.g., "Moving is very pleasant.").

To measure the immersion in the virtual environment, the "presence" scale of the I-group presence questionnaire (IPQ, Schubert et al., 2001) and a question on the perception of the visual speed were used.

The IPQ consists of the scales "spatial presence", "involvement", "experienced realism", and a general item. The general item and the "spatial presence" scale can be combined to form a "presence" scale. The statements are rated on 7-point scales between −3 and 3 with different semantic anchors on either end. The questionnaire aims to assess the subjective experience of feeling present in the virtual environment (Schubert et al., 2001), which can affect the effectiveness of VR (Ijaz et al., 2020). The presence scale was included to check for possible differences in presence ratings between visual flow conditions, which may have affected the intensity of the experience. This may explain differences between the outcome measures in both conditions.

Perception of the speed of the virtual scene was assessed with one item ("The movement in the virtual world was…") rated on a 6-point scale between −3 ("too fast") and 3 ("too slow"). The rating indicates whether visual speed differences were detected and whether one of the visual flow speeds would be perceived as more matching than the other.

Self-perceived fitness was assessed with the two subscales "strength" and "endurance" from the Physisches Selbstkonzeptskalen (PSK, Stiller et al., 2004). They are the central conditional abilities needed for cycling performance. Each scale consists of five statements rated on 4-point scales between 1 ("does not apply") and 4 ("applies") (Stiller et al., 2004). They were included to assess whether visual flow speed affected self-perception of fitness, as has been found for avatars (Kocur et al., 2021). Assuming that visual flow speed acts as performance feedback, which is typically compared to perceived physiological effort for performance evaluation (Wolpert and Kawato, 1998), the visual flow speed manipulation should affect self-perception. Considering the importance of self-efficacy for motivation and exercise adherence (Hutchinson et al., 2008; Perri et al., 2002), a positive impact on self-perceived fitness would be relevant, even in the absence of effects on heart rate or RPE.

The questionnaire was presented with PsychoPy (Version 2022.1.4).

2.4. Procedure

Participants gave informed consent and confirmed that they had no cardiovascular or muscular limitations. The heart rate sensor was put on and they read written instructions about the cycling task and were familiarized with the ASS. The baseline HR was recorded. Then, saddle height was adjusted to individual comfort, and two trackers were attached to the ankles with touch fastening straps. The HMD was adjusted to individual comfort (Fig. 4). The experimenter adjusted the virtual avatar's positioning manually, so that the avatar moved realistically on the virtual bicycle. This was necessary if participants looked down at the virtual bike and avatar. But more importantly, the right ankle tracker had to move through a virtual collider to calculate cadence and visual flow speed. Visual flow speed was adjusted to the appropriate condition in the two cycling tasks. Participants completed both ten-minute cycling exercise on an ergometer (Cyclus2, RBM elektronik-automation GmbH, Leipzig, Germany). The ergometer was set to a fixed incline of 0 %, so that power output (and cycling speed) increased with pedalling cadence. Participants were instructed to cycle however comfortable, keeping their hands on the handlebar. Cadence was allowed to vary but should not be changed jerkily and was recorded every minute by the VR system. When participants were ready to start, the virtual scene was initiated, and the first measures of heart rate and RPE were recorded. After completing the first cycling exercise, participants removed the HMD and filled in the computerized questionnaire. The second exercise bout began after a ten-minute break to ensure that the heart rate was back at the baseline level. The procedure was the same but visual flow was presented at the visual speed of the remaining condition.

2.5. Analysis

The effect of visual flow speed on heart rate and RPE was analysed with linear mixed models, using the lme4 package (Bates, 2010) in R (R Core Team, 2012). All independent variables were centred to their mean. The first measure of every outcome variable was omitted from the dataset as it represents pre-manipulation data. Outliers were defined as values smaller than $Q1 - 1.5*IQR$ or larger than $Q3 + 1.5*IQR$ and removed from the respective dataset before statistical analysis.

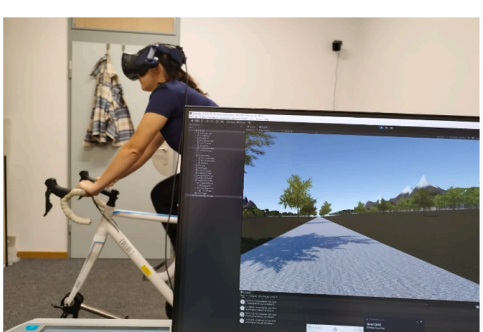

Fig. 4. Experimental setup from experimenter view.

The maximal models for both outcome measures included visual flow speed (condition), the interaction of condition and measurement time (minute), and the interaction of condition and actual cycling speed (cycling speed) as fixed effects. Cycling speed was calculated from cadence and included as a fixed effect to check for possible distortions of a visual flow speed effect through physiological activation. As random effects, intercepts for participants and random slopes for all within-subjects effects were included. Random slopes were reduced stepwise following the procedure of Matuschek et al. (2017) until a likelihood ratio test with $p < .2$ indicated a loss in goodness of fit. Assumptions of normality, linearity and homoscedasticity were checked visually. Non-significant fixed effects, indicated by a likelihood ratio test with $p <$ .05, were removed from the model. X^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.

To analyse the questionnaire, mean scores of each scale were calculated for each trial. These values were then compared between conditions using linear mixed models with condition as a fixed effect, a random intercept for participant, and a random slope for condition. Actual cycling speed was averaged for every minute and analysed with a linear mixed model containing the fixed effects condition and condition × minute, random slopes for both fixed effects, and a random intercept for participant. Complexity reductions and calculation of X^2 and p-values followed the previously described procedure.

Absolute effect sizes, standard errors, X^2-, and p-values are reported for all fixed effects.

3. Results

3.1. Heart rate

Values below 67 or above 171 beats per minute (bpm) were considered outliers. In total, 18 measurements were excluded from all further analysis. After outlier removal, average heart rate was 119.08 ± 19.22 bpm. Fig. 5 shows the average time course of heart rate throughout a trial, separated by visual flow speed.

The maximal model for heart rate analysis included fixed effects for condition, condition × minute, and condition × cycling speed. It included random slopes for all fixed effects and a random intercept for participant. The estimated intercept was 119.03 ± 2.05 bpm. The effect of condition was significant (−4.49 ± 1.47 bpm, $X^2_{(1)} = 9.12$, $p = .003$), indicating higher heart rates during slower visual flow.

Fig. 6 displays the distribution of heart rates in the two visual flow conditions. The mean heart rates were 120.53 ± 19.55 bpm during slow visual flow and 117.64 ± 18.8 bpm during fast visual flow. Condition × minute

(−0.25 ± 0.15 bpm, $X^2_{(1)} = 2.67$, $p = .102$) and condition × cycling speed (0.96 ± 0.56 bpm, $X^2_{(1)} = 3.02$, $p = .082$) had no significant effect on heart rate.

3.2. Subjective effort

Values above 8 were considered outliers. There were no outliers. On average, effort was rated as 3.66 ± 1.39 on the 10-point ASS. Fig. 7 shows the average time course of RPE throughout a trial, separated by visual flow speed.

The maximal model for RPE analysis included fixed effects for condition, condition × minute, and condition × cycling speed. It included random slopes for all fixed effects and a random intercept for participant. The estimated intercept was 3.66 ± 0.12. Neither condition (−0.19 ± 0.12, $X^2_{(1)} = 2.38$, $p = .123$), nor condition × minute (0.01 ± 0.04, $X^2_{(1)} = 0.15$, $p = .699$) or condition × cycling speed (0.96 ± 0.56, $X^2_{(1)} = 0.04$, $p = .841$) had a significant effect on RPE. Fig. 8 displays the distribution of heart rates in the two visual flow conditions. During slow flow, mean RPE was 3.82 ± 1.44. During fast flow, mean RPE was 3.55 ± 1.33.

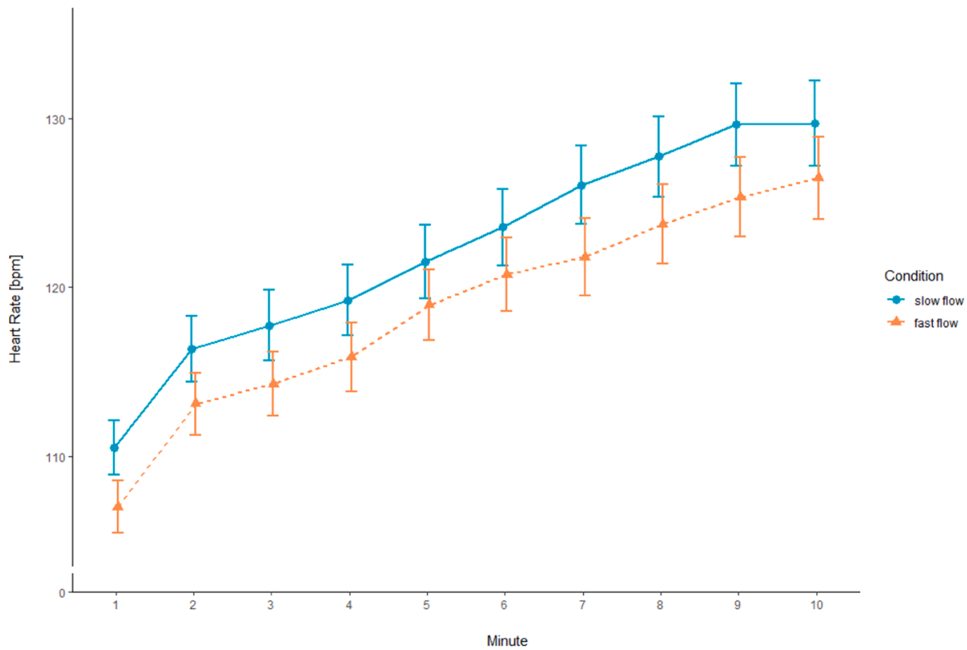

Fig. 5. Average heart rate throughout a trial separated for the two visual flow speeds. The dots/triangles represent the means at the given minute. The length of the error bars represents one standard error.

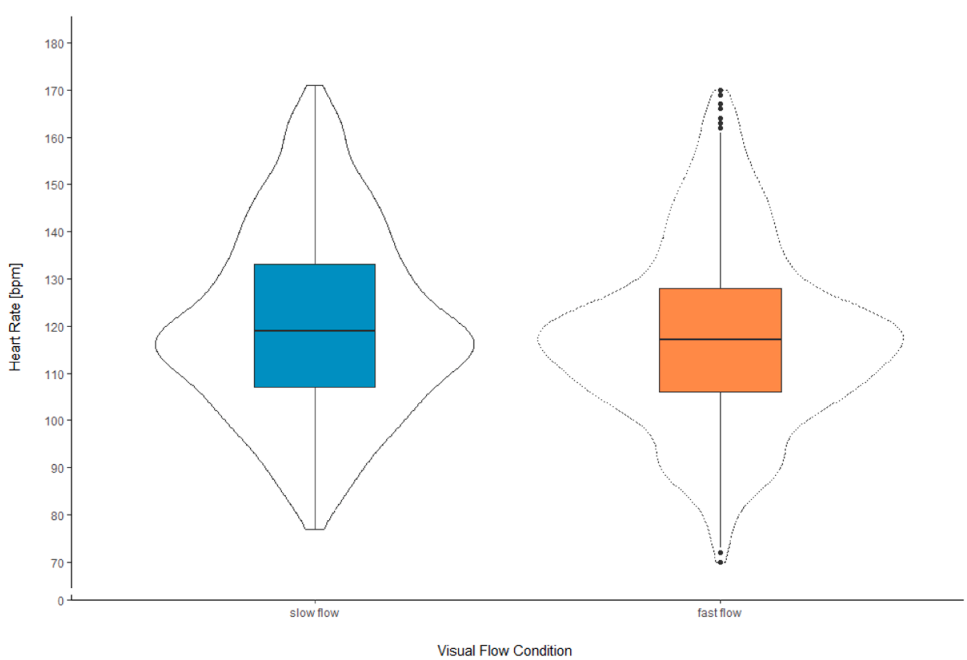

Fig. 6. Heart rate by visual flow speed. The boxplots display the median as the middle line. The lower and upper outlines of the boxes correspond to the first and third quartile, respectively. The length of the whiskers corresponds to 1.5*IQR. Dots outside of the whiskers represent outliers. The violin plots display data distribution.

3.3. Post-experimental questionnaires

3.3.1. Body ownership and agency

The individual scores for both items were transformed to range from 0 to 6 (instead of −3 to 3) so that "6″ represents high agency/ownership. 18 agency ratings were removed as outliers, because they were smaller than 2.5. Agency was rated as 4.9 ± 0.82 on the 6-point scale. No outliers were detected for ownership ratings. Ownership was rated as 2.31 ± 1.61 on the 6-point scale. Condition had no significant main effect on agency (−0.05 ± 0.13, $X^2_{(1)} = 0.14$, $p = .710$) or body ownership (−0.10 ± 0.15, $X^2_{(1)} = 0.39$, $p = .532$).

3.3.2. Physical activity enjoyment

Negatively worded items were recoded before averaging all items for the enjoyment score. There were no outliers detected. On average, enjoyment was rated with 2.95 ± 0.21 on the 5-point scale where "5″ represents high enjoyment. Condition had no significant main effect on enjoyment (−0.05 ± 0.13, $X^2_{(1)} = 2.46$, $p = .117$).

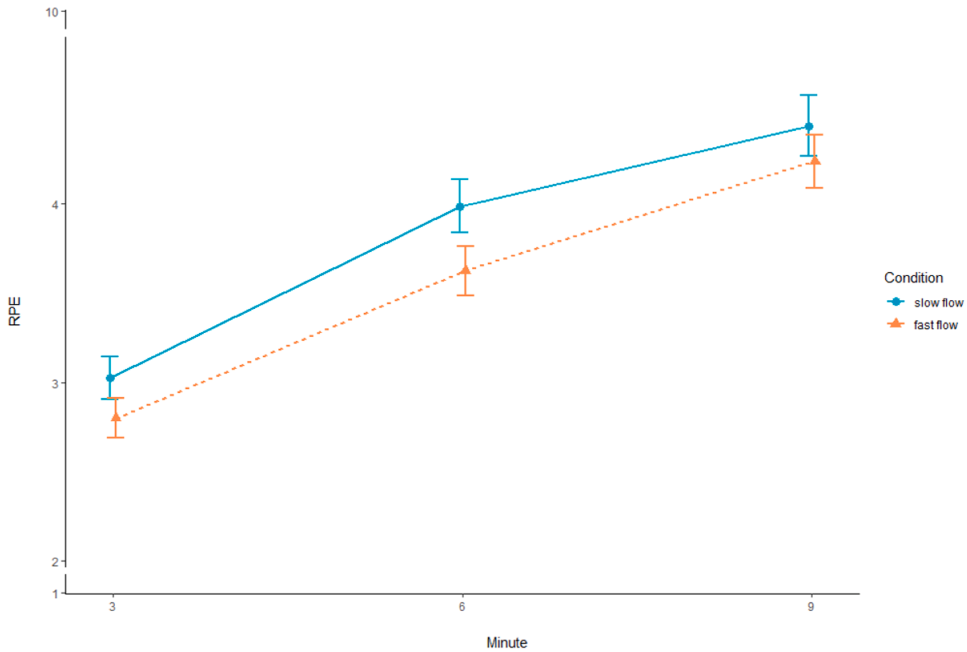

Fig. 7. Average RPE throughout a trial separated for the two visual flow speeds. The dots/triangles represent the means at the given minute. The length of the error bars represents one standard error.

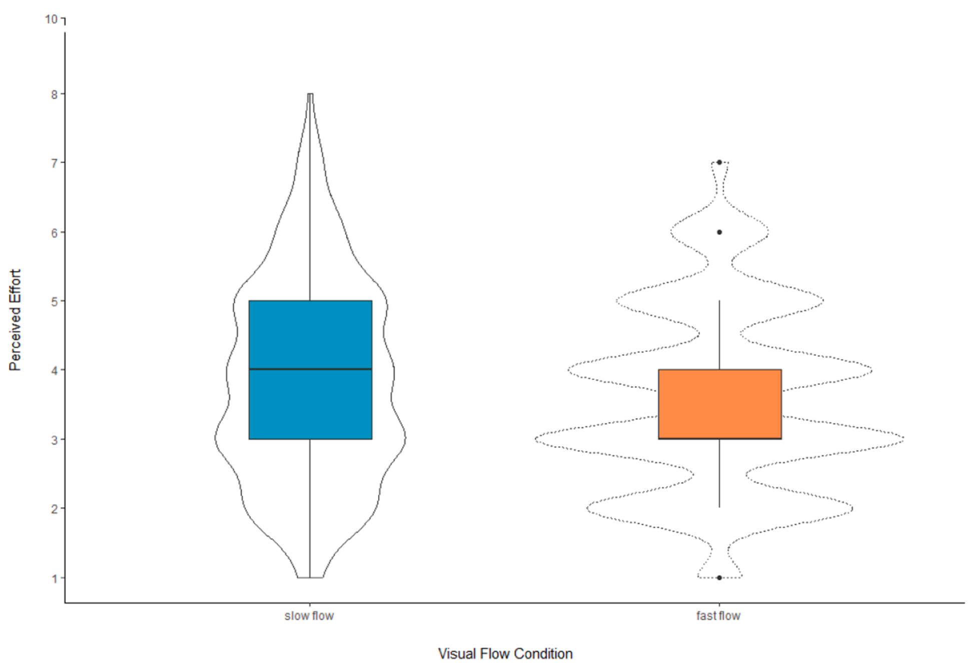

Fig. 8. RPE by visual flow speed. The boxplots display the median as the middle line. The lower and upper outlines of the boxes correspond to the first and third quartile, respectively. The length of the whiskers corresponds to 1.5*IQR. Dots outside of the whiskers represent outliers. The violin plots display data distribution.

3.3.3. Presence

One item of the IPQ had to be inverted. The individual scores were transformed to range from 0 to 6 (instead of −3 to 3), so that "6″ represents greater feelings of presence. The presence score was calculated by averaging the items of the spatial presence scale and the general item. Three scores from three participants were excluded as outliers, because they were smaller than 0.92. On average, presence was rated with 3.88 ± 1.09 on the 6-point scale. Condition had no significant effect on presence ratings (0.18 ± 0.10, $X^2_{(1)} = 3.10$, $p = .078$).

3.3.4. Speed perception

The individual scores were transformed to range from 0 to 6 (instead of −3 to 3). There were no outliers among the visual speed ratings. Visual speed ratings averaged at 2.81 ± 1.50 on the 6-point scale where "3″ represents "adequate speed". Condition had a significant main effect on visual speed perception (−1.83 ± 0.15, $X^2_{(1)} = 85.74$, $p < .001$), indicating that fast visual flow was perceived as faster than slow visual flow. The means suggest that both visual speeds were perceived as divergent from an adequate visual flow speed (slow: 3.70 ± 1.13, fast: 1.89 ± 1.26).

3.3.5. Physical self-concept

Strength and endurance scores were calculated by averaging all answers of the respective scale. One strength item had to be recoded before calculating the average. No outliers were detected. Participants rated their strength with 2.92 ± 0.61 on the 4-point scale, where higher values represent greater self-perceived fitness. Endurance was rated with 2.85 ± 0.73. Condition had no significant effect on either scale (strength: −0.02 ± 0.02, $X^2_{(1)} = 0.46$, $p = .498$; endurance: 0.03 ± 0.02, $X^2_{(1)} = 1.95$, $p = .162$).

3.4. Cycling speed

Cycling speed was averaged for every minute of a trial. Nine measures were excluded as outliers, being above 35.15 km/h. Average cycling speed was 24.49 ± 3.89 km/h. Condition had a significant main effect on cycling speed (−0.79 ± 0.29 km/h, $X^2_{(1)} = 8.91$, $p = .003$), indicating a slight reduction in cycling speed during fast visual flow. Mean cycling speed during slow visual flow was 24.86 ± 3.71 km/h. During fast flow, mean cycling speed was 24.08 ± 4.08 km/h. The interaction condition × minute was not significant (0.04 ± 0.03 km/h, $X^2_{(1)} = 1.45$, $p = .229$).

4. Discussion

The aim of the present study was to elucidate whether false performance feedback in the form of visual flow speed would impact heart rate and RPE during ergometer cycling in VR. Following findings from avatar studies (Czub and Janeta, 2021; Kocur et al., 2021), we hypothesized that faster visual flow would lead to lower heart rates and RPE compared to slower visual flow. The present results demonstrate an effect on heart rate but not on RPE. Furthermore, no subjective aspects were impacted except from visual speed perception.

The absence of effects on body ownership and agency is plausible given that the avatars did not change their appearance and visual flow speed was coupled to cadence in both conditions. However, agency ratings could have been impacted by the different transformation factors of actual cycling speed into visual flow speed (0.5 vs 1.5). This was not the case, suggesting that the key requirement for agency is any kind of coherency between user actions and VR.

One reason why we found significant differences in heart rates in this study, but not in previous studies with a similar setup (Luttmann et al., 2024), could be that visual flow speed was coupled with pedalling cadence, which increased agency ratings and the plausibility of the performance feedback. This was a major limitation of previous setups that could be eliminated for the present study.

The significant condition effect on speed perception shows that participants perceived the difference between the two visual flow speeds. The mean ratings further demonstrate that the diversions from an adequate speed were roughly the same.

Self-perceived fitness was not influenced by visual flow speed, matching preceding studies (Luttmann et al., 2024), but contradicting avatar effects (Kocur et al., 2021). As with all subjective measures, it can be argued that participants rated the PSK items on a very general level and tried to be consistent with it instead of basing it on the acute experience. This could also hold for the enjoyment ratings. Following verbal reports during preceding studies (Luttmann et al., 2024) and results from other visual flow studies (Yasukawa et al., 2021) an effect of visual flow speed on enjoyment was highly anticipated. The present results do not confirm the assumption that exercising with faster visual flow is more enjoyable. While the absence of an effect here is unexpected, the implication changes gravely considering the significant effect on heart rate. The present combination of results implies that cycling with slower visual flow was perceived as equally strenuous and enjoyable as cycling with faster visual flow. However, it led to higher heart rates. Nevertheless, it must be considered that due to the small age range of the sample, the findings might not apply to other demographics.

Although statistically significant, the differences in actual cycling speed of <1 km/h between both visual flow speeds most likely cannot fully attain for the heart rate differences of almost 5 bpm. This is also evident in the non-significant interaction effect of condition and cycling speed on heart rate. There seems to be a dissociation of physiological and psychological aspects of exercise (Hampson et al., 2001), visible by the altered heart rate without an effect on RPE. Heart rate and RPE are very highly correlated (Borg, 1982), although this relation depends on various factors, for example motivation (Rejeski, 1981). While the significant difference in heart rates is of practical relevance, claiming a dissociation between RPE and heart rate must be done with caution. Visible or physiologically relevant changes in heart rate are not necessarily detectable by the participant, especially not without focused attention. Bearing in mind the dissociative properties of VR, participants likely perceived their heart rate more unconsciously, and the difference was not outstanding enough to alter RPE. It could also be that RPE was based on different cues in the two conditions, considering the manifold roots of effort evaluations (Borg, 1982; Rejeski, 1985). Some participants reported a feeling of cycling uphill during the slow visual flow condition, which could have led to an increased focus on leg muscle strain instead of heart rate. However, these are only assumptions that the present data cannot confirm. Checking for attentional focus or reasoning for RPE might be helpful in explaining such effects in future studies. Stress, fear, or frustration might also arise from the visual simulation of different speeds. Such subjective markers are difficult to measure, especially during physical activity, where physiological stress markers are already heightened. The PACES was included to identify effects on the affective evaluation of the task, but there was none found. Ideally, future studies would include an EEG to measure cortical activation. This could elucidate the mechanisms of attentional focus, sense of agency, affective responses, and motor cortex activation.

Avatar effects have been a major motivation for the present study. However, visual flow speed and avatar appearance constitute very distinct stimulus types. In general, the visual system is known to adapt to visual cues, resulting, for instance, in altered sensitivities for similar or diverging speeds (Kar and Krekelberg, 2014). This adaptation leads to an attenuation of stimuli, visible in reduced neural activity. Discrete stimuli show this effect to a lesser extent than continuous stimuli (Schmitter et al., 2021). This differentiation of stimuli might explain why avatar effects have been difficult to reproduce through scene design. Although avatars are also continuously visible, their movements and the complexity of their appearance (compared to a singular stimulus like speed) provide more singular discrete stimuli that may be less likely to be attenuated over time.

5. Limitations

The present study exhibits some limitations. One possible weakness is the simplicity of the visual scene. It was designed to display a realistic and natural scene but including more exciting visuals would have likely increased general enjoyment and engagement with the task. However, a more exciting scene would have caused participants to attend more to the objects and thereby also impacted gaze behaviour, which is critical for visual flow speed perception (Banton et al., 2005). Then again, including more objects would have increased the depiction of the visual flow speed. For this, the study should be repeated in a different, less simple virtual environment.

It can also be argued, that performing both experimental trials consecutively may contort the results. While it is definite that the time closeness of the trials enhances the detection of the visual flow speed difference between them, this must not signify inaccuracy. This design was chosen to investigate the effects of visual flow speed manipulation despite its obviousness. If the effect only appeared when the visual manipulation was subconscious, it would not be as applicable, for example for multiple usage or for highly experienced athletes that can precisely estimate their speed from bodily sensations.

The method would gain precision through individual assessments of maximum HR and cadence, which was refrained from due to test ecological reasons. Further, the specific demographics of the present sample limit the transfer to other populations.

More generally, the specific particularities of VR must be discussed. VR can be presented in different ways, from monitors to CAVEs (Cave Automatic virtual environment)) and HMDs, offering varying levels of immersion. HMDs allow for a much smaller field of view than normal vision, especially vertically. However, HMDs with head motion tracking provide an immersive VR experience by enabling a 360° view through head movements (Campos et al., 2007). In this study, an HMD was used, in which the peripheral view is limited, and head movements are necessary to inspect the scene. In further studies, head movements should be registered. Otherwise, CAVE systems can be used, which have been shown to enable better distance perception than HMDs (Plumert et al., 2005).

6. Conclusion

Visual flow is a central cue during self-motion, conveying performance feedback. Manipulating visual flow speed during cycling in VR was expected to affect subjective and objective measures of effort in equal measure. We found an effect of visual flow speed on heart rate but not on RPE. Future research should investigate individual differences in motivation or attentional focus that could have evened out any visual flow effects on RPE. The coupling of pedaling cadence and visual flow speed methodically improved previous setups, as visible in increased agency ratings. The present results suggest that visual flow speed constitutes a useful parameter for VR-based exercise. This is also important from an applied point of view. The weather and the place do not restrict VR cycling and it provides an excellent opportunity to improve people's fitness in every country. Besides, scene manipulations allow a more natural first-person perspective than avatars that need to be visible to be effective. Even though VR cycling systems with cross-platform and multi-scene exist, our results hint that the manipulation of the visual flow might suffice to promote the fitness of many generations.

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Ethics approval

The experiment was conducted according to the ethical guidelines of the Helsinki declaration. The superordinate project was approved by the corresponding ethics committee (ID: 21–2266–101).

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication

The authors affirm that human research participants provided informed consent for anonymous publication of the data.

Availability of data and materials

The experiment was preregistered at OSF.io. Data and materials (except the VR scene) are available at https://osf.io/c8m6j/?view_only=52f30b90c8d24628bcb0b58776e6568d.

Code availability

Code is available under https://osf.io/c8m6j/?view_only=52f30b90c8d24628bcb0b58776e6568d.

CRediT authorship contribution statement

Carla Luttmann: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Petra Jansen:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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