Exercise in Virtual Reality

The Impact of Visual Flow Speed on Parameters of Stationary Cycling in a Virtual Environment

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Content

Summary

Virtual reality has long been an established instrument in various areas of research. In sports science, it is a valuable tool for influencing aspects of physical activity. Combining physical activity with the immersive medium appears to have several advantages over conventional training programmes. Especially the effects of avatar design have been investigated in this context, demonstrating that certain appearances elicit significant behavioural changes in the user. Visualizing athleticism through the avatar has improved performance and perceived effort in different exercises. Such effects could potentially be achieved through configurations of virtual action feedback. For instance, visual flow conveys information about self-movement speed during locomotive exercise. The effects of virtually manipulated visual flow have been predominantly investigated in cycling time trials or gait studies. However, constant-load exercise, a relevant part of regular physical activity, has rarely been examined.

The present studies investigated the effects of visual flow speed on physiological and perceived effort, affective states, self-perception, and enjoyment during and after short bouts of aerobic cycling exercise. University students participated in three experiments, completing multiple 20- or ten-minute exercises on an ergometer. During each trial, a virtual cycling track was presented through a head-mounted display, inducing the impression of forward motion at a specific velocity while participants cycled at a constant moderate intensity. Following related research, a linear decrease in heart rate, perceived effort, and arousal and a linear increase in valence were expected with increasing visual flow speed. Linear mixed model analyses revealed no significant main effect of visual flow speed on perceived effort or affective states. Heart rate was significantly higher during slow flow in the first and third studies. Ratings of agency and presence increased under fast visual flow in Study 2. Cadence and cycling speed decreased with increasing flow speed in Studies 2 and 3.

The present results suggest that visual flow speed manipulations in virtual reality can affect various parameters of physical activity. However, the prerequisites and moderators of such effects need further investigation. Some results match previous findings from related areas; others are contradictory. The studies at hand reveal some methodological and theoretical aspects that should be considered in future research. Differences between avatars and visual flow, cycling and walking, and the impact of a distance goal for visual flow perception are discussed. All in all, visual flow is proposed as a peculiar stimulus that is susceptive to various influences but no less worthy of use in further investigations of media-supported exercise.

1 Preface

Physical inactivity is one of the most prevalent causes of all kinds of non-communicable illnesses and diseases. Although people generally know of the positive impact of regular exercise on health and overall well-being, most of the population falls below the target amount of weekly exercise. The reasons for not engaging in physical activity are manifold but often boil down to perceiving it as unpleasant. To counter the consequences of a sedentary lifestyle, it is essential to identify factors that facilitate exercise initiation and adherence. Turning exercise into a (more) pleasurable activity might promote its popularity and help establish it as an important approach to public health issues. Making exercise more pleasurable can be accomplished, for instance, by reducing perceived strain or increasing enjoyment during the activity. In this context, various types of media have been helpful. Auditory (e.g., music) and visual (e.g., videos) media can enhance enjoyment and engagement while reducing negative emotions during physical activity. Furthermore, the gamification of exercise can turn it into a pleasurable activity that is more likely pursued in the future. Particularly video games that rely on body movements are a valuable tool in exercise facilitation, combining the advantages of physical activity and video games. Their positive impact on exercise experience is often explained with attentional focus. The constant presentation of visual and auditory cues enables users to focus on the pleasurable game rather than the strain and discomfort that can accompany exercise.

Virtual reality (VR) can enhance these effects by providing a more immersive and captivating virtual environment. It has been an effective tool for eliciting positive emotions and attitudes during and towards physical activity. In addition to the diversion of attention, VR and video games offer options to manipulate virtual environments and avatars. Both the appearance of the virtual scene and the avatar can impact user behaviour and perceptions. Using these virtues, VR can be applied in health promotion contexts to make physical activity more attractive and pursuable for the general public.

Besides the area of health promotion, more pleasurable exercise conditions can be beneficial for recreational and professional athletes. Reducing perceptions of strain while maintaining the objective intensity enables athletes to train at physical loads that would otherwise be too uncomfortable. This way, target intensities can be reached more easily, enabling diverse training effects and facilitating adherence in phases of low motivation. Although VR systems are not (yet) affordable for everyone, many recreational or semi-professional athletes seem willing to invest in training devices.

Aside from bearing practical applications, investigating the possibilities and mechanisms of VR-based exercise is helpful for a better understanding of visual perception, psychological aspects of exercise, and the role of attentional focus in the exercise-affect relation. Existing research has demonstrated that avatar and scene design in VR can affect athletic and motoric performance in various areas like strength, motor learning, and endurance tasks. VR can create specific environments and convey action feedback like movement speed during locomotive exercise. Movement speed is a central performance parameter that is evaluated based on visual flow speed (i.e., the speed of objects moving towards the user). Visually perceiving a certain speed can lead to adaptations of motor parameters to maintain stability or stay aligned with movement goals. Action feedback is further used to evaluate goal attainment and, therefore, is relevant to self-efficacy. Manipulating visual flow speed may be a simple and effective way to alter user behaviour and perceptions during VR-based exercise by providing performance feedback that does not match physical effort. To date, however, most exercise studies in VR focus on the configuration of the virtual avatar(s). Albeit the effectiveness of avatar design, other facets of VR should be considered to broaden the possibilities for exergame developers and users. Applying visual flow speed manipulations allows first-person perspectives and is much easier to implement than the programming of an avatar. Merging results from avatar studies with knowledge about visual flow and the importance of subjective experience in exercise, the present studies investigated the usefulness of visual flow speed as an exercise facilitator for constant-load cycling in VR.

2 Theoretical Background and State of Research

The present research evolved from three central topics that will be elucidated in the following sections. First, some relevant physiological and psychological aspects of physical activity will be explained, clarifying their importance for future behaviour and discussing the role of action feedback. The successive section will reveal the peculiarities of VR and how different VR configurations can affect users. Bringing these areas together, Section 2.3 covers the effects of VR on physical activity, focussing on scene design and virtual action feedback.

2.1 Exercise

Physical activity is a cornerstone of a healthy lifestyle (Lee et al., 2012; Nyberg et al., 2020). It benefits physical health, enables socialisation, and improves overall well-being. Nonetheless, an alarming number of people leads a mostly sedentary lifestyle, lacking sufficient daily movement or regular exercise (World Health Organization, 2022). Therefore, increasing participation in physical activity has become a central interest in public health research. To approach this goal, relevant parameters of physical activity and exercise must be defined, including the state of research on their mutability.

The terms *physical activity* and *exercise* are often used interchangeably, but they have distinct definitions (Mandolesi et al., 2018). *Physical activity* is used as an overarching term encompassing all movement-related behaviours and activities, whether in leisure time, during work, transportation, sports, exercise, or active play (Burkhalter & Hillman, 2011; World Health Organization, 2022). *Exercise*, on the other hand, refers specifically to physical activity that is planned, goal-directed, and repeatedly and regularly executed.

Exercise can be described by parameters like intensity, duration, or frequency (Fröhlich & Ludwig, 2023). The present research is focused on exercise-related behaviour, but the term “physical activity” will be used to describe both exercise and leisure activities.

Like many other human behaviours, physical activity requires a mix of cognitive, emotional, and physical capacities. From the initiation of daily physical activity to performance optimization in high-level athletes–cognitions, emotions, and physical constitution affect behaviour, performance, appraisal, and evaluation on every level of physical activity. Elucidating the bidirectional relations between these factors thus bears relevance for the whole spectrum of physical activities. The following sections cover objective and subjective aspects of physical activity and exercise that may be targets of investigation in public health research and sports or exercise science. The focus lies on the aspects investigated in the studies at hand.

2.1.1 Objective Parameters of Physical Activity

The intensity of physical activity can be described through various parameters that interact profoundly with each other. *Objective parameters* describe the physical load in terms of, for instance, duration, weight, or movement speed or reveal automatic physiological responses to the physical activity. The latter covers measures like heart rate or respiration rate. Movement speed is one of the most important objective parameters for locomotive activities like cycling. During stationary cycling, the physical load is primarily defined by the resistance (in watts). Pedalling cadence complements resistance as a measure of movement speed and is strongly connected to the physiological effort.

Lastly, as a central and likewise accessible measure of physiological strain, heart rate conveys information about metabolic demands.

2.1.1.1 Resistance

Resistance describes the load that needs to be overcome during stationary cycling. It crucially impacts the recruitment of different muscle-fibre types (Ahlquist et al., 1992) and the degree of neuromuscular fatigue (Thomas et al., 2016; Thomas et al., 2015). Especially the strength and endurance of the knee- and hip-extensors (quadriceps femoris and gluteus maximus) determine maximum manageable resistance (Ryan & Gregor, 1992). Resistance/power output is used to define exercise intensity or test protocols and compare performance levels (Faria et al., 2005). The respective resistance needs to be overcome to cycle, which makes it complementary to speed in outdoor cycling. However, resistance cannot be easily transferred into a specific speed, as their relationship highly depends on factors like air drag, incline, cadence, or road resistance. Other natural factors like inertia are absent during stationary cycling (Groot et al., 1994). These differences need to be considered when comparing stationary and outdoor cycling performance.

Stationary cycling bears the advantages of highly controllable circumstances and independence from environmental factors (e.g., weather). Cycling research thus consists of ergometer studies to a fair amount. Such studies demonstrate, among other things, how pacing strategies are affected by knowledge about distance or time to completion. Pacing refers to the regulation of effort, e.g., in a race, to achieve the desired goal as efficiently as possible. Performance must be maximised without risking injury or accidents. Therefore, it is essential for optimal pacing to know how much distance or time still needs to be covered. Incorrect distance feedback can impact pacing strategies (Tucker & Noakes, 2009) and power output (Parry et al., 2012).

2.1.1.2 Cadence

Pedalling cadence describes the number of pedal revolutions per minute (rpm). It is comparable to stride frequency during walking and chiefly involved in the resulting movement speed during cycling. In combination with resistance, cadence affects the involvement of anaerobic and aerobic metabolism and the demand on different muscle-fibre types (MacIntosh et al., 2000; So et al., 2005). Lower cadences create less momentum and thus require more muscle activation than higher cadences to overcome large resistances. Low power outputs, in contrast, can be generated at lower cadences (MacIntosh et al., 2000). Cadence also affects subjective appraisal, with 60 to 80 rpm showing the lowest perceived effort (Löllgen et al., 1980). Higher cadences seem advantageous considering their neuromuscular requirements (Takaishi et al., 1996), especially against large resistances (MacIntosh et al., 2000), because momentum reduces the power needed for each pedal movement. However, this relation is not linear nor unlimited. Very high cadences require consistently fast movements which increases recruitment of fast twitch fibres (MacIntosh et al., 2000) and neuronal demands to coordinate leg movements.

There must be a range where force and endurance are optimally balanced, but defining such a range continues to occupy sports scientists. Neuromuscular fatigue, for instance, predicts a different optimal cadence than VO_{2max} (Takaishi et al., 1996). Expertise or pedalling skills also affect optimal cadence (Lucia et al., 2004; MacIntosh et al., 2000).

The definition of an optimal cadence is not only complex due to metabolic differences–it also seems unreasonable considering the multiple individual aspects that affect cycling comfort. From physical factors like height, the proportion of the body parts, or body weight to customizable aspects like saddle height, upper body positioning, or crank length–various elements influence comfortable and effective cadence and muscle recruitment (So et al., 2005). Defining a narrow range as the optimal cadence is impractical and unrealistic. Nonetheless, specific ranges can be assigned to metabolic states and levels of efficiency and act as guidelines for cadence choices.

The previous considerations are important for choosing an adequate individual cadence. For the studies at hand, they are especially relevant to ensure relatively consistent physiological strain between exercise bouts and participants. In cases where cadence is not restricted to a narrow range, it should be discussed and ideally analysed as a factor of subjective and objective measures of effort.

2.1.1.3 Heart Rate

The heart is responsible for blood flow through the body, including the aeration of deoxygenated blood in the lungs and the transport of oxygenated blood to muscles and organs. A central parameter that quantifies cardiac work is *heart rate*, the "[...] cardiac muscle contraction and relaxation rate [...]" (McArdle et al., 2023, p. 333), expressed in beats per minute (bpm). Heart rate is intrinsically regulated by the sinoatrial node that stimulates normal pumping (McArdle et al., 2023). Extrinsic regulation is based on afferent input from mechanoreceptors (aortic, cardiac, and muscular) and central command from higher brain regions, enabling rapid adjustments to the intensity of physical activity (McArdle et al., 2023; Waldrop et al., 2011). Cardiac output (the product of heart rate and stroke volume) rises steeply at the start of physical activity and continues to increase gradually until it matches metabolic demands (McArdle et al., 2023). Heart rate is thus directly related to and increases with intensity (McArdle et al., 2023; Waldrop et al., 2011). Since it is measurable with simple and non-invasive methods, it is a widely used indicator of physiological strain, especially for personal use.

Metabolic demands during cycling depend on resistance and cadence, meaning that both increased resistance and cadence elevate heart rate (Gotshall et al., 1996; Gronwald et al., 2018). However, the relation of heart rate, resistance, and cadence has also been found to depend on expertise (Lucia et al., 2004), underlining the difficulty of defining a physiologically optimal cadence. Besides, heart rate is a highly individual gauge and cardiac work is suspect to many influences, such as emotional state (Martha Schneider & Schwerdtfeger, 2020), age (Tiwari et al., 2021), sex (Abhishekh et al., 2013), and more. Heart rate during physical activity then additionally depends on the task, fitness, and expertise (Löllgen, 2009).

2.1.2 Subjective Parameters of Physical Activity

The previously described objective parameters are necessary to define the external load of physical activity. However, any external load is differently perceived based on individual fitness, preference, or attitude. Therefore, *subjective parameters* give insight into the cognitive and affective appraisal of physical activity. These perceptions are critical markers for the regulation of physical effort, balancing goal-directed exertion and preventing overload or injury. Subjective appraisal of an activity further determines acute engagement and future behaviour. Consequently, perceived effort and affective responses should not be overlooked when designing and prescribing exercise programs.

2.1.2.1 Perceived Effort

Perceived effort is a central subjective parameter that can be used to plan and evaluate exercise. It is based on input from various sources. Signals from the muscles, the skin, the cardiovascular, and the respiratory system convey information about bodily strain (Borg, 1982; Hampson et al., 2001). Additionally, cognitive aspects like motivation, intention, and self-efficacy are integrated to evaluate the perceived effort (Rejeski, 1985). Affective states can also impact effort perceptions (Borg, 1982), which greatly depends on the individual preference for unpleasant or pleasant emotions during exercise (Di Fronso et al., 2020). Apart from these internal sources, external cues about intensity and performance affect the perception of effort (Baden et al., 2005; Baden et al., 2004). These include knowledge about the objective load and performance feedback during the exercise. The relevance of performance feedback for effort perception is demonstrated by false feedback studies, conveying incorrect information about load or performance. Such false feedback can ameliorate affective responses, reduce perceptions of pain and effort during physical activity (Hutchinson et al., 2008; Williamson et al., 2001), and affect pacing strategies (Nikolopoulos et al., 2001; Wingfield et al., 2018). However, there is ample evidence that incorrect feedback does not affect perceived effort, for instance, in well-trained cyclists (Albertus et al., 2005) or during self-paced running (Faulkner et al., 2011; Puleo & Abraham, 2018). While Albertus et al. (2005) and Puleo and Abraham (2018) found no effect on pacing strategies, inaccurate feedback did affect pacing in the study by Faulkner et al. (2011).

Perceptions of effort are central to load and effort control–to match performance with goals and intentions while avoiding injuries. They enable a process called *teleoanticipation*, which refers to the regulation of effort to ensure optimal task completion without risking overexertion (Hampson et al., 2001). Borg (1982) claims a close relationship between heart rate and subjective ratings of effort, so a rating of “13” on his rating scale would correspond to a heart rate of 130 bpm. However, he also acknowledges the various co-factors of heart rate and the need to integrate heart rate with other physiological parameters. The last decades of exercise research have demonstrated that the relation between heart rate and ratings of perceived exertion (RPE) is not as simple as Borg’s initial statement suggested (Emad et al., 2017). Several studies reveal a correspondence between heart rate and RPE, supporting their close relationship. Iodice et al. (2019) demonstrated that false auditory heartbeat feedback affected RPE during effortful cycling, supporting the relevance of cardiac signals for effort evaluations. Other studies demonstrate that the two parameters can be disjointed under certain circumstances. During cycling, Löllgen et al. (1980) found a correlation between cardiopulmonary work and RPE only during high cadences, suggesting a correlational rather than a causal relation between them. Temperature, exercise modality, and expertise also affect the relation between RPE and heart rate (Hampson et al., 2001). Jameson and Ring (2000) suggest that RPE during cycling are chiefly based on muscular and pulmonary afferences rather than heart rate.

Perceived effort is mainly assessed with rating scales, typically providing word-number combinations for different levels of strain or exhaustion between “no strain” and “so much strain that I need to stop”. Since the first scale for these ratings was introduced by Borg (1982), adaptations have been published for children (Kasai et al., 2021; Robertson et al., 2000) or to measure cognitive effort (Paas, 1992). Some scales have demonstrated more consistent matching and sorting of the word-number combinations than others. The German *Anstrengungsskala Sport* (ASS, Büsch et al., 2022), for instance, shows a higher probability of correct word-to-number assignment than the *Children's Effort Rating Table* (CERT, J. G. Williams et al., 1994). The ASS further displays very consistent sorting, which supports the assumption of equidistance between the scale steps (Büsch et al., 2022).

2.1.2.2 Affect

At the heart of subjective exercise parameters lie (1) the affective reactions to physical activity and (2) the impact of affective states on physical activity. The most essential concept of subjective appraisal is the *basic affect* (Ekkekakis, 2003) or *core affect* (Russell, 1980). Both terms describe the fundamental experience of subjective appraisal that builds the foundation for emotions and moods (Ekkekakis, 2003). "Core affect is that neurophysiological state consciously accessible as the simplest raw (nonreflective) feelings evident in moods and emotions." (Russell, 2003, p. 148). It is irreducible and does not have to be attributed to a cause (Ekkekakis, 2003; Russell, 2003; Russell et al., 1989). Core affect can be described through evaluations of the two orthogonally aligned dimensions *pleasure* and *arousal*. Changes in core affect result from manifold influences that are not consciously accessible. They can evolve into what is commonly known as moods and emotions. Russell (2003) defines *moods* as phases of prolonged unattributed core affect. *Attributed core effect*, on the other hand, describes changes in core affect that are related to an object or cause. For an attributed core effect to be declared as a prototypical *emotion*, many other processes come into play, such as instrumental action or subjective conscious experiences (Russell, 2003). Emotions consist of an affective base and a cognitive evaluation of the stimulus, for example, regarding its meaning (Ekkekakis, 2003). Due to the complexity of such prototypical emotions and the importance of immediate affective responses for behaviour (Kwan & Bryan, 2010), measuring core affect *during* physical activity is more reasonable than measuring it after the activity. Indeed, many studies claiming mood improvements through physical activity have compared affect before and after the activity, excluding immediate affective reactions (for a review, see Ekkekakis et al., 2011). Furthermore, affect after the completion of an activity is largely confounded by a feeling of relief (Wininger, 2007).

Both emotions and core affect have been subject to theoretical reflections and experimental investigations, and both have demonstrated ambiguous relations with physical activity. For the present research, the effects of physical activity on both acute affect and more general emotions or affective attitudes towards physical activity are relevant. Central findings on both aspects are discussed in the following.

A widespread assumption about physical activity is that it elevates the mood and induces positive emotions. That this is only part of the truth becomes obvious considering that: “[...] if the only effect of exercise were to make people ‘feel better’, perhaps not as many people would be physically inactive” (Ekkekakis, 2009, p. 74). Many studies have proven that physical activity and exercise are helpful tools in the treatment of psychological disorders, improving mental health, well-being, and perceived energy (Elkington et al., 2017; Fontaine, 2000; Mandolesi et al., 2018). Physical activity can enhance energy (Plante et al., 2003) and self-reported mood (Ligeza et al., 2021). However, it can also elicit unpleasant and negative feelings, as evidenced by perceptions of strain. Negative affect has been found to increase with intensity, which suggests an involvement of affect in effort regulation (Timme & Brand, 2020).

Core affect and resulting moods and emotions have direct consequences for cognitive and behavioural processes. They affect attention, memory, perception, and decision-making (Russell, 2003), influencing immediate and long-term aspects of physical activity. In an observational study about basketball performance, Uphill et al. (2014) found that successful game involvement was predicted by self-reported happiness, while anger and embarrassment cooccurred with unsuccessful game involvement. Similar results were found in swimming (Samełko et al., 2018), suggesting that positive emotions are crucial for performance. In contrast, Allen et al. (2013) demonstrated that happiness can be associated with high mental effort during good performance and low mental effort during poor performance in male football players. Jaafar et al. (2015) have shown that pleasant visual stimuli increase neuromuscular performance during cycling sprints, as indicated by higher electromyographic activity in the vastus lateralis and vastus medialis than when viewing unpleasant stimuli. Presenting pleasant visual stimuli has also led to reduced RPE and cardiac effort during cycling (Barreto-Silva et al., 2018). Spindler et al. (2019) also successfully induced positive affective states through visual stimuli but found no effects on decision-making abilities under physical strain, suggesting that affect does not impact acute exercise behaviour.

Regarding the arousal dimension of core affect, some theories claim that maximum performance can be achieved at a specific level of optimal arousal (Russell, 2003). It must be noted, however, that too many factors and individual differences affect the arousal-performance relationship to make such definite prescriptions (Hanin, 2000; Wrisberg, 1994). In general, physical activity induces physiological activation. Consequently, arousal increases with intensity and is closely related to perceived effort (Sudeck et al., 2016). At some point of exertion, subjective arousal ratings may be based more on perceptions of fatigue and less on physiological activation. Subjective measures are prone to such differences in interpretation, where arousal can signify excitement, physiological activation, or energy level (Evmenenko & Teixeira, 2022).

Russell (1980) proposed the *Circumplex Model of Affect* to describe and measure core affect. According to this model, affective states can be ordered along the circumference of a circle. The distance between two affective states corresponds to their similarity (Remmington et al., 2000; Russell, 1980). A two-dimensional structure underlies this circle, with a vertical arousal-sleep axis and a horizontal pleasure-displeasure axis (Russell, 1980). Following this structure, the *Affect Grid* was developed to assess acute affective states with a single item. Users mark their affective state on the grid as a combined rating of arousal (vertical) and pleasure (horizontal), which are rated from 1 to 9, respectively (Russell et al., 1989). The model's suitability for measuring affective states was found to depend on the methodological approach, making it an acceptable but not universal gauge (Remmington et al., 2000). It is useful for quick assessments, where multi-item scales would be too lengthy or distracting. It must be noted, however, that as a one-item instrument it can only provide a broad impression of affect, which can be influenced by many factors. The fact that the Affect Grid is a very explicit measure could also lead to unreliable data (Russell et al., 1989), considering social desirability or other reasons for inaccurate responses.

2.1.2.3 Subjective Parameters and Physical Activity Behaviour

Understanding the exercise-affect relation forms the baseline for the effects of external stimuli on performance, for the interindividual differences that affect objective and subjective parameters, and for the short- and long-term behavioural aspects of physical activity. The preceding sections have demonstrated that physical activity and subjective perceptions are highly intertwined–but why are subjective evaluations of exercise so important? One reason is the previously described relevance for acute performance and engagement. A second reason is their impact on long-term exercise behaviour, such as the initiation of and adherence to exercise programs (Sudeck et al., 2016; Timme & Brand, 2020). These characteristics make perceived effort and affective responses to exercise important factors for increasing physical activity in the public, enhancing engagement in rehabilitation, or facilitating consistent training for athletes. Figure 1 visualizes how bodily and cognitive factors form affective responses to exercise which then impact exercise adherence.

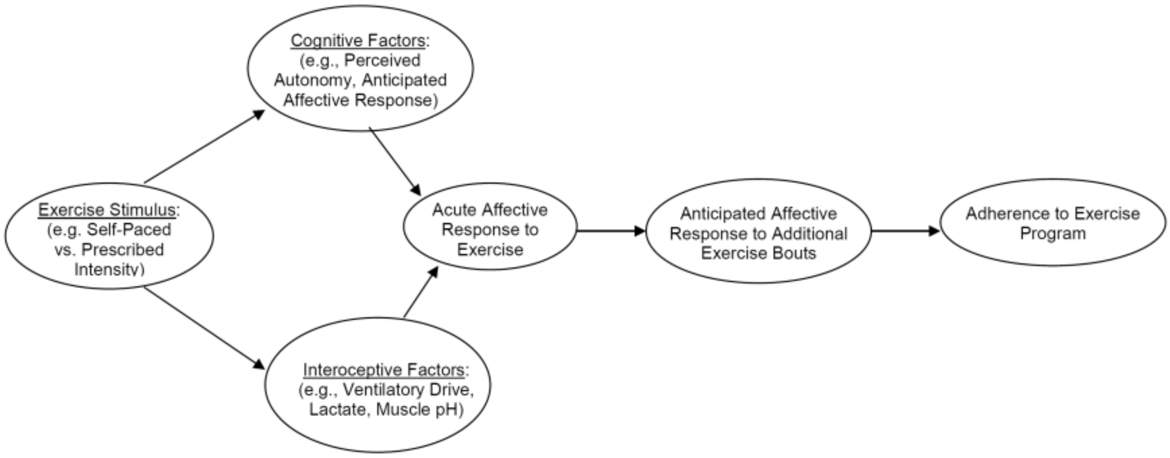

Figure 1

A model of self-paced exercise, affective response, and exercise adherence (D. M. Williams, 2008, p. 482)

Many people avoid physical activity although they know how healthy it is. A possible explanation for this seemingly paradoxical behaviour lies in the theory of *hedonism* (D. M. Williams, 2008). The *hedonistic principle* (Higgins, 1997) assumes that humans choose their behaviour based on the associated pleasure (Russell, 2003). It has been established above that (intense) exercise elicits unpleasant perceptions of strain and fatigue. These perceptions may be consciously evaluated as exciting, rewarding, or enjoyable, but on the basal level of immediate core affect, (intense) exercise is rather unpleasant. Physically active people mostly refer to positive feelings occurring after the exercise or other reasons that motivate them to be active (e.g., socializing, personal goals) (Wienke & Jekauc, 2016). If such factors do not outweigh the immediate negative perceptions of exercise it is not considered a rewarding behaviour and thus not pursued. According to the Affective-Reflective Theory of physical inactivity and exercise (Brand & Ekkekakis, 2018), exercise-related stimuli evoke automatic affective processes and controlled reflective evaluations. When affective and reflective evaluations differ, self-control resources determine which process dictates behaviour. Especially inactive people fail to change their exercise behaviour because negative automatic associations with physical activity dominate their action plans despite reflective knowledge or intention (Brand & Ekkekakis, 2018).

On top of that, athletes often tolerate higher intensities that evoke greater cardiovascular exertion and progress (Glass & Chvala, 2001). This widens the gap between inactive and active people and demonstrates that increasing the tolerance of exercise-induced stress constitutes a relevant factor in health promotion strategies. Ameliorating the immediate responses to exercise by inducing positive emotions or distracting from unpleasant perceptions may change the attitude towards exercise (Sudeck et al., 2016). In fact, enjoyment (Buckworth & Dishman, 2007) and positive affect (Kwan & Bryan, 2010; Margaret Schneider et al., 2009) correlate positively with exercise adherence, while perceived effort and adherence are negatively correlated (Buckworth & Dishman, 2007). Figure 2 demonstrates a possible pathway of how psychoactive drugs (as an example for affect-enhancing/effort-reducing stimuli) can impact physical activity behaviour (Marcora, 2016). The figure shows how perceived effort, affect during exercise, and post-exercise affect influence physical activity behaviour either directly, indirectly, or both. Especially the broad impact of perceived effort is visualized clearly. The model further introduces the concept of self-efficacy as a mediator of physical activity behaviour. This relation has been found before (Wienke & Jekauc, 2016) and is supported by the Social Cognitive Theory of behaviour (Bandura, 2001). Even if the use of psychoactive drugs to achieve activity goals may be unethical, Marcora (2016) could show that reducing perceived effort can be effective in achieving a more positive attitude towards physical activity. The following sections will cover how such effects can be achieved non-invasively.

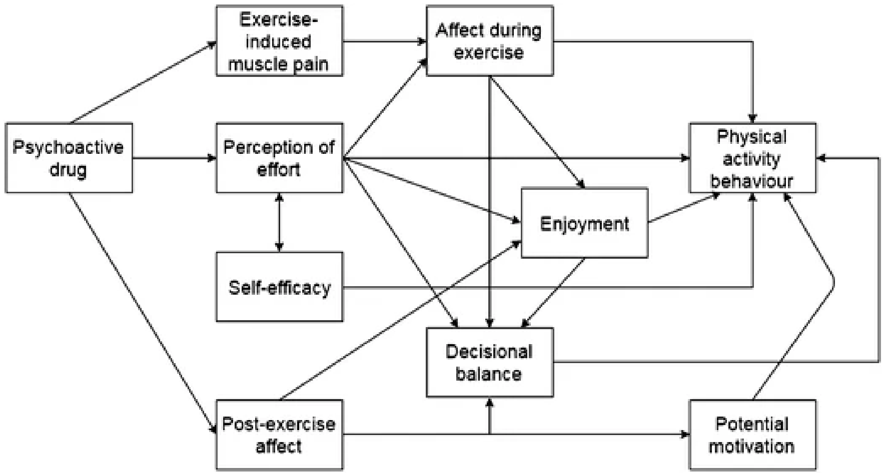

Figure 2

Theory-based psychological mediators of the hypothesised positive effect of psychoactive drugs on physical activity behaviour (Marcora, 2016, p. 2)

2.1.2.4 Attention and Perception during Physical Activity

Bringing together the manifold factors that influence the exercise-affect relation, Ekkekakis (2003) proposed the Dual-Mode Theory (DMT). Similar to D. M. Williams (2008), the theory posits two fundamental sources of affective responses to exercise: (1) Cognitions about the meaning of the exercise, self-perceptions, social contexts, and so forth, and (2) signals of physiological reactions to the exercise. The DMT brings two crucial concepts into the exercise-affect relation: *interoception* and *attentional focus*.

It has been established that both perceived effort and affect are based on the perception of various external and internal signals. *Interoception* covers the perception of internal cues of physiological changes. It is defined as the perception of bodily signals like temperature or pain (Craig, 2002) and signals from the cardiovascular, respiratory, gastrointestinal, and hormonal systems (Herbert et al., 2020). Proprioception, comprising cues from the musculoskeletal system, is sometimes regarded as part of interoception but with a lack of consensus (Herbert et al., 2020). What is certain is that both perceived effort and affect are grounded in the perception of bodily signals. It has further been demonstrated that the same brain structures are involved in emotional processing, viscerosensory state monitoring, cardiovascular arousal processing, and the self-regulation of emotions and behaviour (Herbert & Pollatos, 2012; Herbert et al., 2020; Herbert, Ulbrich, & Schandry, 2007). Evidence for this interrelation has been found by Herbert, Ulbrich, and Schandry (2007), who found negative correlations between interoceptive abilities and covered distance, changes in heart rate, stroke volume, and cardiac output in a cycling exercise.

Poor interoception can predict alexithymia–the inability to perceive and describe one's feelings (Herbert et al., 2011)–and has generally been related to emotion intensity (Herbert et al., 2011; Herbert, Pollatos, & Schandry, 2007). Tsakiris et al. (2011) demonstrated that interoception can affect exteroception by showing that poor interoception allowed more extensive manipulation of body representations in the rubber hand illusion. Similarly, Tajadura-Jiménez and Tsakiris (2014) showed that interoceptive sensitivity determines the perception of self-other boundaries, with low interoception being disadvantageous. On the contrary, better interoceptive awareness seems to relate to an increased tendency to imitate observed movements (Ainley et al., 2014).

Interoceptive abilities can be assessed by three facets: interoceptive sensitivity or accuracy, interoceptive sensibility, and interoceptive awareness (Garfinkel et al., 2015). *Interoceptive sensitivity* is mostly examined through heartbeat detection (HDT) or heartbeat tracking tasks (Garfinkel et al., 2015), where participants need to feel and count their heartbeats without measuring their pulse. Heartbeats occur frequently, are measured with non-invasive methods, and are easily detectable (Garfinkel et al., 2015). In the HDT, the number of counted heartbeats is compared to the actual number of heartbeats measured with an electrocardiogram or optical heartbeat sensors. Sensitivity is calculated as follows (Schandry, 1981):

$$sensitivity = 1 - \left(\frac{|actual\ heartbeats - counted\ heartbeats|}{actual\ heartbeats}\right) \tag{1}$$

Interoceptive sensibility is assessed with questionnaires, thus representing the subjective estimation of one’s interoceptive abilities. As a self-reporting measure, these questionnaires are prone to inaccuracy (Garfinkel et al., 2015). The low correlations of interoceptive sensibility with the other two facets of interoception underpin its dubiety. Besides questionnaires, sensibility can be measured with confidence judgements about interoceptive performance. Combining measures of sensibility and sensitivity yields a score for *interoceptive awareness* (Garfinkel et al., 2015). In the HDT, participants report the number of counted heartbeats and then rate their confidence about their answer. The correlation coefficient between both scores indicates a meta-score of the actual and the perceived sensitivity. This awareness score considers that besides the precise perception of the heartbeat, one must also be aware of this ability. However, a strong correlation (and thus a high awareness score) would also be achieved through low sensitivity and continuously low or high confidence judgments. Especially the combination of low sensitivity and high confidence would falsely suggest high interoceptive awareness. In general, interoceptive awareness must not be interpreted as a definite index of great interoception, as seen by the low correlation between sensitivity and awareness scores (Garfinkel et al., 2015).

Despite the problematic interpretation of the awareness score, the HDT is still a valuable instrument for assessing interoceptive sensitivity because it is one of the few non-invasive measures that reveal how well bodily signals are perceived. Interoceptive sensitivity has shown high test-retest reliability (Ferentzi et al., 2018) and has been linked with emotional processing (Herbert et al., 2011; Herbert, Pollatos, & Schandry, 2007) and cognition (Critchley & Garfinkel, 2018). In a recent review, interoceptive tasks like the HDT showed moderate relations to the amplitude of the heartbeat-evoked potential (Coll et al., 2021). In theory, heart rate is a central performance parameter that also greatly contributes to perceived effort. Consequently, the ability to perceive one's heartbeats is of possible interest in exercise contexts.

Focusing on the perception of such internal bodily signals is considered an *associative* attentional strategy. In contrast, focusing on external sensory cues is a *dissociative* strategy (Lind et al., 2009). The DMT claims that internal and external sensory cues compete for the focus of attention during physical activity (Ekkekakis, 2009) and attentional focus was found to be important for effort perception (Emad et al., 2017; Neumann et al., 2022). A more associative focus leads to higher perceived effort (Pennebaker & Lightner, 1980) and arousal (Yao & Kim, 2019), while dissociation from internal signals can reduce both. In line with the DMT, the effectiveness of an attentional strategy depends on exercise intensity (Ekkekakis, 2003). While dissociation positively impacts perceived effort and affect during low and moderate intensities, an associative focus is necessary to ensure physical integrity during high intensities. Increasing intensity leads to a predominant perception of physiological cues instead of cognitions, thereby inducing an associative attentional focus (Lind et al., 2009). Consequently, attentional focus might explain why perceived effort increases steeply during intense exercise (Ekkekakis, 2009).

Such findings imply that controlling attentional focus might be a successful strategy to regulate subjective appraisal of physical activity. In this context, the presentation of external stimuli during exercise is considered effective because they distract from perceptions of strain. For instance, presenting music or music and video can increase enjoyment and positive affect during exercise, even at high intensities (Jones et al., 2014). Other types of media have evoked similar effects (Bird et al., 2021). The investigation of different attentional foci has revealed that focusing on task-irrelevant stimuli can lead to lower perceived exertion (Emad et al., 2017) but also to reduced performance and perceived pleasure (Bertollo et al., 2015). Whether an external stimulus affects subjective experience positively or negatively seems to depend on the evaluation of the stimulus. If a stimulus is enjoyable or pleasant, it can elevate enjoyment and performance during exercise substantially, while a non-enjoyable stimulus leads to opposite effects (Barreto-Silva et al., 2018; Privitera et al., 2014). Altogether, attentional focus and the stimulus quality seem to affect the relation between attention and exercise. These considerations are particularly important for media-supported exercise.

2.1.3 Action Feedback

A central external stimulus during physical activity is action feedback. Action feedback includes all sensory cues that convey information about the quality, direction, speed, and accuracy of a movement. These signals are used for effort regulation and motor control. Following the Comparator Model (Gray, 1995), every action plan includes an efference copy of the anticipated action effects. The efference copies are compared with the actual sensory feedback to evaluate the quality of an action. This comparison enables adaptation of motor commands and effort and determines the amount of responsibility felt for an action and its effects. Action feedback is thus crucial for self-perception, forming the base for the senses of body ownership and agency. These two senses build the *minimal self* (Gallagher, 2000) and are largely based on comparing interoception and exteroception. The *sense of body ownership* describes the feeling that the body belongs to you and that you can control it. It is “[the] sense that I am the one who is undergoing an experience. For example, the sense that my body is moving regardless of whether the movement is voluntary or involuntary.” (Gallagher, 2000, p. 15). A sense of body ownership arises when actual and expected efferences match, which is also central to the *sense of agency*–the feeling of responsibility for an action and its consequences (Gallagher, 2000). If the consequences of an action match the expectations, a sense of agency arises for the corresponding action (Haggard, 2017). In contrast to the sense of body ownership, a sense of agency only arises with voluntary actions (Haggard, 2017), underlined by the role of choice in agency (Barlas & Obhi, 2013; Caspar et al., 2016). The sense of responsibility for an action leads to a feeling of control and, ultimately, to a sense of competence (Bandura, 2006). The fact that the experiences of competence and self-efficacy play a critical role in physical activity has already been discussed in previous sections. Action feedback now provides an opportunity to influence this aspect of physical activity. That is, the type and quality of sensory action feedback can affect the actor's self-perception which in turn influences performance and the appraisal of the activity.

2.1.3.1 Action Feedback in Locomotion

Locomotion describes all translational movements of the whole body from one place to another (self-motion). This includes walking, running, cycling, or rowing, which can all be considered typical endurance exercises. Sensory cues from the body and the environment are used to control movement parameters like stride length and frequency. Bodily signals include muscle tension and joint angles, while external cues can be air resistance or visual flow. *Visual flow* (or optic flow) is the visible speed of the environment moving towards the actor during self-motion (Warren & Hannon, 1988). It presents as a circle expanding from where the movement is headed (the focus of expansion, FOE) towards the periphery. This circular expansion makes it slower at the FOE and faster on the outsides (Bornstein & Gibson, 1980). The *lamellar flow* at the periphery thus induces a very different perception of movement speed than the *central flow* near the FOE. In fact, speed estimations based on lamellar flow are more accurate (Banton et al., 2005; Campos et al., 2007). Visual flow speed conveys performance information during self-motion (Ludwig et al., 2018) and such performance information is usually used to evaluate (athletic) abilities, goal-oriented motor control, or pleasantness of the activity. Relevant findings on visual flow in VR are discussed in Section 2.3.1.

2.2 Virtual Reality

There are various possibilities to present visual flow during physical activity. Virtual reality (VR) is one of them. Sherman and Craig (2002) define VR as “[...] a medium composed of interactive computer simulations that sense the *participant's* position and actions and replace or augment the feedback to one or more senses, giving the feeling of being mentally immersed or present in the simulation [...]” (Sherman & Craig, 2002, p. 13). Other authors define VR as a computer-generated environment that can be perceived (mostly visually) and is controllable through interaction (Akbaş et al., 2019). The central characteristics that are consistently found in different VR definitions are that it is a *computer-based simulation* that is *interactive*, gives *sensory feedback*, and creates the *feeling of being in the virtual environment*. These characteristics enable realistic experiences and modifications of situations that would be dangerous, expensive, or impossible in the real world. Situations can be repeated frequently and independently of environmental conditions. VR provides action feedback, can induce embodiment of a virtual agent, and thereby affect actions, perceptions, and emotions. These virtues make it a valuable tool in various areas of diagnostics, the treatment of mental health issues, and the promotion and modification of physical activity (Akbaş et al., 2019; Neumann et al., 2018; Riva et al., 2019).

The use of VR has a firm foothold in science, albeit in very different formats. Apart from head-mounted displays (HMDs), which are typically associated with VR, many other configurations can be used to create virtual environments. The different formats of VR vary in their usability, mostly because of differences in costs, setup effort, or programmability. Further, the devices evoke different levels of *immersion*–the degree of involvement (Jennett et al., 2008). Setups can thus be classified as immersive (e.g., HMDs) or non-immersive VR (e.g., desktop VR, video games).

Immersion manifests in three central signs: lack of awareness of time, loss of awareness of the natural world, and involvement and a sense of being in the task environment (Jennett et al., 2008). The feeling of being in the virtual world can also be described as a *sense of presence* (Jennett et al., 2008), and both terms are sometimes used interchangeably. Presence and immersion are closely related concepts, and it is argued that immersion can be measured by measuring presence (Yao & Kim, 2019). Other authors claim that immersion and presence can arise independently (Jennett et al., 2008) or that immersion is a subcomponent of presence (Witmer & Singer, 1998). Immersion is also sometimes used to describe the quality of a medium rather than the personal experience (Slater & Wilbur, 1997). HMDs typically enable higher degrees of immersion than screen or desktop setups (Yao & Kim, 2019), mainly because they provide a larger field of view (FOV) than most screens. Although the FOV of an HMD is smaller than during natural vision, HMDs enable exploration of the surroundings through head movements, which largely contributes to the feeling of being surrounded by the environment (Campos et al., 2007). Secondly, HMDs completely cut off other visual cues, eliminating visual distractions and increasing the sense of presence in the VR.

2.2.1 The Virtual Self

Many VR setups provide a virtual agent representing the user in the virtual world. This agent or *avatar* can be wholly or partly visible from a first- or third-person perspective and is controlled through external devices or user movements. Avatars contribute to the interactivity of VR by providing action feedback. Seeing the virtual body move congruently with one's actions enhances the feeling of control over the avatar (Brugada-Ramentol et al., 2019). Consequently, these visual stimuli can be integrated with proprioceptive cues to control motor parameters. Given the possibilities of VR, avatars can be programmed to provide specific visual action feedback that can also contradict proprioception. Gokeler et al. (2016), for instance, enabled short-term improvements of knee mobility in patients that underwent anterior cingulate ligament reconstruction by presenting virtual avatars with unrestricted knee mobility.

Effects of avatar design on user behaviour, performance, or perception have been largely attributed to the *embodiment* of the avatar. That is, the avatar is perceived as the virtual replacement of the user, which induces an illusionary sense of ownership for the avatar (Maister et al., 2015). Illusions of body ownership have been well-investigated in the context of the rubber hand illusion. These experiments have shown how synchronous visuotactile stimulation of a rubber hand and the real hand leads to misperceptions about the location of the own hand, called *proprioceptive drift*. The stronger the illusion, the larger the tendency to locate the own arm closer to the artificial arm (Tsakiris et al., 2011). Expanding this ownership illusion to the whole body constitutes a large part of VR research. The highly immersive medium has demonstrated the ability to induce such full-body illusions (Maister et al., 2015; Peck et al., 2013; Slater et al., 2010).

It is assumed that avatars resembling the user are more likely to be embodied (Maselli & Slater, 2013). Other studies have shown that avatars can be embodied despite having a different skin colour (Kilteni et al., 2013), gender (Schulze et al., 2019), age

(Banakou et al., 2018), or being non-human (Aymerich-Franch, 2012). Banakou et al. (2013) showed that adult participants embodied an avatar that looked like a 4-year-old child, and even a geometric figure can be perceived as a virtual representation of the user (Aymerich-Franch, 2012) when user and avatar movements are synchronized.

Moreover, perspective plays a critical role in embodiment. A first-person perspective (1PP) usually facilitates embodiment (Gorisse et al., 2017; Maselli & Slater, 2013), while a third-person perspective (3PP) may allow for a more objective or neutral perception of the avatar (Neyret et al., 2020). A 1PP has been sufficient to induce embodiment, even without additional sensory input (Carey et al., 2019) or albeit asynchronous tactile stimulation (Maselli & Slater, 2013). Embodiment can also be achieved with a 3PP but comes with restrictions on target location and reaching movements (Debarba et al., 2015). Furthermore, a 1PP enables a more natural (and familiar) perception of the immediate surroundings, which is especially helpful in navigation (Medeiros et al., 2018).

The embodiment of the avatar brings some consequences. Numerous studies have demonstrated that avatar appearance can induce behavioural and attitudinal changes in the user (Banakou et al., 2013; Czub & Janeta, 2021; Kocur et al., 2021; Ratan et al., 2020), referred to as the *Proteus Effect* (Yee & Bailenson, 2007). The Proteus Effect implies that users infer characteristics, abilities, and attitudes from the outer appearance of the avatar and then behave accordingly (Yee & Bailenson, 2007; Yee et al., 2009). Self-Perception Theory (Bem, 1972) offers an explanation for this effect, suggesting that people usually make inferences about themselves by perceiving their behaviour and appearance like a third party would. They then adapt their beliefs and behaviour to match these inferences, so that, for instance, people behave more aggressively when wearing black uniforms (Frank & Gilovich, 1988). Similarly, the appearance of a virtual avatar can impact behaviour and attitudes through inferences and assumptions about abilities and character traits. This has been demonstrated in live-action roleplay games, showing that players act according to their virtual appearance and the complexion of their counterparts (Yee et al., 2009). Since then, the Proteus Effect has been found in video games (Yang et al., 2014), exergames (Li et al., 2014; Peña et al., 2016), and VR (Kilteni et al., 2013; Kocur et al., 2021; Neyret et al., 2020). Banakou et al. (2018) used avatars resembling Albert Einstein, thereby successfully increasing user performance in a cognitive task. Additionally, this embodiment improved attitudes towards the elderly. Embodying Sigmund Freud in VR has shown analogue modulations of problem-solving and mood regulation (Osimo et al., 2015). Other cognitive qualities like size estimation have been impacted by avatar design so that adults embodying child-like avatars showed a reduced ability to estimate object sizes compared to those embodying adult avatars (Banakou et al., 2013). Similarly, the avatar’s age affected post-embodiment walking speed (Reinhard et al., 2020). Such effects have also been attributed to priming, suggesting that visual stimuli in the VR activate associated behaviours independent of an embodiment of the avatar (Peña et al., 2009).

2.2.2 The Virtual Environment

In addition to avatars, the design of the virtual environment itself also offers many opportunities to influence users. First and foremost, the virtual scene sets the situational context. It is possible to create natural or abstract environments, recreate real places, include all kinds of objects or creatures, and design all these aspects individually regarding their size, colour, and interactivity. VR can therefore be used as a flexible and economical tool to induce specific emotions. Visualizing fog, destroyed objects, and injured or dead people can evoke stress and anxiety (Crescentini et al., 2016). Fear can be induced through dark surroundings and disfigured zombies approaching (Lin, 2017), and showing calm natural scenes can improve relaxation (Anderson et al., 2017).

The sense of presence is considered highly related to the realism of the virtual world (Gonçalves et al., 2023; Yao & Kim, 2019) and higher levels of presence, together with a suspension of disbelief, are associated with more natural behaviour in VR (Harter et al., 2011; Slater & Wilbur, 1997). Gonçalves et al. (2023) provide a comprehensive review of different approaches to realism in VR, discussing the concepts of fidelity, plausibility, immersion, coherence, and internal consistency. The authors differentiate between subjective (perceived) and objective (device-dependent) realism. The most relevant implication of this review is that subjective realism does not depend on naturalism but rather on coherent depictions of action effects that either follow the real-world or an inherent taxonomy. According to Slater (2009), such valid effectual actions create a *plausibility illusion* which (together with presence) determines realistic responses and behaviour in VR.

Section 2.1.3 has covered the relevance of action feedback for regulating physical effort, motor control, and developing a sense of agency. In line with the Comparator Model (Gray, 1995), the sense of agency derives from the comparison of anticipated and actual sensory outcomes of a voluntary action (Kalckert & Ehrsson, 2012). However, research is still unequivocal about the prerequisites of the sense of agency. It requires active movement (Kalckert & Ehrsson, 2012) and, most notably, spatial (Farrer et al., 2008) and temporal congruence (Kalckert & Ehrsson, 2012; Keenaghan et al., 2020). Further, freedom of action choice (Barlas & Obhi, 2013) and the strength of perceived body ownership (Banakou & Slater, 2017; Kalckert & Ehrsson, 2012; Kong et al., 2017) have been associated with increased agency. Villa et al. (2018) demonstrated that, although both aspects are relevant for the sense of agency, movement execution is more influential than goal attainment. Contrarily, David et al. (2016) found outcome feedback to be more meaningful for the sense of agency. Wen et al. (2015) also suggest that goal-related feedback outweighs movement feedback when the action-feedback relation is uncertain. Despite this lack of clarity about the origin of agency, it can be evoked by showing manipulated action feedback. Users then report agency for actions they did not execute at all or in a different quality. This has been demonstrated for speaking (Banakou & Slater, 2017), hand movements (Brugada-Ramentol et al., 2019; Kalckert & Ehrsson, 2012), or walking (Kokkinara et al., 2016).

2.3 VR-based Exercise

The previous sections have demonstrated how both physical activity and VR can impact perception and behaviour. Given their individual advantages, the effects of combining physical activity and media have been the object of a large proportion of recent research. Studies on exercising with video games have shown increased enjoyment, engagement, and performance compared to conventional exercise (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 & Kim, 2019). Such effects have been attributed to distractive properties, the gamification of the exercise, or avatar design (Li et al., 2014; Peña et al., 2016).

As a highly immersive medium, VR enables substantial dissociation from internal cues, which has positively affected subjective parameters in cycling (Mestre et al., 2011; Wender et al., 2022). VR has been useful in teaching motor skills (Kilteni et al., 2013; Pastel et al., 2023) and pacing strategies (Hoffmann, 2011) and can increase physical performance (McClure & Schofield, 2020). Subjective and objective exercise parameters have been affected by displaying coaches (Mestre et al., 2011), opponents (Mouatt et al., 2020), or presenting manipulated action feedback (Parry et al., 2012). Matsangidou et al. (2017) manipulated virtual weight size in a strength endurance task and showed a significantly larger time to exhaustion when the virtual weight was smaller than the real weight. Heart rate, perceived effort, and pain were similarly reduced by this visual manipulation. Wender et al. (2022) also found effects of VR on pain and performance. They demonstrated that VR with a low perceptual load enabled higher exercise intensity despite greater leg muscle pain compared to conventional cycling.

The Proteus Effect has affected perception, behaviour, and attitudes in various areas (see Section 2.2.1; Ratan et al., 2020). Exercise is no exception to this. To induce the Proteus Effect in exercise contexts, avatars are designed to convey different levels of athleticism or physical ability through age, body weight, or muscularity. Kocur and colleagues have demonstrated that muscular avatars impact performance and perception in strength (Kocur et al., 2020) and endurance tasks (Kocur et al., 2021). That is, embodying a muscular avatar reduced RPE and improved strength during an isometric grip task (Kocur et al., 2020), and reduced RPE and heart rate across time during incremental cycling (Kocur et al., 2021). In both studies, the athletic appearance of the avatar made the same exercise appear less strenuous, while performance could be upheld or increased. Czub and Janeta (2021) also showed increased performance (but no differences in RPE) in a VR-based weightlifting exercise with a muscular avatar compared to exercising in front of a mirror. Similarly, the avatar's age has affected post-embodiment walking speed in young adults (Reinhard et al., 2020). These findings demonstrate how stereotypes associated with appearance affect user behaviour and appraisal.

All in all, utilizing VR has been helpful in influencing subjective and objective parameters and perceptions of physical activity and exercise across disciplines.

2.3.1 Visual Flow in VR-based Exercise

In the context of VR-based exercise, scene design is essential for providing action feedback. The role of action feedback for subjective and objective performance parameters and the sense of agency has been established in previous sections. In VR-based exercise, such feedback can be easily manipulated, conveying false information about the timing, direction, location, or quality of actions. However, some peculiarities must be considered.

On the one hand, VR mainly provides visual feedback. As action effects in the real world are perceived as multisensory, VR lacks some facets for assessing action quality. Adding auditory or tactile feedback can enrich the experience and make it more realistic (Löchtefeld et al., 2016). However, the possibilities for this depend on the VR system and the task. Visual signals thus play a central role in locomotive movements in VR. Here, the second peculiarity of VR comes into play: the limited FOV of HMDs, which influences the experience of presence (see Section 2.2) and the perception of visual signals. It could be shown that movement speed is estimated differently in VR compared to real-world experiences (Janeh et al., 2017), which depends largely on the FOV (Hussain et al., 2020). This is mainly rooted in the reduced proportion of visible lamellar flow with a reduced FOV. Besides, speed is usually underestimated when only visual but not vestibular stimuli provide movement information (Jörges & Harris, 2022), which is the case in many VR setups. As it is rarely a question of analysing specific speeds but rather differences between slow and fast or appropriate and inappropriate speeds, VR is nevertheless well suited for investigating the effects of visual flow speed.

Speed perception is a critical aspect of traffic research, considering that speeding is one of the major causes of car accidents (Høye, 2020; Job & Brodie, 2022). By modifying the width or spacing of road markings and thereby altering visual flow and speed perception, such dangerous behaviour can be influenced (Garach et al., 2022; Iio et al., 2023). The effects of manipulated visual flow speed on behavioural and perceptual parameters have been demonstrated in VR for passive movements like driving or rollercoaster riding. Pretto and Chatziastros (2006) showed that fast visual flow slowed down users of a driving simulation. In a study on flow and enjoyment, Stephens and Smith (2022) demonstrated that both aspects increased with visual flow speed during driving and rollercoaster riding.

Active movements, especially walking, display somewhat ambiguous relations between visual flow speed and motor parameters. On the one hand, visual flow speed manipulations in VR have been found to evoke decelerated walking to avoid stumbling or falling–no matter if the visual flow is sped up or slowed down (Janeh et al., 2017). Other studies suggest linear adaptations of gait parameters to conflicting visual flow (Porras et al., 2017). Due to the brain's fast integration of visual information, visual flow outweighs other sensory cues in the primary phases of motor control. That is, even when visual flow contradicts proprioceptive information, movements are initially adapted according to the visual cue, although this effect diminishes over time (Prokop et al., 1997).

Speed perception further affects distance estimation, which is crucial during activities where a target distance must be completed. Hence, manipulated visual flow speed should influence the estimated distance to completion and consequently affect effort monitoring and pacing. Parry et al. (2012) have found that slower visual flow improved cycling performance. Participants completed a 40-km ride on an ergometer, aiming to match their power output to a previously assessed baseline. Despite this matching task, participants increased their power output when being presented with slow visual flow. Moreover, they reported lower perceived effort in this condition. The authors assume that the visual flow conveyed false feedback on the remaining distance/time, leading to underestimations of effort compared to the baseline trial (Parry et al., 2012).

Yasukawa et al. (2021) also looked into VR-cycling and found no effects of visual flow speed on exercise parameters. However, they revealed that fast visual flow increased ratings of pleasure and vitality on the Two-Dimensional Mood Scale.

The past sections clarified that avatar appearance and visual flow convey performance information. Avatar design does this more indirectly by visualizing athleticism through muscle mass or body size. Visual flow, on the contrary, is a straightforward sensory consequence of the movement and thus immediately related to the physical effort. The faster the movement, the faster the visual flow. This inherent logic makes visual flow a reliable source for performance evaluation, even when it is manipulated. Above all, virtual visual flow must be *plausible* since plausible action-effect associations improve the subjective realism of VR and enable natural behaviour in virtual environments (Gonçalves et al., 2023; Slater, 2009).

2.3.2 Risks of VR-based Exercise

Despite the previously described merits of VR, it should be used with precaution. Merging a virtual and the real world while sealing users off from their surroundings comes with peculiar risks. The following aspects specifically apply to the use of HMDs and should be considered for private and scientific applications.

Users of commercial HMDs are provided with safety instructions to minimize accidents and injuries. Especially for applications that require volumetric movements, users are instructed to clear the playing area of obstacles. Some devices let users define a *Chaperone*–a safe playing area with visible borders in VR. Still, available space differs substantially between users and collisions with furniture, other people, or pets are not unusual. Such incidents can be rooted in scarce space, wrong setup, or high immersion into the VR. The latter often leads to injuries because the VR prompts falling or jumping (Jelonek, 2023).

These concerns are less relevant for in-place applications like stationary cycling, but locomotive exercise sets a different challenge: minimizing discomfort and sickness during simulated forward movement. Motion sickness is a familiar phenomenon in passive movement. It arises from disparities between visual and vestibular information and induces discomfort to the point of dizziness, nausea, difficulties in motor control, disorientation, or having to throw up (Golding, 2016; Nürnberger et al., 2021). A particular case is the *visually induced motion sickness* (VIMS), which arises when only visual movement cues are present (Kennedy et al., 2010), like during self-motion simulations in VR. The presentation of visual flow in VR is thus accompanied by the risk of VIMS or *cybersickness* (motion sickness induced by technological devices). Chattha et al. (2020) could show that gender and the pleasantness of the virtual scene affect VIMS. In a recent review, Chang et al. (2020) identified aspects of hardware, content, and users as central drivers of cybersickness. Despite technological advances, hardware issues like latency, FOV, or flicker affect user comfort in VR by creating temporal or spatial mismatches. Regarding the simulation of self-motion, large visual flow speeds and low oscillatory frequencies seem to increase symptoms of motion sickness. Further content factors for cybersickness are the controllability and graphic realism of the VR or the duration of usage. User factors include age, gender, and previous experience (Chang et al., 2020). Additionally, displays with stereoscopic view provoke a vergence-accommodation conflict–a "[...] mismatch between vergence, where the eyes meet as the object of interest, and accommodation, where the eye lenses are tuned to focus on" (Ozkan et al., 2023, p. 102), which typically contributes to cybersickness (Kramida, 2016). All these factors must be balanced between user comfort and sense of presence.

Creating a sense of presence in a virtual environment is one of the key virtues of VR. However, being totally submerged in a virtual setting, possibly in combination with embodying a virtual avatar, can also have adverse psychological effects. VR has effectively induced dissociation and out-of-body experiences (Aardema et al., 2010; van Heugten-van der Kloet et al., 2018), as well as depersonalization and derealization (Peckmann et al., 2022). These effects are mostly temporary (Barreda-Ángeles & Hartmann, 2023) but should be considered by frequent users. While realism is important for the sense of presence, VR-based exercise should not be configured in a way that encourages users to prefer it over activities in the real world. This would have psychological and social consequences that are not worthwhile.

Lastly, despite the usability of VR in various learning and training contexts, its mechanisms often lack transferability to reality, which can impede progress and attenuate reactions to real-life cues (Engelbrecht et al., 2019). Therefore, VR should be used as an extension of conventional exercise and not replace it.

3 Summary of the State of Research

Music, video games, and VR have demonstrated their impact on various objective and subjective parameters of physical activity. Given the interplay of these parameters and their relevance for immediate and long-term behaviour according to the hedonistic principle (Higgins, 1997), Affective-Reflective Theory of physical inactivity and exercise (Brand & Ekkekakis, 2018), and Social Cognitive Theory (Bandura, 2001), all facets of effort should be considered when investigating effects of media on physical activity. In this context, VR has emerged as a beneficial medium, offering an immersive virtual experience and thus exceeding the positive effects of video games. The possibilities of avatar and scene design enable body ownership and agency illusions, which impact perception and behaviour in exercise and other contexts. Avatars have received a lot of attention, with studies investigating the Proteus Effect (Yee & Bailenson, 2007) in different areas. Such effects have been associated with body ownership illusions (Maselli & Slater, 2013), Self-Perception Theory (Bem, 1972), and visual priming (Peña et al., 2009). Similar effects have been elicited by conveying false feedback and manipulating the sense of agency in VR. Following the Comparator Model (Gray, 1995), the sense of agency is critically based on comparisons of anticipated and perceived output of voluntary actions. Since visual flow provides relevant performance feedback in locomotion, it constitutes an action-related stimulus that could affect the sense of agency in VR-based cycling. In fact, a lot of research on VR-based locomotion is aimed at identifying the impact of manipulated visual flow speed. However, most of these studies examine passive motion (e.g., driving, rollercoasters), comfortable walking, or pacing strategies (e.g., during time trials). Moderate-intensity exercise, which constitutes a great part of training programs and recreational sports, is rarely investigated.

Taking together the presented findings about avatar effects, false feedback, visual flow, and the different exercise parameters, three studies were planned. The overall aim was to investigate how visual flow speed affects objective and subjective parameters of moderate-intensity cycling in VR. This was tested with three similar setups that are described in the following sections.

4 First Study

Effects of Visual Flow Velocity on Cycling Experience in Virtual Reality[1]

4.1 Goals and Hypotheses

The goal of the first study was to investigate the effects of visual flow speed on heart rate, perceived effort, arousal, and affective valence during moderate-intensity cycling. The study aimed to reproduce avatar effects (Kocur et al., 2021) through visual flow speed manipulations. Additionally, based on the relevance of attentional focus for subjective exercise parameters, the role of interoception for visual flow speed effects was investigated. The goal was to uncover individual differences in the impact of visual flow speed manipulations due to interoceptive abilities.

Avatar design has impacted user behaviour and performance (Kocur et al., 2021; Yee et al., 2009), and manipulated action output has evoked agency illusions in VR (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 configurations (Kocur et al., 2021).

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[1] The corresponding paper to this study is published: Luttmann, C., Mayer, M., Siebertz, M., Jost, L., Henze, N. & Jansen, P. (2024). Effects of Visual Flow Velocity on Cycling Experience in Virtual Reality. *German Journal of Sports and Exercise Research*. 10.1007/s12662-024-00964-4

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, it was hypothesized that:

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

H2: Perceived effort 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. It was therefore expected 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 actual performance 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.

4.2 Method

4.2.1 Design

In a repeated measures within-subject design, each participant completed three experimental trials, each one week apart. During each trial, participants cycled on an ergometer for 20 minutes. A virtual cycling track was presented through an HMD, creating the impression of moving forward. The speed of the virtual scene varied across three conditions: medium speed at 20 km/h, slow speed at 16 km/h (-20 %), and fast speed at 24 km/h (+20 %). The order was randomized and counterbalanced between participants. All experimental procedures were in accordance with the Declaration of Helsinki, and all participants provided informed consent. The study was preregistered at OSF.io[2].

4.2.2 Participants

A power analysis was conducted using G*Power software (Faul et al., 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 = .19), the analysis for a repeated measures ANOVA (within factors, α = .05, f = .15, β = .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 to 35 years enrolled in the movement science degree course were recruited via an online newsletter. Exclusion criteria for participants were acute or

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[2] https://osf.io/wx8kg/?view_only=5fef93566c6349afa5ffe49d1a02e6cb

chronic cardiovascular or muscular diseases, sensitivity to motion and cybersickness, and anxiety triggered by a heightened interoceptive focus during the heartbeat detection task. Eighty-two 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 female, 45 male). One subject had to terminate an experimental trial prematurely due to dizziness caused by the VR, but the trial was analysed as planned. For two participants, one post-experimental 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.

4.2.3 Material

4.2.3.1 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 (Figure 3), 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 2020.3.38f1) and presented in VR by Unity and SteamVR (Valve Corporation, Washington, USA). The avatars were created in Daz Studio 3D (DAZ

Productions, Utah, 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.

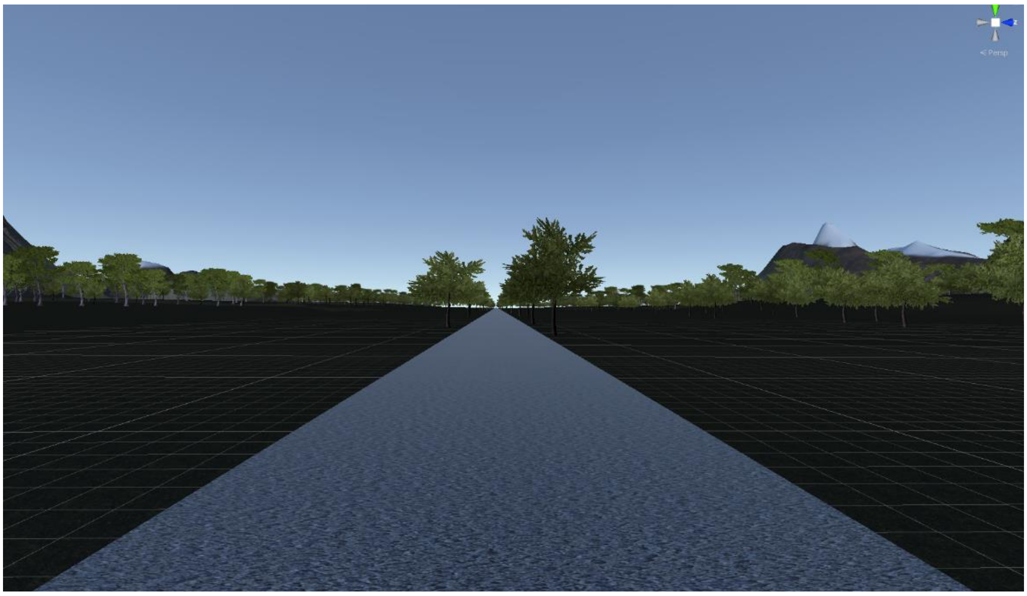

Figure 3

VR scene showing a straight street surrounded by mountains and trees

4.2.3.2 Outcome Measures

During cycling, heart rate, perceived effort, arousal, and valence were recorded every five minutes, resulting in five measures for each variable. Heart rate was measured by a chest strap 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. Perceived effort was assessed with the ASS (Büsch et al., 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 at each scale step that shows consistent matching of the respective label pairs (Büsch et al., 2022). Arousal and valence were assessed with a German adaptation of the Affect Grid (Russell et al., 1989). Participants reported a value between 1 and 9 for each dimension, indicating low or high arousal and negative or positive valence (Russell et al., 1989). Because of its fast and easy use, the Affect Grid 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). Pedalling cadence was recorded every five minutes to ensure it was kept over 50 rpm.

4.2.3.3 Measuring Interoception

A six-interval HDT and confidence judgments were conducted at the beginning of every experimental trial. The task was programmed in and presented by PsychoPy (Version 2021.2.3). Interval length ranged from 25 to 50 seconds in five-second steps, presented in a random order. A custom-built optical heartbeat sensor (SE050, Iduino) was attached to the participant's earlobe, transmitting data 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 data from a simultaneously recorded electrocardiogram (ECG). ECG data was recorded with BrainVision Recorder (Brain Products, Gilching, Germany) and analysed 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 interval. Participants could initiate the next interval by pressing a key that started a five-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”). Interoceptive sensitivity was calculated for each interval and 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 who counted zero heartbeats in more than two intervals automatically received a “0” as their awareness score to avoid contradiction.

4.2.3.4 Post-Experimental Questionnaire

After cycling, participants completed a computerized questionnaire consisting of the I-group presence questionnaire (IPQ, Schubert et al., 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 et al., 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 that aim to measure these constructs for virtual environments. Each scale consists of four to five statements that are rated on 7-point scales 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 impacts the effectiveness of VR (Ijaz et al., 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 that are rated on 7-point scales 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 4-point scales between 1 and 4 that are averaged to calculate the scale scores (Stiller et al., 2004). These scales were chosen because strength and endurance are crucial abilities for cycling performance. The items assessed whether visual flow speed affects post-exercise self-perception, which has been found for avatars (Kocur et al., 2021). An effect of visual flow on self-perceived fitness could underscore its impact on self-perception, even in the absence of changes in the outcome measures.

Table 1

Overview of Measured Variables, Material, and Measurement Time

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 minutes
Perceived effort	ASS (Büsch et al., 2022)	
Affect (arousal and affective valence)	German version of Affect Grid (Russell et al., 1989)	
Cadence	Ergometer (Cyclus2)	During cycling, at 5, 10, 15, 20 minutes
Presence	IPQ (Schubert et al., 2001)	After cycling
Body ownership and agency	"Body ownership" and "agency" scales of BRQ (Banakou et al., 2018)	
Self-perceived strength and endurance	"Strength" and "endurance" scales of PSK (Stiller et al., 2004)	

4.2.4 Procedure

In each trial, participants completed a 20-minute 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 based on 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 (Fünten et al., 2013).

The pedalling cadence had to be kept above 50 rpm to ensure a consistent workload while allowing individually comfortable pedalling 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, perceived effort, arousal, and valence were recorded. After completing the cycling exercise, participants removed the HMD and filled in the computerized questionnaire.

4.2.5 Analysis

The four outcome measures, heart rate, perceived effort, arousal, and valence, were analysed regarding their differences between visual 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 data set as it represented pre-manipulation data.

For statistical analyses, the lme4 package (Bates, 2010) was used to perform linear mixed effects analyses in R (R Core Team, 2012). The maximal models for each outcome measure included visual flow speed (condition), measurement time (measure), and trial time (trial) as fixed effects[3]. As random effects, intercepts for participants and random slopes for all within-subjects effects[4] were included. Random slopes were reduced stepwise following the procedure of Matuschek et al. (2017). Complexity reductions were stopped when a likelihood ratio test with $p < .2$ 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, 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. In addition to the preregistered analyses, pairwise comparisons were calculated when visual inspection suggested a non-linear 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.

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[3] 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.
[4] 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.

To analyse the post-experimental questionnaires, scale means were calculated for each trial. The means were then analysed using linear mixed 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 analyse their effects on presence scores by comparing the respective models. All variables were normalized 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 in the appendix (Section 10.1).

4.3 Results

4.3.1 Heart Rate

The model for the 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 bpm. Measure had a significant main effect on heart rate (5.50 ± 0.23 bpm, $\chi^2_{(1)} = 164.98$, $p < .001$), indicating an increase of heart rate throughout a trial. Trial and condition had no significant main effects on heart rate. The absence of a trial effect confirmed that objective effort was consistent in the three trials. The absence of a condition effect was unexpected. However, visual inspection of heart rate in the different conditions (see Figure 4) suggested a non-linear relationship of visual flow speed and heart rate, so the analysis was repeated for split datasets containing only two conditions. Heart rate differed significantly between slow and medium visual flow conditions (-0.40 ± 0.16 bpm, $\chi^2_{(1)} = 5.90$, $p = .015$), underlining the non-linear 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 visual flow, explorative analyses were executed for this portion of the data. Neither interaction term (condition × awareness; condition × sensitivity) had a significant effect on heart rate.

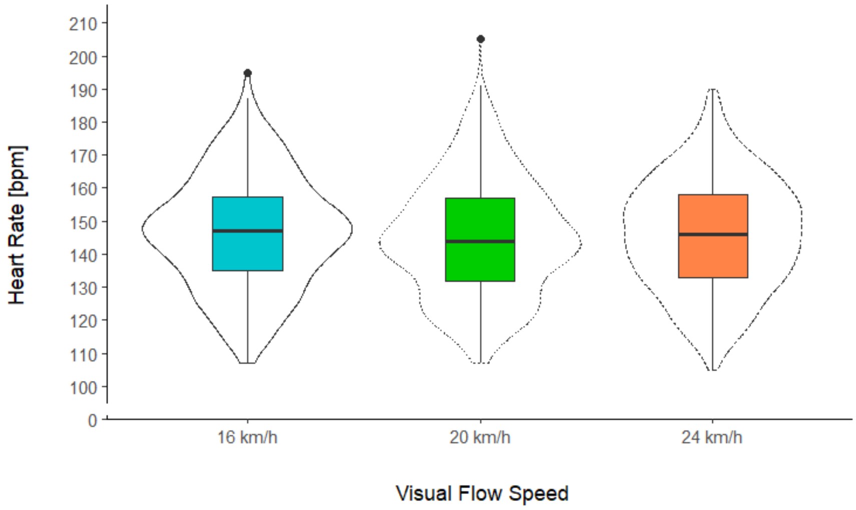

Figure 4

Mean heart rate separated 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

4.3.2 Perceived Effort

The model for the perceived effort 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 perceived effort (0.67 ± 0.03, $\chi^2_{(1)} = 148.87$, $p < .001$), indicating an increase throughout a trial. Trial had a significant main effect (-0.20 ± 0.05, $\chi^2_{(1)} = 14.10$, $p < .001$), suggesting a small training effect from trial to trial. Condition had no main effect on perceived effort and visual inspection did not suggest a non-linear relationship. Pairwise comparisons or exploratory analyses of the effect of interoceptive abilities were thus not calculated.

4.3.3 Affective States

4.3.3.1 Valence

The model for the 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, $\chi^2_{(1)} = 4.53$, $p = .033$), indicating a decrease in pleasure throughout a trial. Trial and condition had no significant main effects on valence. Visual inspection (see Figure 5) suggested a non-linear relationship of visual flow speed and valence, so the analyses were repeated for split datasets containing only two conditions. Condition had no significant effect in either analysis. Explorative analyses were not calculated.

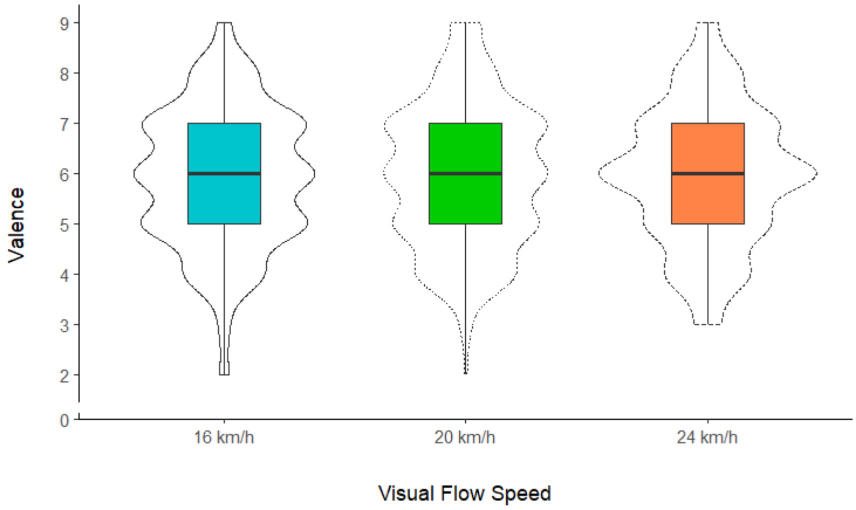

Figure 5

Mean valence seperated 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

4.3.3.2 Arousal

The model for the 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, $\chi^2_{(1)} = 25.68$, $p < .001$), indicating an increase in arousal throughout a trial. Trial had a significant main effect (-0.17 ± 0.08, $\chi^2_{(1)} = 5.39$, $p = .020$), suggesting a reduction of arousal from trial to trial. Condition had no significant main effect on arousal. Visual inspection (see Figure 6) suggested a non-linear relationship of visual flow speed and arousal, so the analysis was repeated for split datasets containing only two conditions. Condition had no significant effect in either analysis. Explorative analyses were not calculated.

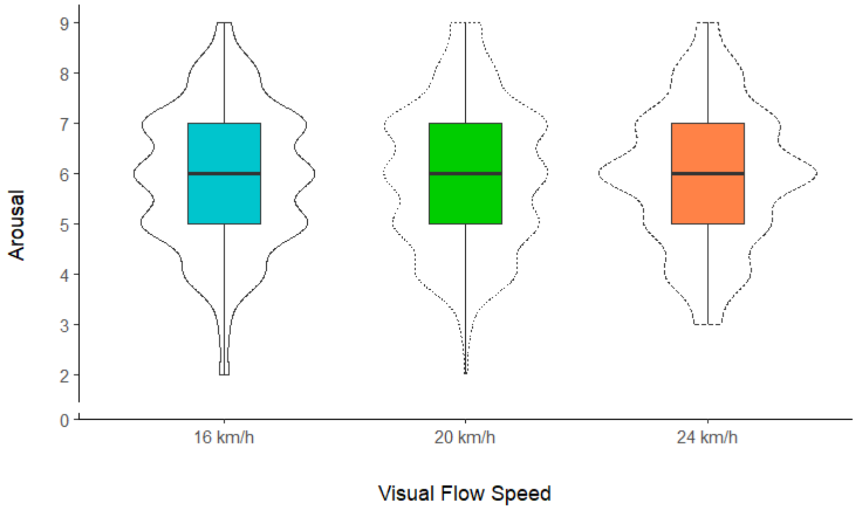

Figure 6

Mean arousal separated 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

4.3.4 Interoception

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

4.3.5 Post-Experimental Questionnaires

4.3.5.1 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, $\chi^2_{(1)} = 10.33$, $p = .001$; endurance: 0.07 ± 0.02, $\chi^2_{(1)} = 15.63$, $p < .001$), suggesting a time effect on self-perceived fitness. However, the estimates are of small absolute value regarding the scale steps of the PSK.

4.3.5.2 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, $\chi^2_{(1)} = 21.70$, $p < .001$).

4.3.5.3 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, $\chi^2_{(1)} = 4.17$, $p = .041$), suggesting a reduction over time.

4.4 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 post-experimental 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 effects similar to those of avatar manipulations.

4.4.1 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. This 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 non-linear 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 the hypothesis but contradicting the assumption of a linear decrease with increasing visual flow speed. Presumably, any visual input deviating from medium speed elevates heart rate. This result is similar to findings from walking studies showing bidirectional changes in gait parameters for isometric and non-isometric 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. The main aim was to investigate the influence of different speeds, not the influence of non-isometric speed gains. Thus, 20 km/h were considered a moderate speed, matching the moderate resistance. Due to the different absolute resistances, participants may have perceived different visual flow speeds as matching. This should have been assessed in the post-experimental 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.

4.4.2 Visual Flow and Perceived Effort

Perceived effort increased throughout a trial, corresponding to the physiological effort depicted by increasing heart rate. The significant trial effect indicates a small training effect for perceived effort, although this effect is irrelevant for practical application, considering the scale steps of the ASS. Visual flow speed did not affect perceived effort significantly, contradicting the hypothesis and previous findings (Parry et al., 2012). This might be explained by the small speed differences, as mentioned above. Furthermore, it remains unclear whether 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 session. The comparison of the present results 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 perceived effort can be interpreted as an amelioration of the exercise, since heart rate was affected by visual flow speed. Assuming a more significant effect for larger speed differences, a heart rate elevation without increased perceived effort during slower visual flow would enable greater training effects without changing objective exercise intensity.

4.4.3 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. The hypothesis that valence would be 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 perceived as neither pleasurable nor unpleasurable. Visual flow speed did not impact this perception, contradicting previous findings about greater pleasure during fast visual flow (Yasukawa et al., 2021). However, the present exercise had a much longer duration and possibly influenced affective states differently. Other impressions might have overlapped with the visual flow-induced pleasure, and eventually they evened each other out. These impressions could be physical strain, boredom, or superordinate emotions.

Arousal significantly increased throughout a trial, which matches increasing perceived 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 the primary hypotheses could not be confirmed, the present results indicate that 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 evoking unpleasant affective states.

4.4.4 The Role of Interoception

Interoceptive abilities have not been found to impact the effect of visual flow speed 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 and interaction effects were only calculated for heart rate. 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 HDT 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 et al., 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. Further, 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 et al., 2017), it may be a more suitable moderator of virtual illusion effects.

4.5 Limitations

The present results are limited chiefly by their low absolute values. Further, verbal reports from participants suggest that the virtual scene was boring and too monotonous. The scene was programmed to seem realistic without being too exciting so participants would not be 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 VR. However, due to the within-subject design, the impact of low immersion should be balanced between the conditions. Another limitation was that visual flow speed was independent of pedalling cadence. Participants with a greater variance in cadence throughout a trial potentially noticed this independence and likely felt low agency for the virtual movement speed. A restriction of cadence may resolve this issue. It further remains unclear whether medium visual flow speed was perceived as such and whether speed differences were large enough to affect the outcome measures. Future studies should include more significant differences and an assessment of speed perception.

4.6 Conclusion

The present study identified hints of a relation between visual flow speed and physiological effort when cycling at a constant load in VR. Larger and more explicit speed differences could evoke significant effects. Further, albeit contradictory to 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 VR-based exercise contexts. Subsequent experiments should take the methodological limitations into account.

5 Second Study

Visual Flow Speed Affects Sense of Agency but not Effort during Cycling in Virtual Reality[5]

Study 1 showed significantly different heart rates between slow and medium visual flow but no other effects of the visual flow speed manipulation. This was partly ascribed to a lack of discriminability of the visual flow conditions due to the inter-trial distance of one week and the speed differences of ± 20 %. Consequently, speed differences were increased to ± 50 % and all trials were executed in one session. Medium visual flow speed was assessed individually to ensure that both fast and slow visual flow were perceived as unmatching. Further, large cadence variations revealed the independence of actual and virtual cycling speed and likely explained the low agency ratings in Study 1. Cadence was thus restricted to a ten-rpm range around an individually comfortable cadence to ensure a consistent workload and enhance the perceived interactivity between the real and virtual cycling speed.

5.1 Goals and Hypotheses

The second study examined the effects of visual flow speed on perceived effort and heart rate during short moderate-intensity exercise bouts. Expecting linear relations between visual flow speed and both dependants, only slow and fast visual flow were investigated.

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[5] The corresponding paper to this study is under review: Luttmann, C & Jansen, P. Visual Flow Speed Affects Sense of Agency but not Effort during Cycling in Virtual Reality.

While the effects of visual flow speed on gait behaviour and distance perception have received considerable scientific attention (Keil et al., 2021; Mohler et al., 2007; Porras et al., 2017), the impact on constant-load cycling has rarely been investigated (Study 1). Findings from bodily illusions in VR suggest that the visualization of athleticism affects exercise parameters so that heart rate and perceived effort are reduced or performance is enhanced (Czub & Janeta, 2021; Kocur et al., 2021). The main goal of this study is to investigate whether this effect of visualized athleticism can also be obtained with a manipulation of the virtual scene. Thus, objective and subjective effort were expected to decrease with increasing visual flow speed. Although heart rate and RPE are tightly coupled with physical effort, the VR is expected to provide credible performance feedback that alters both measures of effort in the same way as avatar design. The following hypotheses were tested:

H1: More athletic avatars have impacted physiological effort in cycling (Kocur et al., 2021). Faster visual flow signifies faster forward movement and thus better performance. This visualization of athleticism was expected to evoke lower heart rates during the fast visual flow condition.

H2: Similar to the effects on heart rate and due to the tight coupling of heart rate and perceived effort, it was hypothesized that RPE are lower during the fast visual flow condition.

5.2 Method

In a repeated measures within-subject design, participants completed two ten-minute cycling trials at a constant resistance in one experimental session. Visual flow speed of the virtual scene was presented at one of two different levels, respectively (medium + 50 % or medium - 50 %). The order of visual flow speed conditions was randomized and counterbalanced between participants. Medium visual flow speed was assessed beforehand to ensure that both experimental conditions would be perceived as unmatching. This design was chosen to adapt to the limitations of Study 1, where speed differences were assumed to be too small, while the distance between exercise bouts was too large. Due to the expected linear relationship between visual flow speed and the dependent variables, medium speed was calibrated but not tested individually to reduce total test time and effort. The study was preregistered at OSF.io[6].

5.2.1 Participants

Based on the effect size $f = .19$ found by Kocur et al. (2021), a power analysis with G*Power (Faul et al., 2009) yielded a required sample size of $N = 55$ (repeated measures ANOVA, $\alpha = 0.05$, $f = 0.15$, $\beta = 0.80$). Sixty-six participants (32 female, 34 male) were recruited to ensure a symmetric distribution to both condition orders and to account for data exclusion. Participants were recruited via an online newsletter and had to confirm they had no acute or chronic cardiovascular or muscular diseases or known sensitivity to motion or cybersickness.

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[6] https://osf.io/bprgc/?view_only=3907dfc6c2724f81b29883821f28a51b

5.2.2 Material

5.2.2.1 Virtual Reality

For the VR system, an HTC Vive HMD (HTC Vive, Taoyuan, Taiwan) was used in combination 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 was programmed in Unity (Version 2020.3.38f1) and presented in VR by Unity and SteamVR (Valve Corporation, Washington, USA). The avatars were created in Daz Studio 3D (DAZ Productions, Utah, USA) and imported into Unity as rigged models. To synchronize the movement of the avatar to the participant's movement, the Final IK Unity Asset (RootMotion, Tartu, Estonia) was used. The virtual scene consisted of a straight road surrounded by trees and mountains.

5.2.2.2 Outcome Measures

During cycling, cadence was calculated from the rotation time of the right pedal by the VR system. The displayed cadence was a moving average of the last five values to prevent too sudden variations. Cadence had to be kept constant at an individual value ± five rpm, which was assessed beforehand. Inside this ten-rpm range, the displayed number was green. Otherwise, it turned red. Heart rate was measured by a chest strap 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. It was recorded at the last ten seconds of every minute. Perceived effort was assessed with the ASS (Büsch et al., 2022), ranging from 1 ("not strenuous") to 10 ("so strenuous that I have to stop"), every three minutes. At these time points, the rating scale was presented in VR and participants answered verbally without stopping the exercise.

5.2.2.3 Post-Experimental Questionnaire

After each trial, participants completed a computerized questionnaire consisting of the IPQ (Schubert et al., 2001), the scales “body ownership” and “agency” of the BRQ (Banakou et al., 2018), the scales “strength” and “endurance” of the PSK (Stiller et al., 2004), and a question about the perception of the visual flow speed.

The IPQ aims to assess the subjective experience of feeling present in the virtual environment (Schubert et al., 2001), which affects the effectiveness of VR (Ijaz et al., 2020). It consists of three scales (“spatial presence”, “involvement”, “experienced realism”) and a general item. Each scale consists of four to five statements that are rated on 7-point scales from -3 to 3. The general item is rated in the same way. A general presence score was calculated from the general item and the spatial presence scale. Presence ratings may explain differences in the outcome measures between conditions and among subjects reporting different degrees of presence.

The BRQ contains five statements on 7-point scales from -3 to 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) in the two conditions. Since the avatar was not manipulated, body ownership was expected to remain stable across conditions. 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 represent central factors for cycling performance.

Each scale contains five statements that are rated on 4-point scales from 1 to 4 (Stiller et al., 2004). The scale were included because avatars have impacted self-perceived fitness after cycling (Kocur et al., 2021). Even in the absence of an effect on heart rate or RPE, an effect of visual flow speed on self-perceived fitness could reveal its impact on self-perception.

A question about the virtual speed was added to evaluate speed perception and determine possible differences between participants with different perceptions. The virtual speed was rated on a 7-point scale from -3 (“too fast”) to 3 (“too slow”). The whole questionnaire was programmed in and presented by PsychoPy.

5.2.3 Procedure

Participants received written information about the study and provided their informed consent. After giving some demographic information, they were seated on the ergometer (Cyclus2, RBM elektronik-automation GmbH, Leipzig, Germany) at a comfortable saddle height and began cycling at the target resistance to determine their comfortable pedalling cadence. During the experiment, cadence had to be kept at this level ± five rpm. The resistance on the ergometer was kept constant at 60 % of the estimated maximum power output throughout the two trials. Maximum power output was estimated based on sex and body weight because determining maximum power output is time-consuming. With all participants being sports students, their fitness level was assumed to be homogeneous. For male participants, body weight (kg) was multiplied by 3 and for female participants by 2.5 to calculate maximum power output (Fünten et al., 2013). Next, participants put on the HMD displaying the experimental scene moving at five km/h. Using two keys that were mounted to the handlebar, participants reduced or increased visual flow speed by five km/h increments until it subjectively matched their cycling at the target cadence and resistance. This visual flow speed was set as their medium speed. Slow visual flow was 50 % slower, and fast visual flow was 50 % faster than the medium speed. Participants were then familiarized with the ASS on the computer and seated on the ergometer with the HMD. The positioning of the virtual avatar was manually adjusted by the experimenter so that the body moved realistically on the virtual bicycle. Visual flow speed was adjusted to the appropriate condition for the first trial. When participants were ready to start, the virtual scene was initiated, and the first measures were recorded. Participants then completed two ten-minute cycling exercises with heart rate being recorded every minute and perceived effort being recorded every three minutes. After completing each trial, participants removed the HMD and filled in the computerized questionnaire. The second trial was started after a break of at least five to a maximum of ten minutes until the heart rate decreased back to the level before the assessment of the comfortable cadence.

5.2.4 Analysis

The two visual flow speed conditions and trials were coded as 0 and 1, respectively. All independent variables were then normalized to their mean. Separate linear mixed model analyses were performed for each dependent variable using the lme4 package (Bates, 2010) in R (R Core Team, 2012). All dependent variables were analysed with the fixed effects "visual flow speed", "minute", and "trial". Interindividual differences in the outcome measures between participants were included in all models by adding the random effect "participant". For each measure, a maximal model with random slopes for all fixed effects was defined. Random slopes were reduced stepwise following the procedure of Matuschek et al. (2017). Complexity reductions were stopped when a likelihood ratio test with $p < .2$ indicated a loss in goodness of fit. Subsequently, non-significant fixed effects, indicated by a likelihood ratio test with $p < .05$, were removed from the model. Assumptions of normality, linearity, and homoscedasticity were checked visually.

The questionnaires were analysed by calculating the respective scale scores and performing linear mixed model analyses. The fixed effects were visual flow speed and trial. Random slopes for each fixed effect and a random intercept for participant were included. The model reduction procedure was analogous to the outcome measure analyses. Cadence was analysed exploratorily with linear mixed models to determine differences between conditions that could account for the results of heart rate and perceived effort. The procedure was analogous to the analyses of heart rate and perceived effort.

For each model, absolute effect sizes, χ^2-, and *p*-values are reported. Complete estimates, standard errors, confidence intervals, χ^2-, and *p*-values are provided in tabular form in the appendix (Section 10.2).

5.3 Results

Six participants were excluded from all analyses because unprecise motion tracking disturbed the correct cadence display. Consequently, data from 60 participants (30 male, 30 female) was analysed. The first measure of each variable was omitted from statistical analyses as it was uninfluenced by visual flow speed. Quartiles (Q) and interquartile range (IQR) were used to identify outliers. Values below Q1 - 1.5 * IQR or above Q3 + 1.5 * IQR were removed from the dataset.

5.3.1 Heart Rate

Heart rate averaged at 135.97 ± 17.87 bpm after removing outliers. Values below 84 or above 188 bpm were considered outliers. 18 recordings from two participants were over 188 bpm and removed from the dataset for heart rate analysis. Heart rate increased rapidly in the first minute and then continued to rise slowly until the end of the exercise (see Figure 7).

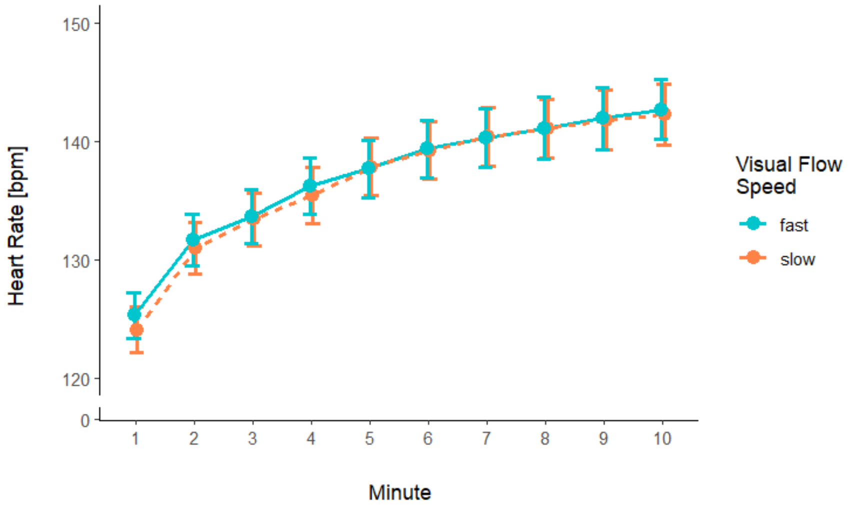

Figure 7

Heart rate over the course of a trial, separated by visual flow speed. The points represent mean heart rates. The length of the whiskers corresponds to one standard error

Statistical analysis of heart rate revealed an estimated intercept of 136.75 ± 2.31 bpm. Heart rate increased throughout a trial, indicated by the significant effect of "Minute" (1.74 ± 0.11, $\chi^2_{(1)} = 97.21$, $p < .001$). Heart rate in the second trial was significantly higher than in the first trial (2.82 ± 0.44, $\chi^2_{(1)} = 31.94$, $p < .001$). Visual flow speed did not affect heart rate (0.19 ± 0.44, $\chi^2_{(1)}$ = 0.19, p = .662). Figure 8 shows the mean heart rates separated by conditions.

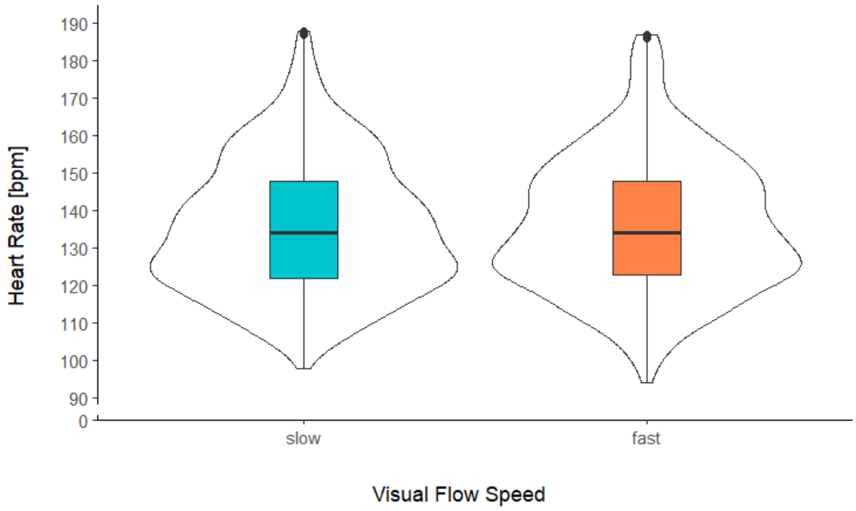

Figure 8

Heart rate separated by visual flow speed conditions. 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

5.3.2 Perceived Effort

Perceived effort followed the heart rate course (see Figure 9) and averaged at 3.90 ± 1.85, suggesting a low to medium subjective exertion. No outliers were identified.

Statistical analysis of perceived effort revealed an estimated intercept of 4.76 ± 0.11. Perceived effort increased throughout a trial, indicated by the significant effect of “Minute” (0.25 ± 0.01, $\chi^2_{(1)}$ = 248.29, p < .001). Perceived effort in the second trial was significantly higher than in the first trial (0.35 ± 0.06, $\chi^2_{(1)}$ = 30.84, p < .001). Visual flow speed had no effect on perceived effort (-0.11 ± 0.06, $\chi^2_{(1)}$ = 3.29, p = .07). Figure 10 shows the mean RPE separated by conditions.

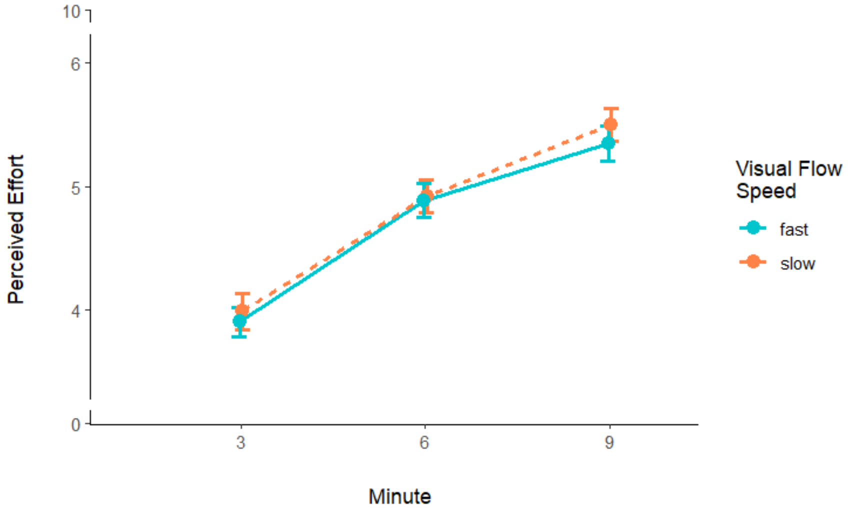

Figure 10

RPE over the course of a trial, separated by visual flow speed. The points represent mean RPE. The length of the whiskers corresponds to one standard error

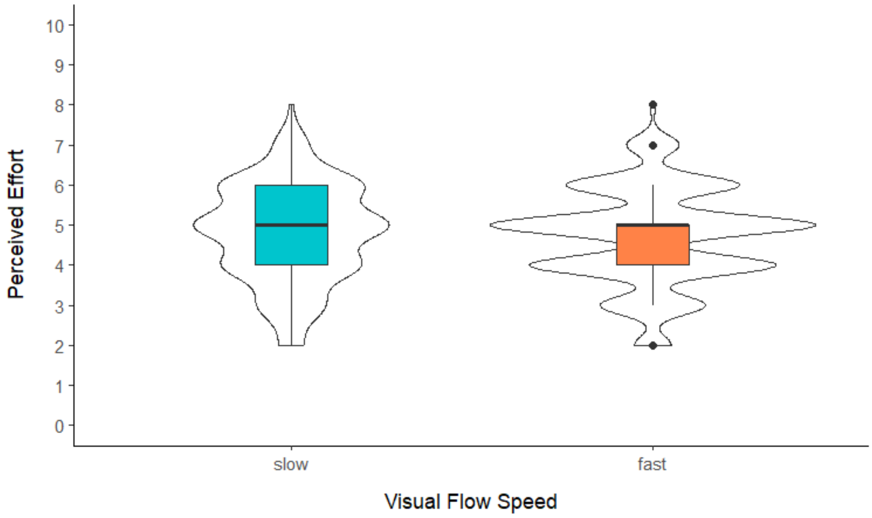

Figure 9

RPE separated 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

5.3.3 Cadence

Cadence was analysed exploratorily to check whether visual flow speed affected motor control during cycling. Cadence averaged at 58.77 ± 8.10 rpm after removing outliers. Values below 34.84 or above 83.88 rpm were considered outliers. 20 recordings from one participant were above 83.88 rpm and removed from the dataset for cadence analysis.

Analysis with linear mixed models revealed an estimated intercept of 58.77 ± 1.05 rpm. Cadence increased slightly throughout a trial, indicated by the significant effect of "Minute" (0.10 ± 0.02 rpm, $\chi^2_{(1)} = 16.33$, $p < .001$). Cadence in the second trial was significantly higher than in the first trial (0.54 ± 0.17 rpm, $\chi^2_{(1)} = 9.59$, $p = .002$). Faster visual flow coincided with significantly lower cadences (-0.79 ± 0.17 rpm, $\chi^2_{(1)} = 19.50$, $p < .001$). Mean cadences, separated by conditions, are shown in Figure 11.

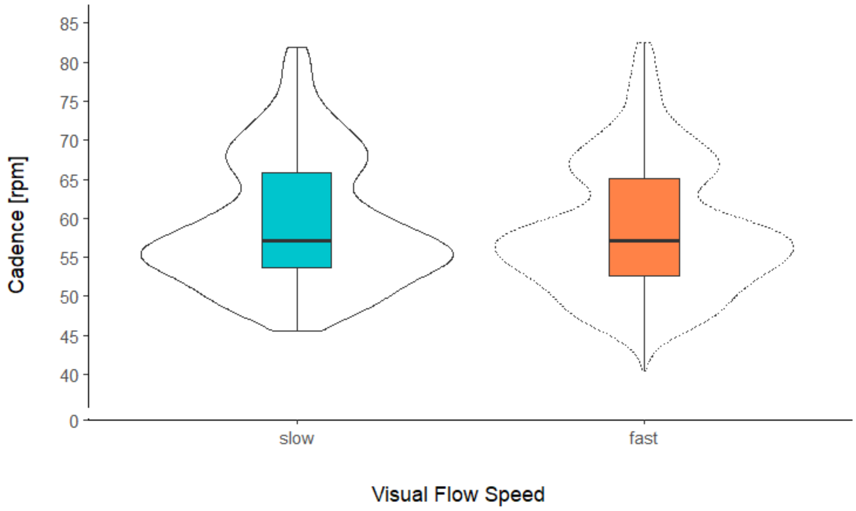

Figure 11

Cadence during the two trials, separated 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

Since cadence was restricted to a ten-rpm range around the comfortable cadence, cadence violations were calculated and statistically analysed. There were 3.30 ± 4.24 cadence violations on average after removing outliers. Values above 17.5 were considered outliers. Fifteen participants had more than 17.5 violations in a minute. These 56 recordings were removed from the dataset for cadence violation analysis. Linear mixed model analysis revealed an estimated intercept of 3.53 ± 0.40. There were no significant differences between the individual measures (0.03 ± 0.05, $\chi^2_{(1)}$ = 0.26, *p* = .612) or conditions (-0.24 ± 0.29, $\chi^2_{(1)}$ = 0.69, *p* = .407). There were significantly more violations during the second trial (0.82 ± 0.29, $\chi^2_{(1)}$ = 7.37, *p* = .007). Mean cadence violations, separated by conditions, are shown in Figure 12.

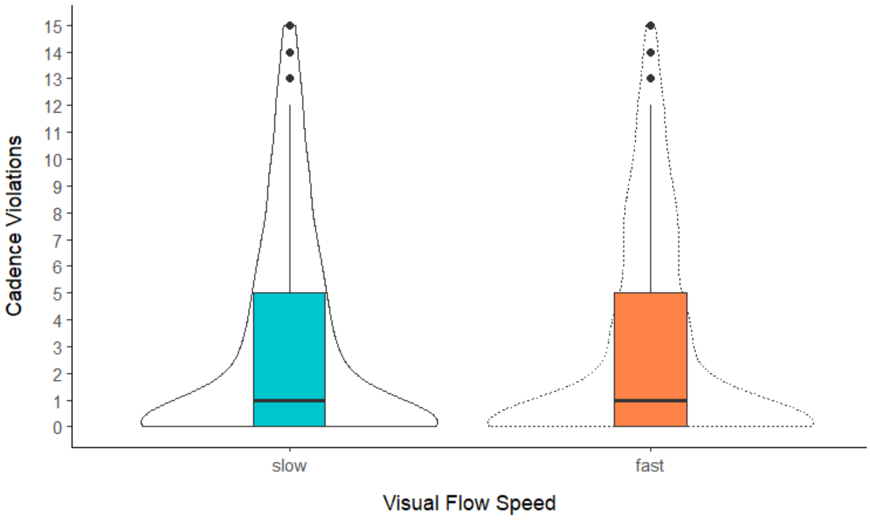

Figure 12

Cadence violations during the two trials, separated 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

5.3.4 Post-Experimental Questionnaires

The answers for the questions about presence, body ownership, agency, and speed perception were transformed to range between 0 and 6. Figure 13 shows all scale means and standard errors separated by condition. No outliers were detected.

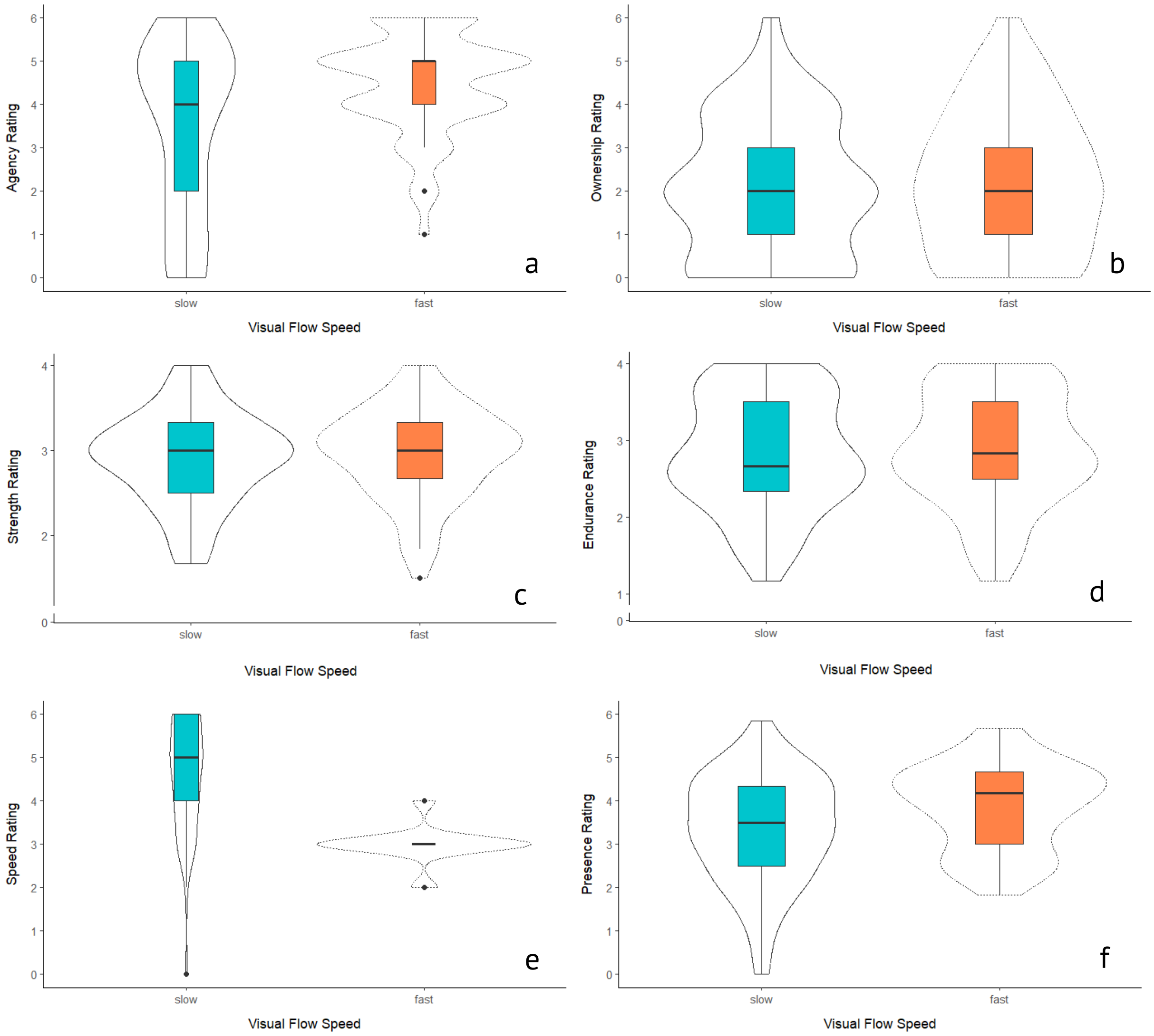

Figure 13

Questionnaire scores at the two trials, separated 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. **a.** Agency. **b.** Ownership. **c.** Self-perceived strength. **d.** Self-perceived endurance. **e.** Speed rating. **f.** Presence

5.3.4.1 Agency and Body Ownership

The estimated intercept for agency was 3.98 ± 0.17. Agency was significantly lower in the second trial (-1.12 ± 0.19, $\chi^2_{(1)} = 27.81$, $p < .001$). Agency was significantly higher during faster visual flow (1.09 ± 0.19, $\chi^2_{(1)} = 26.58$, $p < .001$). The estimated intercept for body ownership was 2.13 ± 0.19. Body ownership did not differ significantly between trials (-0.08 ± 0.16, $\chi^2_{(1)} = 0.23$, $p = .630$) or conditions (0.17 ± 0.16, $\chi^2_{(1)} = 1.12$, $p = .291$). Data distribution is displayed in Figures 13a and 13b.

5.3.4.2 Physical Self-Concept

The estimated intercept for strength was 2.93 ± 0.07. Strength ratings were significantly higher after the second trial (0.06 ± 0.03, $\chi^2_{(1)} = 4.67$, $p = .031$). Visual flow speed did not affect strength ratings significantly (0.05 ± 0.03, $\chi^2_{(1)} = 3.75$, $p = .053$). The estimated intercept for endurance was 2.86 ± 0.10. Endurance ratings were significantly higher after the second trial (0.07 ± 0.03, $\chi^2_{(1)} = 6.83$, $p = .009$). Visual flow speed did not affect endurance ratings significantly (0.05 ± 0.03, $\chi^2_{(1)} = 3.15$, $p = .078$). Data distribution is displayed in Figures 13c and 13d.

5.3.4.3 Speed Perception

Speed perception could not be analysed with linear mixed models, due to a lack of variance between participants. A linear model was calculated with visual flow speed and trial as factors. The estimated intercept for speed perception was 3.77 ± 0.08. Speed was perceived as significantly slower during the second trial (0.61 ± 0.17, $p < .001$). Speed was perceived as significantly faster during faster visual flow (-1.61 ± 0.17, $p < .001$), as can be seen in Figure 13e. With the scale ranging from 0 (“too fast”) to 6 (“too slow”), a value of 3 can be interpreted as “matching”.

5.3.4.4 Presence

The estimated intercept for presence was 3.61 ± 0.13. Presence did not differ significantly between trials (-0.19 ± 0.11, $\chi^2_{(1)} = 2.92$, $p = .088$). Presence was significantly higher during faster visual flow (0.54 ± 0.11, $\chi^2_{(1)} = 20.03$, $p < .001$). Data distribution is displayed in Figure 13f.

5.4 Discussion

The present study aimed to identify the impact of visual flow speed on constant-load cycling experience, investigating heart rate and perceived effort during two consecutive exercise bouts in VR. The hypotheses that faster visual flow evokes lower heart rates and perceived effort could not be confirmed. It was assumed that visual flow speed provided direct performance feedback. While this might hold true regarding speed perception, it does not convey information about general abilities or characteristics like athleticism, apparently. Instead, it seems to primarily affect the realism of virtual locomotion and impact motor control, as seen by the questionnaire and cadence data. It was reasonable to assume that movement speed is a direct representation of athletic ability and should thus impact heart rate and perceived effort similar to avatars with different athleticism (Kocur et al., 2021). While the present results cannot confirm this, they demonstrate an impact of visual flow speed on subjective experiences and on pedalling behaviour. A change in body ownership due to visual flow speed was not expected, but it supports the interrelation of body ownership and agency (Braun et al., 2018), considering the similar effect on agency. The significant trial effects on most scales suggest that, after cycling with slow visual flow, the impact of fast visual flow increases. As Hietanen et al. (2008) have shown, adaptations to movement speed affect subsequent speed perception. After adaptation to a certain speed, discriminability for faster speeds decreases while slower speeds are more easily discriminated. Additionally, speed adaptation effects are stronger for stimuli that accelerate towards the periphery, such as optic flow during self-motion (Hietanen et al., 2008). This could explain the differences in speed perception between both condition orders, although the applied break presumably nullified any adaptations. The aim of this study was to transfer findings from avatar effects to scene design as an alternative display of athleticism. No time or adaptation effects have been found in avatar studies, so they were not suspected to come up in the present design. An interaction effect of condition and trial was not included in the statistical models because not all four combinations of the two variables were investigated in the present design. However, the results suggest an effect of the condition order. This should be investigated in future studies using the appropriate design.

Especially the presence, agency, and speed perception ratings suggest that faster visual flow was perceived as more appropriate for the exercise. Verbal reports match this impression, since several participants described the exercise during slow visual flow as “frustrating” or “like cycling uphill”, although the incline did not change. Adding to that, cadence was significantly lower during fast visual flow. Slower visual flow has previously evoked larger walking speeds (Mohler et al., 2007), suggesting that participants perceived themselves as moving too slowly and adapted their effort to move faster. The present cadence results match this assumption. However, diverging results have also been found for gait behaviour, suggesting that the main goal during locomotion with conflicting visual flow is maintaining balance (Janeh et al., 2017). Again, adaptation of the visual system may interfere with effects of visual flow speed (Kanai & Verstraten, 2005). Prokop et al. (1997) have previously assumed that the proprioceptive system regains control after some adjustment to the conflicting visual flow. The visual adaptation to the visual flow speed may also account for its declining effect over time.

5.4.1 Visual Flow and Heart Rate

Heart rate followed a typical pattern of a rapid initial increase, transitioning into a slight linear increase throughout a trial (Figure 7). Despite the break between trials, heart rate was higher during the second exercise bout. However, it is not unusual for the heart rate being higher during the second of two consecutive physical activities (Bar-Yoseph et al., 2022). The break was applied to standardize both exercise bouts but may have had to be longer to reduce the time effects on heart rate.

The hypothesis that heart rate would be lower during cycling with faster visual flow could not be confirmed by the present data. Solely the visualization of heart rate suggests differences between the conditions (Figure 8). In the first trial, heart rate was lower in the faster condition, as expected. However, this switches for the second trial, suggesting that the time effect is greater than the influence of visual flow speed. Due to the adaptation of the visual system, speed perception accuracy typically decreases over time (Hietanen et al., 2008), suggesting that visual flow loses sensory salience throughout a trial. Specifically the perceived speed of stimuli moving in the same direction is reduced after an adaptation of 500 ms (Kanai & Verstraten, 2005). These perceptual adaptations may explain the lack of durable effects of visual flow speed on heart rate.

Another explanation could be that heart rate during physical activity highly depends on muscular and respiratory effort (Löllgen, 2015). The present results suggest that visual external cues do not affect heart rate sufficiently to withstand the effects of physiological effort during consecutive exercise bouts. Avatar design has previously induced heart rate differences. Kocur et al. (2021), for instance, report significant effects of avatar muscularity on heart rate across time during short incremental cycling exercise. However, their null effects of avatar design on average heart rate raise the assumption that heart rate differed at certain times of the exercise bout but not generally. Assumably, this is rooted in the incremental exercise protocol. Parry et al. (2012) report no significant effect of visual flow speed on heart rate during cycling, but their results demonstrate higher power outputs during slow visual flow. Consequently, the unaltered heart rate suggests an effect of visual flow speed on physiological effort. Because resistance was fixed in the present study, no such relation was examined. The higher cadences observed here hint towards a similar tendency to increase effort during slower visual flow. During time trials, as in the study of Parry et al. (2012), movement speed is highly important for the evaluation of goal attainment. In continuous cycling without a target distance, speed cues presumably lack salience to evoke similar effects on physiological effort.

5.4.2 Visual Flow and Perceived Effort

Perceived effort increased with exercise duration and was rated slightly higher in the second trial, corresponding to the heart rate observations. Visual flow speed fell short of affecting perceived effort significantly (*p* = 0.07). RPE are greatly based on physiological signals of effort, which may explain the similar courses of heart rate and perceived effort (Rejeski, 1985). However, movement speed was expected to act on perceived effort like athletic avatars did (Kocur et al., 2021). The null effect is especially surprising considering that multiple participants verbally reported that the slow condition felt more exhausting or created the feeling of cycling uphill. These and similar evaluations should be considered for post-experimental questionnaires.

As with all subjective measures, it is imaginable that participants tried to fulfil certain expectations about their fitness when rating their perceived effort. They may have matched their ratings between the two trials because they knew it was the same objective intensity. The significant effect of trial stands against this explanation.

Figure 10 shows that the trial effect on perceived effort was greater for participants who started with fast visual flow, suggesting that either fast visual flow counters a portion of the trial effect or slow visual flow enhances it. In combination with the absence of an effect on heart rate and the verbal reports, the present results indicate slightly lower perceived effort at the same physiological effort. However, the absolute value of the point estimate bears no practical relevance, as it corresponds to one tenth of a scale step. As for heart rate, visual flow speed seems to be an insufficient cue to evoke measurable changes in perceived effort. However, the results support the coupling between RPE and heart rate. With RPE being substantially based on the perception of heart rate (Borg, 1982), diverging effects of visual flow on both parameters were not expected.

In total, the present results suggest that the Proteus Effect cannot be transferred to visual speed manipulations during constant-load cycling. Although visual flow speed is a more direct performance cue than avatar appearance, it may only be effective for short periods of time due to visual adaptation processes (Hietanen et al., 2008). The athleticism of the avatar may be a more salient visual cue that does not lose its impact over time.

5.5 Limitations

Due to technical limitations, visual flow speed was not coupled with cycling cadence. This may have impeded realism and feelings of agency. However, the restriction of cadence prevented large variations, presumably making the independence of visual flow and cadence barely visible. Further, it was previously not considered that visual flow speed would affect the subsequent trial, especially after a break. Study 1 led to the assumption that the exercise bouts need to be closer to increase the visibility of the speed differences, which was in line with the study design by Kocur et al. (2021). However, the order of visual flow speeds seems to impact subsequent exercise bouts. The study is further limited by the homogeneity of the sample because all participants were sports students. This impairs transfer to other populations. Maximum power output was estimated based on sex and body weight, which was mainly grounded in test economy but potentially inaccurate. Further, the manipulation check should have assessed whether the incline was perceived to be different between conditions. The present null effects may stem from the fact that participants perceived the change in movement speed as a result of a changed incline because then, actual effort and movement speed would no longer be mismatched.

5.6 Conclusion

In the present study, visual flow speed did not affect constant-load cycling experience. Neither perceived effort nor heart rate differed significantly between the visual flow speeds. Solely the subjective ratings after exercising with fast visual flow suggest differences in the subjective appraisal of the scene. Verbal reports of the participants revealed that most of them noticed a difference between the medium speed they calibrated and the slow visual flow condition, but not between the medium and fast visual flow. In total, both perceived effort and heart rate are largely based on actual physiological effort, and the impact of visual flow on them seems insufficient. However, the effects on subjective appraisals are worth pursuing, as such perceptions might influence long-term exercise behaviour (Ekkekakis, 2009; Teixeira et al., 2022).

Identifying visual flow speed as a factor that can affect pleasure, comfort, or self-efficacy during exercise would contribute to the classification of exercise facilitators. Although this was not sufficiently achieved with the study at hand, the results prompt questions about the specific characteristics of visual speed perception in VR. Visual adaptation seems to play a role that should not be neglected. Thus, testing different intervals between the exercise bouts or applying speed changes within an exercise might elucidate the roles of timing and visual adaptation in the relationship of visual flow and exercise. Both subjective experiences and the psychophysiological bases of visual flow perception are auspicious and relevant research areas. The present data provides a useful base for subsequent studies that aim to promote the sensible use of virtual reality during physical activity.

6 Third Study

Heart Rate Increases with Visual Flow Speed in Virtual Reality Cycling[7]

In Study 2, no effects of visual flow speed on perceived effort and heart rate were found. However, ratings of agency, presence, and perceived speed suggested that fast visual flow was perceived as more accurate or realistic. Eliminating a major limitation of Studies 1 and 2, cadence and virtual speed were coupled in Study 3. Further, the ergometer was set to a fixed incline, allowing resistance to increase with cadence. These two modifications increased interactivity with the VR and enabled exploration of visual flow speed-dependent cadence modulations.

6.1 Goals and Hypotheses

The goal of the third study was to identify the effects of visual flow speed on perceived effort and heart rate during short moderate-intensity cycling. Additionally, the enjoyment of physical activity was investigated after each trial.

Visual stimuli are integrated with vestibular, proprioceptive, and somatosensory signals in the insula (Cullen, 2019). This brain area is not only central for monitoring moving stimuli (Shinder & Newlands, 2014), but also associated with the senses of body ownership (Tsakiris et al., 2007) and agency (Farrer & Frith, 2002). Therefore, visual flow speed was expected to provide performance feedback during cycling and induce a sense

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[7] The corresponding paper to this study is under review: Luttmann, C & Jansen, P. Heart Rate Increases with Visual Flow Speed in Virtual Reality Cycling.

of agency for the virtual movement speed. Because visual flow speed is directly related to the devoted physical effort, unmatching visual flow speeds were expected to affect the perceived effort. Following findings that the display of increased athleticism leads to lower heart rates (Czub & Janeta, 2021; Kocur et al., 2021), higher visual flow speeds were expected to evoke lower heart rates and perceived effort 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: Perceived effort is lower during faster visual flow than during slower visual flow.

6.2 Method

6.2.1 Design

In a repeated measures within-subject design, each participant completed two experimental trials. Visual flow speed of the virtual scene was set to one of two different levels, respectively (0.5 * actual speed or 1.5 * actual speed). The order of visual flow speed conditions was randomized and counterbalanced between participants. Actual speed was calculated from cadence as follows:

$$speed\left[\frac{km}{h}\right] = 0.152 + (0.417 * cadence\,[rpm]) \tag{2}$$

The cycling ergometer was set to a fixed incline so that resistance (and speed) increased with cadence. All experimental procedures were conducted in accordance with the Declaration of Helsinki. All participants provided informed consent. The study was preregistered at OSF.io[8].

6.2.2 Participants

A power analysis with G*Power (Faul et al., 2009) was conducted to determine the sample size. The analysis yielded a required sample size of $N = 72$ for a repeated measure ANOVA with $\alpha = .05$, $f = 0.15$, and $\beta = 0.8$. To account for subject exclusion, the sample size was increased by 10 % ($N = 80$). Exclusion criteria were acute or chronic cardiovascular or muscular diseases and sensitivity to motion and 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 $N = 73$ (35 female, 38 male; 22.63 ± 2.28 years).

6.2.3 Material

6.2.3.1 Virtual Reality

The VR system consisted of an HTC Vive HMD (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. The two avatars (male and female) were created in

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[8] https://osf.io/mzejx/?view_only=1273c12e13ed4ae6826a2f961649783f

Daz Studio 3D (DAZ Productions, Utah, USA) and imported into Unity as rigged models. The Final IK Unity Asset (RootMotion, Tartu, Estonia) was used to synchronize the participant's and the avatar's movements.

6.2.3.2 Outcome Measures

During cycling, heart rate was measured by a chest strap sensor (Polar H10, Polar Electro Oy, Kempele, Finland) that measured continuously and transferred data to a smartphone app (PolarBeat, Polar Electro Oy, Kempele, Finland) via Bluetooth. Heart rate was recorded in the last ten seconds of every minute. Perceived effort was assessed every three minutes with the ASS (Büsch et al., 2022), ranging from 1 ("not strenuous") to 10 ("so strenuous that I have to stop"). 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.

6.2.3.3 Post-Experimental Questionnaire

The computerized questionnaire consisted of the "presence" scale of the IPQ (Schubert et al., 2001), the items "body ownership" and "agency" of the BRQ (Banakou et al., 2018), the scales "endurance" and "strength" of the PSK (Stiller et al., 2004), the Physical Activity Enjoyment Scale (PACES, Jekauc et al., 2020), and a question on the perception of the visual speed. The questionnaire was presented with PsychoPy (Version 2022.1.4).

The IPQ assesses the sense of presence and 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 (Schubert et al., 2001). 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.

To measure body ownership and agency, 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” of the BRQ were included. The statements are rated on 7-point scales between -3 and 3 (Banakou et al., 2018) and 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 perceived effort.

Self-perceived fitness was assessed with the two subscales “strength” and “endurance” from the PSK. 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, like it 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 & 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 perceived effort.

Enjoyment of the exercise was measured with the PACES. The 16 statements 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.”).

The perceived 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 speed differences were detected and whether one of the visual flow speeds would be perceived as more matching than the other.

6.2.4 Procedure

Participants gave informed consent and confirmed that they had no cardiovascular or muscular limitations. They were instructed about the cycling task and familiarized with the ASS. The heart rate sensor was put on, 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. A baseline heart rate was recorded. The positioning of the virtual avatar was adjusted manually by the experimenter so that the avatar moved realistically on the virtual bicycle. This was necessary in case participants looked down at the virtual bicycle and the avatar. More importantly, the right ankle tracker had to move through a virtual collider to measure cadence and calculate visual flow speed. Visual flow speed was adjusted to the appropriate experimental condition. Participants then completed the first 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 speed) increased with pedalling cadence. Participants were instructed to cycle however comfortable while keeping their hands on the handlebar. Cadence was allowed to vary but should not be changed jerkily. When participants were ready to start, the virtual scene was initiated, and the first measures of heart rate and perceived effort were recorded. After completing the 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 heart rate was back at the baseline level. The procedure was the same but visual flow was presented at the speed of the remaining condition.

6.2.5 Analysis

The effect of visual flow speed on heart rate and perceived effort was analysed with linear mixed models using the lme4 package (Bates, 2010) in R (R Core Team, 2012). All independent variables were normalized 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.

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 (speed) as fixed effects. 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, scale means 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 the calculation of χ^2- and p-values followed the previously described procedure.

Absolute effect sizes, standard errors, χ^2-, and p-values are reported for all fixed effects. Complete data, including confidence intervals, can be found in the appendix (Section 10.3).

6.3 Results

6.3.1 *Heart Rate*

Values below 67 or above 171 bpm were considered outliers. 18 measurements from three participants were excluded from heart rate analysis. After outlier removal, average heart rate was 119.08 ± 19.22 bpm. Figure 14 shows the average time course of heart rate throughout a trial, separated by visual flow speed.

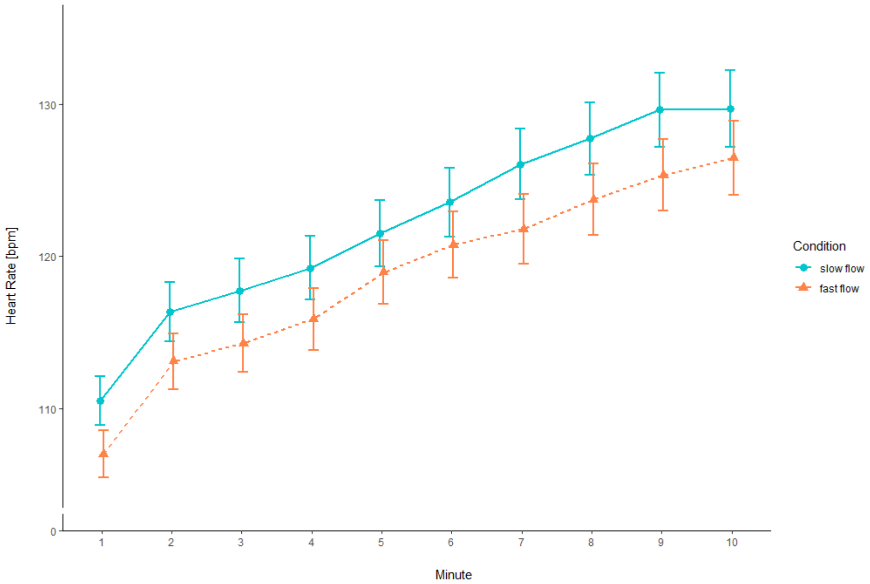

Figure 14

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

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, $\chi^2_{(1)}$ = 9.12, *p* = .003), indicating higher heart rates during slower visual flow. Figure 15 displays the distribution of heart rates in the two visual flow conditions. Condition × minute (-0.25 ± 0.15 bpm, $\chi^2_{(1)}$

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

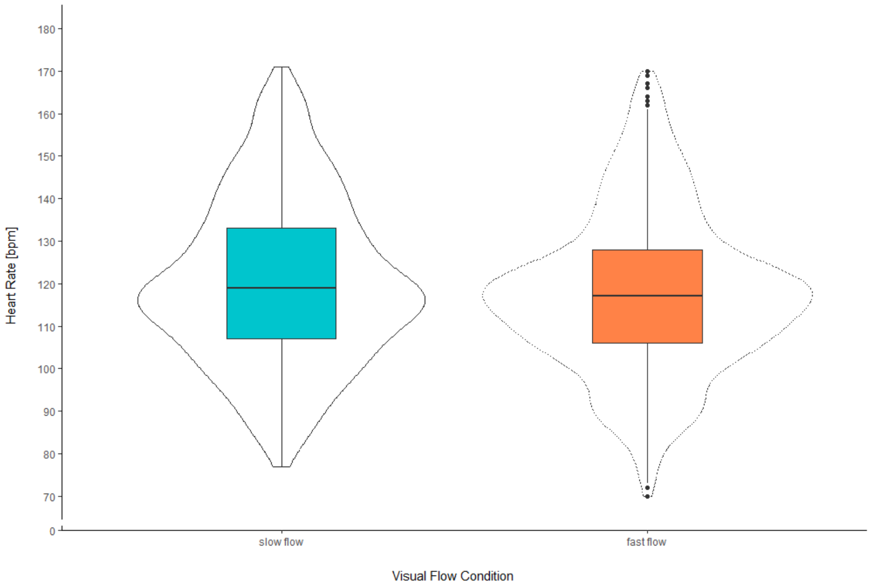

Figure 15

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

6.3.2 Perceived Effort

For perceived 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. Figure 16 shows the average time course of perceived effort throughout a trial, separated by visual flow speed.

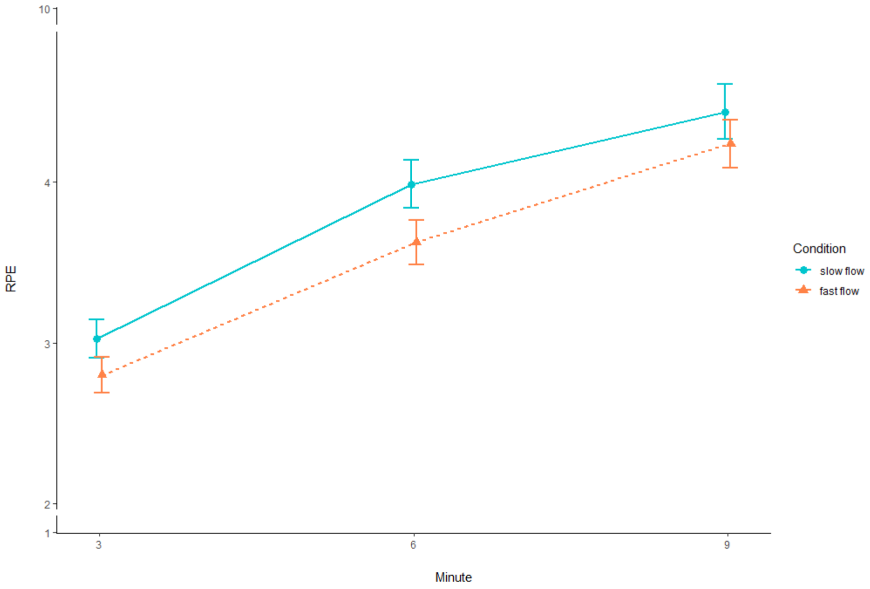

Figure 16

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

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, $\chi^2_{(1)} = 2.38$, $p = .123$), nor condition × minute (0.01 ± 0.04, $\chi^2_{(1)} = 0.15$, $p = .699$), or condition × cycling speed (0.96 ± 0.56, $\chi^2_{(1)} = 0.04$, $p = .841$) had significant effects on perceived effort. Figure 17 displays the distribution of RPE in the two visual flow conditions.

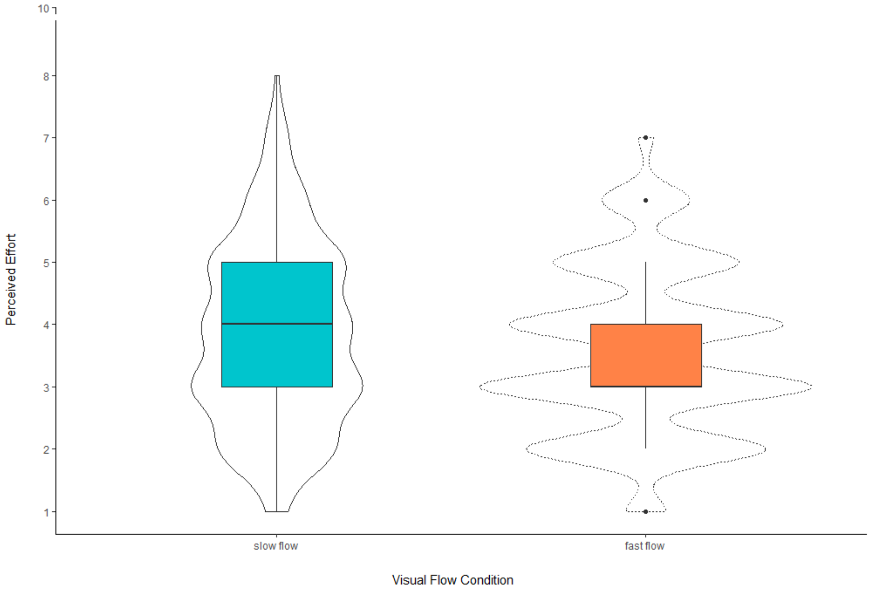

Figure 17

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

6.3.3 Cycling Speed

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

6.3.4 Post-Experimental Questionnaires

6.3.4.1 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, $\chi^2_{(1)}$ = 0.46, *p* = .498; endurance: 0.03 ± 0.02, $\chi^2_{(1)}$ = 1.95, *p* = .162).

6.3.4.2 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), where 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, $\chi^2_{(1)}$ = 3.10, *p* = .078).

6.3.4.3 Body Ownership and Agency

The individual scores for both items were transformed to range from 0 to 6 (instead of -3 to 3), where 6 represents high agency/body ownership. 18 agency ratings from 15 participants were removed as outliers because they were smaller than 2.5. Agency was rated with 4.9 ± 0.82 on the 6-point scale. No outliers were detected for body ownership ratings. Body ownership was rated with 2.31 ± 1.61 on the 6-point scale. Condition had no significant main effect on agency (-0.05 ± 0.13, $\chi^2_{(1)}$ = 0.14, *p* = .710) or body ownership (-0.10 ± 0.15, $\chi^2_{(1)}$ = 0.39, *p* = .532).

6.3.4.4 Physical Activity Enjoyment

Negatively worded items of the PACES 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, $\chi^2_{(1)} = 2.46$, $p = .117$).

6.3.4.5 Speed Perception

The individual scores were transformed to range from 0 to 6 (instead of -3 to 3). There were no outliers among the speed ratings. 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 speed perception (-1.83 ± 0.15, $\chi^2_{(1)} = 85.74$, $p < .001$), indicating that fast visual flow was perceived as faster than slow visual flow. The means suggest that both speeds were perceived as inadequate (slow: 3.70 ± 1.13, fast: 1.89 ± 1.26).

6.4 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 perceived effort during ergometer cycling in VR. Following findings from avatar studies (Czub & Janeta, 2021; Kocur et al., 2021), faster visual flow was hypothesized to lead to lower heart rates and perceived effort compared to slower visual flow. The present results demonstrate an effect on heart rate but not on perceived effort. Furthermore, no subjective aspects were impacted except for speed perception.

The absence of effects on body ownership and agency is plausible since 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 (Gonçalves et al., 2023; Slater, 2009).

One reason significant differences in heart rates were found in this study but not in Studies 1 and 2 could be that visual flow speed depended on 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 the results from Studies 1 and 2 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 general level and tried to be consistent instead of basing their ratings on the present experience. This could also hold true for the enjoyment ratings.

Following verbal reports during Studies 1 and 2 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, although it led to higher heart rates.

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 five bpm. There seems to be a dissociation of physiological and psychological aspects of exercise (Hampson et al., 2001), visible in the absence of an effect on perceived effort. Heart rate and RPE have shown to be highly correlated (Borg, 1982), although this relation depends on various factors, such as motivation (Rejeski, 1981). While the significant difference in heart rates is of practical relevance, claiming a dissociation between perceived effort and heart rate must be done with precaution.

Moreover, visible or physiologically relevant changes in heart rate are not necessarily detectable by the participant, especially not without focussed 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 perceived effort. It could also be that RPE were 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 cannot be confirmed by any data. Checking for attentional focus or reasoning for RPE might be helpful to explain such effects in the future.

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 & Krekelberg, 2014). This adaptation leads to an attenuation of stimuli that is 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 it has been difficult to reproduce avatar effects 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.

6.5 Limitations

The present study is limited by the simplicity of the virtual scene. It was designed to display a realistic and natural scene but including more exciting visuals would have likely increased general enjoyment and engagement in the task. However, a more exciting scene would have impacted gaze behaviour, which is critical for visual flow speed perception (Banton et al., 2005). Furthermore, due to the small age range of the sample, the findings might not apply to other demographics.

6.6 Conclusion

Visual flow is a central cue during self-motion that conveys performance feedback. Manipulating visual flow speed during cycling in VR was expected to affect subjective and objective measures of effort equally. An effect of visual flow speed on heart rate was found, but not on perceived effort. Future research should look deeper into individual differences in motivation or attentional focus that could have evened out any visual flow effects on perceived effort. The coupling of pedalling cadence and visual flow speed improved previous setups, evidenced by increased agency ratings. The present results suggest that visual flow speed constitutes a useful parameter for VR-based exercise that needs more specific research to identify relevant factors and prerequisites.

7 General Discussion

7.1 Summary

All presented studies have investigated the impact of visual flow speed manipulations on different aspects of cycling exercise in VR. Previous research demonstrated effects of visualized athleticism or visual flow on heart rate and/or RPE in stationary cycling (Kocur et al., 2021; Parry et al., 2012). These findings suggested that visual flow would affect objective performance measures and subjective appraisal of a cycling exercise. In the present studies, participants completed multiple short exercises on a cycling ergometer while a virtual track was presented through an HMD. The speed of the virtual track varied between the trials while objective intensity remained constant. During and after cycling, several performance and self-perception measures were collected. Table 2 provides an overview of the results of all three studies. Most of the present data show that heart rate, perceived effort, and affect did not differ between visual flow speed conditions. A main effect of visual flow speed on heart rate has only been observed in Study 3.

The possible reasons for this non-conformity of the data with the respective hypotheses are elaborated thoroughly in the following sections. Theoretical reasons lie in the specificity of the measured variables and their interrelations, the transfer of findings from other contexts, or the ambiguity of previous research. Due to the scarcity of studies investigating visual flow speed in VR-based exercise, methodological differences may also justify the divergent results.

Table 2

Effects of Visual Flow Speed in Study 1, 2, and 3 Sorted by Dependent Variable

Dependent Variable	*Study 1*	*Study 2*	*Study 3*
Heart Rate	**HeartRate$_{slow}$ > HeartRate$_{medium}$**	n.s.	**HeartRate$_{slow}$ > HeartRate$_{fast}$**
Perceived Effort	n.s.	n.s.	n.s.
Affect	n.s.	-	-
Cadence/Cycling Speed	-	**Cadence$_{slow}$ > Cadence$_{fast}$**	**CSpeed$_{slow}$ > CSpeed$_{fast}$**
Physical Self-Concept	n.s.	n.s.	n.s.
Agency/Ownership	n.s.	**Agency$_{fast}$ > Agency$_{slow}$**	n.s.
Presence	n.s.	**Presence$_{fast}$ > Presence$_{slow}$**	n.s.
Perceived Speed	-	**Speed$_{fast}$ > Speed$_{slow}$**	**Speed$_{fast}$ > Speed$_{slow}$**
Enjoyment	-	-	n.s.

7.2 Effects on Objective Parameters and Perceived Effort

7.2.1 Avatars Versus Visual Flow

Following Kocur et al. (2021), heart rate was expected to be lower during fast visual flow (as the analogue of an athletic avatar). This assumption could be partly confirmed. Nonetheless, the present results remain ambiguous and show how visual flow differs from embodied stimuli. Avatars constitute a very complex stimulus that might be less prone to visual adaptation (Schmitter et al., 2021). Visual adaptation describes the reduced sensitivity for a stimulus after sufficient exposure time. It is typically paired with a visual after-effect, where heightened sensitivity for differing stimuli affects the perception of colour, shape, direction, or speed (Hietanen et al., 2008). One widely known example is seeing the inverse of an image after staring at it for some time (Thompson & Burr, 2009). Similar adaptations occur for visual flow. Sensitivity for the speed and direction of the visual flow decreases with time of perception. Consequently, the salience and intensity of this specific perception decrease, while changes are perceived as more drastic (Hietanen et al., 2008). Car drivers will know this from changing to city traffic after driving on a highway for some time, feeling like they are moving in slow-motion at 50 km/h. This specific type of visual adaptation, termed *motion adaptation* (Thompson & Burr, 2009), is highly pronounced in circularly expanding movements like visual flow (Hietanen et al., 2008). For such simple stimuli as visual flow, visual adaptation effects have been readily demonstrated, while more complex cues (like faces or bodies) have rarely been tested for adaptation (Webster & MacLeod, 2011).

Due to the multitude of cues, avatars enable more exploration than a singular stimulus like visual flow speed. This might also facilitate the detection of differences between avatars compared to visual flow speeds. This facilitation is not to be confused with an increased sensitivity to speed changes due to motion adaptation but rather offering an alternative approach–that the selected differences between the speeds were too small to be noticed at all. This particularly applies to Study 1, where the speeds differed by just 4 km/h and trials were spaced one week apart. Verbal reports in Study 1 and speed ratings in Study 2 suggest that fast visual flow was perceived closer to the medium or matching speed than slow visual flow, although the differences were identical. Apparently, the slowed-down visual flow is more easily detected. When speed differences were larger and related to the actual cycling speed, a significant effect on heart rate was found (Study 3).

Another methodological aspect is that Kocur et al. (2021) employed a ramp protocol instead of a constant-load exercise. A ramp protocol was not considered representative of regular exercise and thus exchanged by a constant-load protocol for the present studies. Besides, the hypothesized effects were not deemed exclusive to specific exercise protocols or intensities, so this difference seemed negligible. However, the increasing intensity in a ramp protocol could have prevented habituation to the physical effort, which potentially affected the susceptibility of heart rate.

7.2.2 Motor Control and Pacing

Apart from heart rate, cadence and speed are central measures of cycling performance. Cadence represents more of a motor control parameter and can be compared to stride frequency during walking. Both parameters are not only related to the produced movement speed but also to balance control. The relevance of stride frequency in both walking and cycling suggests transferability of visual flow speed effects between the two contexts. However, research is unequivocal about the linearity of such effects. While some studies show a linear relation between visual flow speed and gait parameters (Ludwig et al., 2018; Mohler et al., 2007), others indicate symmetrical differences between divergent and matching visual flow speeds (Janeh et al., 2017). Such effects of visual flow speed on motor control are the primary target of many walking studies. Consequently, the findings from these studies do not relate to locomotive exercise like cycling, where the participant experiences physical exertion. The effects of visual flow speed on cadence in Study 2 can be interpreted in two ways. (1) Fast visual flow prompted participants to prioritize motor control and decrease their pedalling cadence. (2) Slow visual flow prompted participants to increase their cycling speed through increased cadence (because power output was fixed). Given the importance of cadence for economical cycling (Gronwald et al., 2018; Lucia et al., 2004), the relation of visual flow speed and pedalling cadence is worth pursuing with appropriate study designs.

The impact of visual flow speed on cycling speed was only measured in Study 3, where power output increased with cadence. Cycling speed decreased with increasing visual flow speed, which matches the findings from Parry et al. (2012) and the assumed prioritization of motor control, but contradicts the overall assumption that fast visual flow would increase performance—at least at first glance. Considering the significantly reduced heart rate, it can be argued that performance was, in fact, improved during fast visual flow.

Reproducing the effects found by Parry et al. (2012) was not expected because the present exercises did not include a target distance that required effort regulation. In the presence of a target distance, effort and action feedback must be compared regularly to optimize performance. Here, visual flow speed offers information about the completed distance (resulting from the movement speed) and is thus crucial for pacing. Interestingly, slow visual flow can influence participants to increase their power output, despite being asked to match it to a previous time trial (Parry et al., 2012). This study demonstrates the potential impact of visual flow on cycling performance, but the effects on RPE and performance are likely rooted in effects on the pacing strategy. Consequently, they do not apply to the present constant-load moderate-intensity exercises. In retrospect, the absence of a distance goal may explain the lack of effects on perceived effort and the inconsistent effect on heart rate in the present studies. Visual flow speed may have been perceived as dispensable for effort regulation. In the studies at hand, participants may have relied chiefly on proprioceptive and interoceptive cues of exertion. Visual flow during constant-load exercise could lack importance and salience compared to avatars and visual flow during time trials, at least regarding effects on heart rate and perceived effort.

7.2.3 Perceived Effort

Despite being the most anticipated, no significant effects of visual flow speed on perceived effort were found in either study. Again, visual flow speed may not be as influential during constant-load exercise as expected. Previous considerations about avatars and exercise goals particularly apply to perceived effort (see Sections 7.2.1 and 7.2.2).

Considering the significant effects on other performance parameters (heart rate and/or cadence/speed), the null effects on perceived effort suggest that visual flow speed can evoke a disjunction of objective and subjective effort. This has been found before (Hampson et al., 2001) and is supported by findings showing that RPE during cycling are primarily based on pulmonary and muscular afferences (Jameson & Ring, 2000). The disjunction of physiological and perceived effort further implies that visual flow speed can be used to achieve specific exercise intensities without increasing perceptions of strain. This is specifically helpful for inexperienced or unmotivated athletes. Although fast visual flow was expected to facilitate exercise, the finding that visual flow speed affects parameters of cycling at all is certainly more relevant. Either way, expanding and confirming the present results, especially from Study 3, would be beneficial for practitioners.

7.3 Effects on Affective Appraisal, (Self-)Perception, and Presence

7.3.1 Affect and Enjoyment

Current affective states and subsequent emotional evaluations were expected to be positively impacted by increasing visual flow speed. No such effects were found, contradicting related research (Stephens & Smith, 2022; Yasukawa et al., 2021). However, passive movements like driving require no physical effort to produce forward motion. Consequently, affective states remain unaffected by unpleasant perceptions of strain. During rollercoaster riding, for instance, movement speed can be perceived on an affective level without needing to offset energetic costs. In contrast, movement speed during self-controlled locomotion is strongly related to physical effort, which likely impedes such positive effects of visual flow speed on affect and enjoyment that have been observed in passive motion (Stephens & Smith, 2022).

Yasukawa et al. (2021) looked into visual flow speed in cycling and did not find effects on psychophysiological parameters (e.g., heart rate, perceived effort) but on affect. In contrast to Study 1, affect was measured after completion of the exercise, which could explain the deviant results. Study 3 included a post-exercise measure of enjoyment, which was unaffected by visual flow speed. However, the studies can hardly be compared because the PACES (Jekauc et al., 2020) used in Study 3 targets higher-level emotions, while the Two-Dimensional Mood Scale used by Yasukawa et al. (2021) measures core affect. Measuring affect after an exercise is not advised, considering the impact of superordinate cognitions and emotions associated with the completion of the activity (Ekkekakis, 2009; Wininger, 2007). The PACES was included to determine effects on the general attitude towards physical activity. Despite instructing participants to refer to the recent cycling exercise, the wording of the questions potentially prompted more overarching evaluations.

Affective states during physical activity are predominantly assessed with single-item scales like the Feeling Scale (Hardy & Rejeski, 1989) or the Felt Arousal Scale (Svebak & Murgatroyd, 1985). The Affect Grid (Russell et al., 1989) displays both dimensions simultaneously and was therefore preferred for the studies at hand. Such single-item scales enable fast assessment, reducing cognitive effort and distraction from the task (Allen et al., 2022). However, although participants were thoroughly instructed beforehand, there is room for interpretation of the terms “arousal” and “valence”. Individual baselines were considered statistically, but external influences on affective states could hardly be controlled. While some participants based their ratings solely on the task at hand, it is conceivable that others incorporated unrelated emotions or general attitudes into their evaluation.

On another note, it was assumed that the null effects on the psychophysiological measures observed by Yasukawa et al. (2021) were rooted in the short duration of their exercise (five minutes). The measured parameters likely adapted primarily to the physical activity itself, making possible conditional differences indetectable in such a short time. Consequently, a duration of a minimum of ten minutes was considered mandatory for the present studies, enhancing the relevance for practical application. However, the longer duration also increased the likelihood of boredom or listlessness, considering the monotonous scenery, especially in Study 1. Arguably, effects on current affect and subsequent emotional evaluations were superimposed by such negative perceptions.

7.3.2 Physical Self-Concept

Kocur et al. (2021) demonstrated significant improvements in self-perceived fitness after cycling with a muscular avatar. As has been discussed for other parameters, the explicit visualization of athleticism through the avatar likely provides a more relevant cue for self-perception than movement speed. On top of that, some other considerations might clarify the lack of effects in the studies at hand.

Notably, perceived effort during exercise remained unaffected by visual flow speed. It can thus be assumed that self-efficacy was not affected as well. Therefore, the consistent lack of effects on RPE and PSK scores appears plausible. The absence of an exercise goal is likely a key factor for both null effects. In all three studies, attainable performance was restricted by the intensity prescription. Further, neither remaining distance nor duration were communicated to the participants. There was no goal or performance level to accomplish and thus no opportunity to compare expected and actual physical ability on a general level.

Furthermore, participants all studied movement science. Arguably, they participated in regular physical activity, although this was not assessed. Physically active people have more “data” to build their self-concept on, which could reduce their susceptibility to short-term manipulations.

7.3.3 Sense of Agency and Presence

An exciting and unintentional finding derives from comparing Study 3 with Studies 1 and 2. Initially, it was not realisable to couple cadence and virtual speed. The motion tracking of the pedals and the instruction to keep a constant cadence concealed this missing interaction between the real and the virtual world to some extent. Nonetheless, the setups in Studies 1 and 2 lack critical aspects of VR: interaction with and control over the virtual world. Both have been realised through the movements of the avatar, but they were only visible during downward gaze. Closing this gap has not only improved the methodical quality of the experiment but also demonstrated the importance of having visible control over the virtual environment, as seen by the enhanced sense of agency in Study 3 compared to the other two studies (Slater, 2009). It could also be one of the reasons why, in Study 3, there was a significant effect of visual flow speed on heart rate, but not in Studies 1 (only in pairwise comparison) and 2. Despite the advantage of this interactivity, agency ratings in Study 2 were already largely enhanced compared to Study 1, simply because cadence was restricted to a ten-rpm range. This approach offers an alternative for setups where a coupling of real and virtual speed is impossible.

The significantly higher ratings of agency and presence during fast visual flow in Study 2 hint that it was perceived as more adequate or plausible. This matches the speed ratings from Study 2 and verbal reports from Study 1, suggesting that slow flow was easier to detect as “unmatching”. Presence was generally mediocre in all three studies, which could be grounded in the constant presence of real-world stimuli like the auditory and tactile cues from the ergometer. It could further be conceivable that the monotonous scene promoted a more internal focus.

7.4 Interoception and Attention

Only Study 1 included interoception as a moderating factor of visual flow speed effects on exercise parameters. The assumption that low interoception would abet the impact of manipulated visual flow speed was based on evidence from body ownership illusions. In a study on the rubber hand illusion, low interoception coincided with larger proprioceptive drift, suggesting a more intense ownership illusion (Tsakiris et al., 2011). Besides, the DMT suggests a competition between external and internal stimuli in forming affect and perceptions of effort (Ekkekakis, 2009). This implies that attentional focus affects the subjective appraisal of an activity, which is supported by previous research findings (Emad et al., 2017). The present results, however, could not demonstrate a protective nature of interoception against visual flow speed manipulations. Given the null effects of visual flow speed on perceived effort, arousal, and valence, the interaction with interoception was not statistically tested for these variables. Possible explanations for the absence of an interaction effect on heart rate are reviewed in the following.

One reason that has been discussed in Section 2.1.2.4 is the quality of the HDT for measuring interoception. Despite being widely used, heartbeat detection and similar tasks have received ongoing criticism for their low correlation with other interoceptive measures. Another explanation for the present results could be that heart rate is either not the most relevant internal cue during cycling exercise (Jameson & Ring, 2000) or simply not well detectable under exercise circumstances. During moderate intensities, exerted muscle force might be easier to perceive than heart rate. Especially due to the alternating movement of both legs, eccentric and concentric muscle tension can be distinctively perceived, while heartbeats are a more constant stimulus. Considering that interoceptive measures require quiet surroundings, it seems conclusive that heart rate is difficult to detect amid noises from the ergometer and increased breathing activity. Examining the ability to perceive changes in leg muscle tension could constitute a more adequate measure for the targeted effect. Proprioception has rarely been included in definitions of interoception (Herbert et al., 2020), suggesting that the perception of muscle tension, muscle length, or joint angles is presumably distinct from cardiovascular or intestinal perceptions. Consequently, unique methods have arisen where participants reproduce or report joint angles (Gritsenko et al., 2007) or muscle force (Ballardini et al., 2019). Horváth et al. (2023) recently reviewed different methods for measuring proprioception, demonstrating that they exhibit high site- and test-specificity. The authors also argue that good proprioception during such explicit tasks does not necessarily mean more consideration of proprioceptive cues during movement, which could also be the case for heartbeats (Ponzo et al., 2021). Above all, even if heartbeats or muscle tension were perceived, heart rate during physical activity is usually not regulated based on such perceptions. Rather, heart rate regulations require adaptations of physical effort which were limited by the prescribed intensity. The moderating role of interoception on the effect of visual flow speed was expected to be the smallest for heart rate due to the strong physiological basis of this parameter. Since the other variables were not inspected regarding this effect, further explanations would be purely speculative.

Despite the absence of an effect of interoception, the underlying theoretical considerations remain sensible and should be investigated further to determine which individual factors influence the effectiveness of visual flow speed manipulations. Instead of measuring interoception through an HDT, future studies could target proprioception or include eye-tracking. Since gaze direction substantially influences the accurate perception of visual flow speed (Banton et al., 2005; Campos et al., 2007), analysing fixations and eye movements could elucidate individual differences in effect sizes. Besides, pupil diameter, fixation disparity, and other parameters have been associated with attentional focus, revealing whether attention is turned inwards or outwards (see Annerer-Walcher et al., 2021 for an overview). While measures of interoception like the HDT are useful to investigate the ability to perceive internal signals, they cannot capture whether this ability is actually exerted. Being able to perceive one's heartbeat in an explicit task does not imply increased attention to heart rate during physical activity. Measuring attentional focus during the activity might close this gap.

7.5 Methodological Rationales

The quintessence of the previous discussions is that the investigation of visual flow during moderate-intensity cycling in VR unites numerous theoretical frameworks. This complicated the choice of experimental material and methods. A central outcome of the three studies at hand is thus the (start of the) identification of adequate methods and setups for related research.

For instance, speed differences of 20 % appear to be insufficient to evoke meaningful effects (Study 1). Above all, however, a relative transformation of visual flow speed seems important. For this, cadence and visual flow speed must be coupled, increasing the sense of agency and enabling the exploration of pedalling behaviour

(Study 3). The increased speed differences also contributed to the enhanced visibility of the manipulation. This was deemed necessary following verbal reports from Study 1, suggesting that many participants did not detect the speed differences. That is also why the trials in Studies 2 and 3 were executed in one session. Additionally, instead of defining absolute visual flow speeds, participants in Study 2 subjectively calibrated visual flow speed to match their cycling. The most accurate estimation of visual flow speed was achieved by calculating it from the actual cadence (Study 3). Both modifications increased the plausibility of the visual flow speed, which is important to investigate natural behaviour (Slater, 2009).

Altogether, the three studies at hand targeted the same research question, but with somewhat distinct methods. The findings reveal a few methodological aspects to consider and provide a starting point for related research.

7.6 Limitations

The present results must be interpreted with some precaution due to a few methodological limitations. A central flaw that could be eliminated for the third study was the independence of pedalling cadence and visual flow speed in the first two experiments. The pedals were tracked with motion sensors to synchronize the avatar with the participant’s movements. This synchronization was considered sufficient to induce body ownership and agency to a certain degree. However, the independence of the visual flow speed from the pedalling cadence likely substantially reduced the sense of agency. Especially because the avatar was only visible during downward gaze, and participants were instructed to look straight ahead. Unfortunately, the pedal trackers were too prone to interferences from vibrations, which gravely impeded consistent tracking. To be able to base visual flow speed on pedalling cadence, stable tracking is needed. Otherwise, visual flow speed would change abruptly, promoting motion or cybersickness. The impact of this methodological flaw was likely reduced, but not eliminated, by restricting pedalling cadence in Study 2. The adapted attachment of the trackers prevented tracking distortions almost entirely, thus allowing the coupling of cadence and visual flow speed. The higher agency ratings in the third study suggest that this was a necessary adaptation to enable interactivity while allowing individual effort regulation (Slater, 2009).

One aspect that particularly affected the pleasantness and enjoyment of the activity was the monotony of the virtual scene. It was programmed with a basic appearance to create a realistic but unspectacular scenery that would not prompt permanent looking around. This was especially important to ensure consistent visual flow speed, given the differences between central and lamellar flow (Campos et al., 2007). Nonetheless, it can be argued that participants did not actively attend to the virtual scene for the whole trial. Attentional focus was not assessed but could have diluted any visual flow speed effects.

7.7 Implications and Conclusions

Although the results presented here partly lack statistical significance or immediate practical relevance, they do bear importance for this relatively new and specific research field. The effects of exergames and VR on enjoyment and performance have recently received a lot of scientific attention. However, most studies focus on general effects of VR or the appearance or presence of avatars, opponents, or teammates.

Performance feedback, especially during locomotion, has been investigated to a much lesser extent and existing visual flow research is mainly focused on gait or driving behaviour. The present manuscript has demonstrated that moderate-intensity endurance exercise has rarely been investigated in the context of VR-based exercise. Moreover, the present studies conjoined various theoretical approaches, which complicated the specification of hypotheses. The findings thus primarily revealed methodological and theoretical obstacles that are relevant for subsequent investigations.

The principal methodological obstacle was the coupling of cadence and VR. This aspect has produced two (contradicting) implications. (1) Agency ratings in Study 2 were acceptable without coupling of cadence and VR, suggesting that the plausibility of the visual flow speed primarily affected felt agency and that missing interactivity between the real and virtual world can be concealed through behavioural restrictions. (2) Agency ratings in Study 3 were higher than in both other studies, and only Study 3 could demonstrate a significant main effect of visual flow speed on heart rate, with the coupling being the major difference in setups. The coupling further enabled a relative manipulation of visual flow speed, which enhanced the sense of presence and enabled more natural cycling behaviour.

The present studies also reveal the importance of context for the perception and integration of visual flow when compared to data from time trials and mundane or passive movements. Future studies should consider that an exercise or movement goal and required physical effort impact the weight of visual flow in self-motion.

7.8 Outlook

Based on the studies presented here, the impact of visual flow speed on various cycling parameters remains a relevant and considerable topic in VR-based exercise research. Some aspects are particularly worthy of further investigation.

First, although it was not possible to measure attentional focus in the present studies, the theoretical considerations that arose from discussions about interoception clarified that it would be an interesting aspect to investigate. Using eye-tracking to determine the impact of gaze direction and measure attentional focus could produce relevant data for exercise contexts that could also be useful in traffic research.

Moreover, eye-tracking can be used to measure physiological activation (Bradley et al., 2008; Pengnate, 2019), bearing advantages over explicit subjective ratings (Desmet, 2018). Skin conductance can also reveal the level of activation, but the most used and most reliable measuring site is the palm of the hand (Boucsein, 2012), which is inaccessible during cycling. Valence is sometimes assessed through facial expressions (Höfling et al., 2020; Kring & Sloan, 2007), which is also inapplicable due to the HMD occluding most of the face. Valid and applicable methods must be identified to pursue this approach. Considering verbal reports from participants and the relevance of affect for physical activity, the possibilities of VR to impact subjective appraisal should clearly be a goal of future research about exercise initiation and adherence.

In a more physiological regard, the impact of VR configurations on cadence and power output/speed bears relevance for understanding motor control, pacing, and the relation between objective and subjective measures of effort. Here, differences between miscellaneous forms of locomotion and exercise goals require clarification. It should also be clarified which conditions promote motion adaptation. Moreover, the peculiarities of visual flow in VR-based locomotive exercise are as interesting as they are uncertain. Specifying relevant characteristics of the VR and identifying meaningful fields of application is critical for prospective studies on visual flow and cycling.

8 Declarations

8.1 Ethical Standards

All experiments were conducted according to ethical declaration of Helsinki. I communicated all considerations necessary to assess the question of ethical legitimacy of the studies.

8.2 Informed Consent to Participate and to Publish

Informed consent to participate and to publish anonymous results was obtained from all individual participants included in all studies.

8.3 Acknowledgements

I want to thank Manuel Mayer for providing the virtual scene used in all three studies and for supporting me in the setup of the VR system.

8.4 Open Research Practices

All three studies were preregistered at OSF.io. Experimental and analysis scripts and data files are uploaded to OSF.io.

8.5 Competing Interests

There were no competing interests for any of the studies.

8.6 Funding

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10 Appendix

10.1 Complete Results from Study 1

Table 3

Analysis of Heart Rate by Measure, Condition, and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	145.91	1.70	142.53 – 149.29		
Measure	5.50	0.23	5.04 – 5.97	164.98	<.001
Condition	-0.11	0.11	-0.33 – 0.11	0.97	.324
Trial	-0.80	0.50	-1.79 – 0.20	3.12	.078

Table 4

Analysis of Heart Rate by Measure, Condition, and Trial During Fast and Medium Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	145.14	1.81	141.54 – 148.73		
Measure	5.54	0.25	5.04 – 6.03	163.01	<.001
Condition	0.18	0.23	-0.29 – 0.64	0.60	.438
Trial	-0.60	0.64	-1.88 – 0.68	0.94	.331

Table 5

Analysis of Heart Rate by Measure, Condition, and Trial During Slow and Medium Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	145.14	1.81	141.55 – 148.73		
Measure	5.55	0.25	5.04 – 6.06	155.79	<.001
Condition	-0.40	0.16	-0.72 – -0.07	5.90	.015
Trial	-0.61	0.46	-1.53 – 0.32	1.80	.180

Table 6

Analysis of Heart Rate by Measure, Condition, and Condition × Awareness During Slow and Medium Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	145.13	1.81	141.53 – 148.73		
Measure	5.55	0.25	5.04 – 6.06	155.80	<.001
Condition	-0.40	0.17	-0.73 – -0.07	5.80	.016
Condition × Awareness	0.13	0.37	-0.62 – 0.87	0.12	.733

Table 7

Analysis of Heart Rate by Measure, Condition, and Condition × Sensitivity During Slow and Medium Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	145.13	1.81	141.53 – 148.73		
Measure	5.55	0.25	5.04 – 6.06	155.80	<.001
Condition	-0.40	0.17	-0.73 – -0.07	5.80	.016
Condition × Sensitivity	0.13	0.26	-0.39 – 0.65	0.25	.167

Table 8

Analysis of Heart Rate by Measure, Condition, and Trial During Slow and Fast Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	146.29	1.69	142.94 – 149.65		
Measure	5.42	0.24	4.94 – 5.90	159.17	<.001
Condition	-0.11	0.11	-0.34 – 0.11	0.99	.319
Trial	-0.61	0.65	-1.91 – 0.69	0.87	.352

Table 9

Analysis of RPE by Measure, Condition, and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	5.17	0.12	4.93 – 5.41		
Measure	0.67	0.03	0.61 – 0.74	148.87	<.001
Condition	-0.01	0.01	-0.03 – 0.01	0.68	.411
Trial	-0.20	0.05	-0.31 – -0.10	14.10	<.001

Table 10

Analysis of Valence by Measure, Condition, and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	5.31	0.13	5.06 – 5.56		
Measure	-0.09	0.04	-0.16 – -0.01	4.53	.033
Condition	-0.01	0.01	-0.04 – 0.02	0.91	.342
Trial	-0.04	0.07	-0.17 – 0.09	0.52	.472

Table 11

Analysis of Valence by Measure, Condition, and Trial During Fast and Medium Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	5.34	0.13	5.08 – 5.61		
Measure	-0.10	0.04	-0.18 – -0.01	5.96	.015
Condition	-0.03	0.03	-0.09 – 0.04	0.67	.415
Trial	-0.00	0.08	-0.17 – 0.16	0.00	.968

Table 12

Analysis of Valence by Measure, Condition, and Trial During Slow and Medium Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	5.34	0.13	5.08 – 5.61		
Measure	-0.07	0.04	-0.15 – 0.01	3.16	.076
Condition	0.00	0.03	-0.05 – 0.06	0.01	.930
Trial	-0.05	0.08	-0.20 – 0.10	0.49	.485

Table 13

Analysis of Valence by Measure, Condition, and Trial During Slow and Fast Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	5.29	0.14	5.02 – 5.56		
Measure	-0.09	0.04	-0.18 – -0.00	4.16	.042
Condition	-0.01	0.01	-0.04 – 0.02	0.63	.426
Trial	-0.01	0.08	-0.17 – 0.16	0.01	.928

Table 14

Analysis of Arousal by Measure, Condition, and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	5.95	0.11	5.73 – 6.17		
Measure	0.20	0.04	0.13 – 0.28	25.68	<.001
Condition	-0.01	0.02	-0.04 – 0.03	0.26	.608
Trial	-0.17	0.08	-0.32 – -0.02	5.39	.020

Table 15

Analysis of Arousal by Measure, Condition, and Trial During Fast and Medium Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	5.98	0.14	5.70 – 6.26		
Measure	0.21	0.04	0.13 – 0.29	22.61	<.001
Condition	-0.01	0.03	-0.08 – 0.06	0.07	.795
Trial	-0.29	0.09	-0.47 – -0.11	9.66	.002

Table 16

Analysis of Arousal by Measure, Condition, and Trial During Slow and Medium Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	5.98	0.14	5.70 – 6.25		
Measure	0.21	0.04	0.13 – 0.29	25.44	<.001
Condition	0.01	0.03	-0.05 – 0.07	0.19	.666
Trial	-0.09	0.08	-0.26 – 0.07	1.27	.261

Table 17

Analysis of Arousal by Measure, Condition, and Trial During Slow and Fast Visual Flow

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	5.93	0.11	5.71 – 6.15		
Measure	0.19	0.04	0.11 – 0.27	20.14	<.001
Condition	0.00	0.02	-0.03 – 0.04	0.19	.891
Trial	-0.34	0.10	-0.54 – -0.15	11.46	<.001

Table 18

Analysis of Strength by Condition and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	2.82	0.07	2.67 – 2.96		
Condition	-0.00	0.00	-0.01 – 0.00	0.98	.323
Trial	0.05	0.02	0.02 – 0.09	10.33	.001

Table 19

Analysis of Endurance by Condition and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	2.72	0.08	2.56 – 2.89		
Condition	0.00	0.00	-0.01 – 0.01	0.15	.696
Trial	0.07	0.02	0.04 – 0.10	15.63	<.001

Table 20

Analysis of Presence by Condition and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	2.97	0.08	2.81 – 3.12		
Condition	-0.01	0.01	-0.03 – 0.01	0.35	.554
Trial	-0.20	0.04	-0.28 – -0.12	21.70	<.001

Table 21

Analysis of Presence by Condition, Trial, and Awareness

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	2.97	0.08	2.81 – 3.12		
Condition	-0.01	0.01	-0.03 – 0.01	0.35	.554
Trial	-0.20	0.04	-0.28 – -0.12	21.70	<.001
Awareness	-0.05	0.18	-0.40 – 0.30	0.08	.773

Table 22

Analysis of Presence by Condition, Trial, and Sensitivity

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	2.97	0.08	2.81 – 3.12		
Condition	-0.01	0.01	-0.03 – 0.01	0.35	.554
Trial	-0.20	0.04	-0.28 – -0.12	21.70	<.001
Sensitivity	0.08	0.13	-0.17 – 0.33	0.40	.526

Table 23

Analysis of Agency by Condition and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	0.82	0.16	0.51 – 1.13		
Condition	0.02	0.02	-0.02 – 0.07	1.02	.314
Trial	-0.06	0.09	-0.24 – 0.11	0.52	.471

Table 24

Analysis of Ownership by Condition and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	-1.08	0.16	-1.39 – -0.77		
Condition	-0.05	0.03	-0.10 – 0.00	3.36	.067
Trial	-0.20	0.10	-0.39 – -0.00	4.17	.041

10.2 Complete Results from Study 2

Table 25

Analysis of Heart Rate by Minute, Condition, and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	136.75	2.31	132.12 – 141.37		
Minute	1.74	0.11	1.51 – 1.96	97.21	<.001
Condition	0.19	0.44	-0.70 – 1.08	0.19	0.662
Trial	2.82	0.44	1.93 – 3.71	31.94	<.001

Table 26

Analysis of RPE by Minute, Condition, and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	4.76	0.11	4.53 – 4.99		
Minute	0.25	0.01	0.22 – 0.27	248.29	<.001
Condition	-0.11	0.06	-0.23 – 0.01	3.29	.069
Trial	0.35	0.06	0.23 – 0.47	30.84	<.001

Table 27

Analysis of Cadence by Minute, Condition, and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	58.77	1.05	56.67 – 60.86		
Minute	0.10	0.02	0.05 – 0.14	16.33	<.001
Condition	-0.79	0.17	-1.14 – -0.45	19.50	<.001
Trial	0.54	0.17	0.20 – 0.87	9.59	.002

Table 28

Analysis of Cadence Violations by Minute, Condition, and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	3.53	0.40	2.74 – 4.33		
Minute	0.03	0.05	-0.08 – 0.13	0.25	.612
Condition	-0.24	0.29	-0.81 – 0.34	0.69	.407
Trial	0.82	0.29	0.24 – 1.39	7.37	.007

Table 29

Analysis of Agency by Condition and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	3.98	0.17	3.63 – 4.32		
Condition	1.09	0.19	0.71 – 1.48	26.58	<.001
Trial	-1.12	0.19	-1.51 – -0.74	27.81	<.001

Table 30

Analysis of Ownership by Condition and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	2.13	0.19	1.75 – 2.51		
Condition	0.17	0.16	-0.16 – 0.50	1.12	.291
Trial	-0.08	0.16	-0.41 – 0.25	0.23	.630

Table 31

Analysis of Endurance by Condition and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	2.86	0.10	2.67 – 3.05		
Condition	0.05	0.03	-0.01 – 0.10	3.15	.078
Trial	0.07	0.03	0.02 – 0.13	6.83	.009

Table 32

Analysis of Strength by Condition and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	2.93	0.07	2.79 – 3.07		
Condition	0.05	0.03	-0.00 – 0.10	3.75	.053
Trial	0.06	0.03	0.00 – 0.11	4.67	<.031

Table 33

Analysis of Speed Perception by Condition and Trial

Predictors	*Estimates*	*std. Error*	*t-value*	*p*
Intercept	3.77	0.08		
Condition	-1.61	0.17	0.165	<.001
Trial	0.61	0.17	0.165	<.001

Table 34

Analysis of Presence by Condition and Trial

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	3.61	0.13	3.34 – 3.88		
Condition	0.54	0.11	0.32 – 0.77	20.03	<.001
Trial	-0.19	0.11	-0.42 – 0.03	2.92	.088

10.3 Complete Results from Study 3

Table 35

Analysis of Heart Rate by Condition, Condition × Minute, and Condition × Speed

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	119.03	2.05	114.95 – 123.12		
Condition	-4.49	1.47	-7.41 – -1.57	9.12	.003
Condition × Minute	-0.25	0.15	-0.55 – 0.05	2.67	.102
Condition × Speed	0.96	0.56	-0.16 – 2.07	3.02	.082

Table 36

Analysis of RPE by Condition, Condition × Minute, and Condition × Speed

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	3.66	0.12	3.42 – 3.91		
Condition	-0.19	0.12	-0.44 – 0.06	2.38	.123
Condition × Minute	0.01	0.04	-0.06 – 0.08	0.15	.699
Condition × Speed	0.00	0.03	-0.06 – 0.07	0.04	.841

Table 37

Analysis of Strength by Condition

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	2.85	0.08	2.79 – 3.05		
Condition	0.03	0.02	-0.01 – 0.08	1.95	.162

Table 38

Analysis of Endurance by Condition

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	2.85	0.08	2.69 – 3.02		
Condition	0.03	0.02	-0.01 – 0.08	1.95	.162

Table 39

Analysis of Presence by Condition

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	*χ^2*	*p*
Intercept	3.87	0.11	3.64 – 4.09		
Condition	0.18	0.10	-0.02 – 0.38	3.10	.078

Table 40

Analysis of Agency by Condition

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	*χ^2*	*p*
Intercept	4.90	0.08	4.75 – 5.06		
Condition	-0.05	0.13	-0.32 – 0.22	0.14	.710

Table 41

Analysis of Ownership by Condition

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	*χ^2*	*p*
Intercept	2.31	0.16	1.98 – 2.63		
Condition	-0.10	0.15	-0.40 – 0.21	0.39	.532

Table 42

Analysis of Enjoyment by Condition

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	*χ^2*	*p*
Intercept	2.95	0.02	2.91 – 3.00		
Condition	0.03	0.02	-0.01 – 0.06	2.46	.117

Table 43

Analysis of Speed Perception by Condition

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	*χ^2*	*p*
Intercept	2.81	0.11	2.59 – 3.03		
Condition	-1.83	0.15	-2.13 – -1.54	85.74	<.001

Table 44

Analysis of Cycling Speed by Condition and Condition × Minute

Predictor	*Estimate*	*std. Error*	*Confidence Interval*	χ^2	*p*
Intercept	24.53	0.41	23.71 – 25.35		
Condition	-0.79	0.29	-1.37 – -0.20	8.91	.003
Condition × Minute	0.04	0.03	-0.03 – 0.10	1.45	.229