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Interactive Feedforward for Improving Performance and Maintaining Intrinsic Motivation in VR Exergaming

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Figure 1: a) The exergame is based on a computer-controlled stationary exercycle and played while wearing a head-mounted display. b) A "self modelling cue" helps the player to identify a "ghost" avatar with their own previous performance. c) Low-intensity cycling and avoiding trucks during warm-up, recovery and cool-down phases. d) High-intensity race against the "ghost."

ABSTRACT

Exergames commonly use low to moderate intensity exercise protocols. Their effectiveness in implementing high intensity protocols remains uncertain. We propose a method for improving performance while maintaining intrinsic motivation in high intensity VR exergaming. Our method is based on an interactive adaptation of the feedforward method: a psychophysical training technique achieving rapid improvement in performance by exposing participants to self models showing previously unachieved performance levels. We evaluated our method in a cycling-based exergame. Participants competed against (i) a self model which represented their previous speed; (ii) a self model representing their previous speed but increased resistance therefore requiring higher performance to keep up; or (iii) a virtual competitor at the same two levels of performance. We varied participants' awareness of these differences. Interactive feedforward led to improved performance while maintaining intrinsic motivation even when participants were aware of the interventions, and was superior to competing against a virtual competitor.

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INTRODUCTION

Physical inactivity has been identified as the fourth leading cause of death globally [50]. It is well established that a sedentary lifestyle increases the risk of developing diseases such as type 2 diabetes and cardiovascular disease [87] which account for 30% of global mortality. The American College of Sports Medicine (ACSM) recommends adults should do at least 150 minutes of moderate exercise or 75 minutes of vigorous exercise per week [63]. However, when people begin physical activity regimens, 40% to 65% are predicted to drop out within 3 to 6 months [2, 3, 17]. Intrinsic motivation, i.e. motivation derived from enjoyment and satisfaction gained from an activity, has been identified as an important predictor of adherence to an exercise program [1, 30, 72]. Indeed, lack of time and maintaining motivation are the most commonly cited barriers to continuing exercise [26] so tackling these two challenges is key to improving global health.

High-intensity interval training (HIIT) – short intermittent bouts of vigorous activity, interspersed with periods of rest or low-intensity exercise [32] – can reduce the time required for a healthy exercise regime. Studies show that HIIT is equally beneficial or superior to traditional aerobic exercise in many fitness and health related measures [33, 49, 61]. Participants

also enjoy it more and prefer it to longer, lower intensity aerobic exercise [6, 83]. However, it remains a challenge to motivate people to exercise at sufficient intensity [28, 65] and maintain a regime of vigorous exercise [9, 62].

There is evidence that exergames increase enjoyment and intrinsic motivation compared to conventional exercise and distract from uncomfortable bodily sensations [4, 5, 25, 59, 75]. Exergames can be effective in motivating players to exercise at light-to-moderate intensity [4, 35, 59, 67]. There is some evidence that exergaming also holds promise for motivating exercise at a high intensity [36, 47, 58, 88]. However, motivating players to work at high intensity in an exergame remains a challenge, as hard exercise often reduces pleasure [7, 23, 66].

We propose to improve a player's exercise performance in a VR HIIT exergame while maintaining intrinsic motivation using an *interactive feedforward* method. Conventional feedforward is an established method to help an individual learn or improve a skill or performance, "in which an image of success is constructed to illustrate achievement beyond the individual's current ability" and which can result in "remarkably rapid changes of behaviour and improvements of performance" [19]. Feedforward is a type of *self modelling*, an intervention procedure using recordings of oneself engaged in adaptive behaviour to learn skills or adjust to challenging environments as part of a training or therapy protocol [18]. To improve performance with feedforward, two conditions must be met: 1) a self model of an individual must be "constructed", usually by editing videos, to create essentially a future image of improved behaviour, and 2) the individual should see themselves in a desired performance. Dowrick suggests that an enhanced self model may serve not only as a model to which you aspire but as a competitor to elicit improvement in performance [19]. Our interactive feedforward method is the first to use an enhanced self model as a competitor in this way. The dynamic behaviour of an enhanced interactive self model can only be effectively simulated in a virtual environment.

Our exergame and setup using a stationary exercycle and head-mounted display (HMD) are shown in Figure 1. In order to create a self model, we recorded the player performing an exergame session on the bike. We then replayed this recording as a self model in subsequent HIIT sessions in the form of a "ghost" avatar so the players compete against their own previous performance. For the self model to function as markedly improved, we increase the bike resistance while players race against the self model. Thus the effort required to outrace or maintain the same pace as the ghost is higher due to the increase in resistance of the exercise bike. We call this *interactive feedforward* as, in contrast to how feedforward is typically used, individuals are not merely passive recipients of a self model (e.g. in the case of a video [21]) but interact with it in real-time in a VR feedforward experience. This is related to the practice of setting challenges or targets; however, the target is presented through a self model rather than using typical targets without reference to self. We hypothesise that interactive feedforward, in which players identify with the self model while perceiving it as performing at a level they have not previously achieved, will improve performance more

than an unenhanced self model [14, 74, 86]. We operationalise performance as average power output, which is a measure of performance widely used in sport and exercise science.

Ideally, we would like our method to be superior in all regards, increasing both performance and intrinsic motivation. However, this goes against human psychophysiological constraints, which have been shown to reduce positive affect as physical exertion nears or surpasses the ventilatory threshold [23]. We cannot change the fact that vigorous exercise feels 'hard', therefore it is unrealistic to expect interactive feedforward to improve performance while significantly *increasing* intrinsic motivation. It is plausible, however, that good exergame design can mitigate loss of intrinsic motivation [25, 27, 69, 75]. Hence, we hypothesise that interactive feedforward will not be significantly worse than an unenhanced self model in its effect on intrinsic motivation. To test this we use *non-inferiority testing* [51, 73], which is widely used in clinical trials but has hardly been used in HCI. It tests whether a method is not worse than a justifiable margin compared to a known method. The non-inferiority margin was selected based on the results of other studies using the Intrinsic Motivation Inventory (IMI) Interest/Enjoyment subscale, considering differences in IMI scores that were meaningful with regard to a context or treatment [12, 27, 39, 56, 69].

Interactive feedforward can be regarded as a suitable method for performance improvement in exergames only if it works when players are aware it is being used. It is impractical and potentially unethical to count on players' ignorance in the long term. Users are likely to notice marked changes in intensity as they play an exergame. When using feedforward with video, individuals are usually involved in the creation of the self modelling video and hence fully aware of the method [19–21]. We therefore also investigated whether awareness of resistance increase in an exergame compromised its efficacy.

Our concept of interactive feedforward is based on competition against a self model ("self competition"). This is different from competition against a virtual competitor ("non-self competition") which is widely used in racing games. Feedforward theory [19] and empirical evidence [79] suggest that self models are more powerful than models of others, as participants are able to identify and relate more closely to self models. Furthermore, there is evidence to suggest that competition against others can have a detrimental effect on intrinsic motivation, especially in less fit individuals [16, 68]. We therefore hypothesise that interactive feedforward not only improves an individual's performance more than competition against a virtual non-self competitor but is also more effective in intrinsically motivating players. In summary, we investigated the following research questions:

RQ1 How effective is interactive feedforward in improving performance as measured by average power output while maintaining intrinsic motivation?

RQ2 How robust are the effects of interactive feedforward to a player's awareness that the method is being used?

RQ3 How do interactive feedforward and non-self competition differ in terms of performance and intrinsic motivation?

Self modelling and feedforward have mostly been used with video ("video self modelling") [13,19–21,29,79,80,84,85]. To our knowledge, feedforward has never previously been used in interactive exergaming. We make the following contributions:

1. An exergaming system for interactive feedforward in virtual reality.

2. An empirical study investigating the efficacy of interactive feedforward in improving physical performance while maintaining intrinsic motivation in our exergame.

3. An investigation of the robustness of the approach with regard to a player's awareness of the method being used.

4. A comparison of self competitive interactive feedforward and competition with others.

RELATED WORK

Internal barriers (e.g. lack of willpower, lack of time) are more frequently cited as reasons for not exercising than external barriers (e.g. lack of transport, cost) [89]. Lack of time and motivation are the major barriers for most people [26]. Motivation can be divided into intrinsic (doing an activity for its own sake, enjoyment) and extrinsic (driven by external outcomes, e.g. losing weight and improving fitness) [71]. Intrinsic motivation plays a very important role in long-term adherence to exercise [1, 30, 72], whereas extrinsic motivation such as competitive pressure may lead to tension and feelings of compulsion, and can diminish intrinsic motivation [16, 68]. Gamification can reduce the detrimental effects of competitive group dynamics [52]. Therefore, we aim to develop an exergaming approach that intrinsically motivates the player.

High-intensity interval training (HIIT) has emerged as a more time-efficient, yet equally beneficial, alternative to traditional moderate-intensity aerobic exercise [31]. Its reduced duration compared to continuous exertion exercise helps to address the major exercise barrier of lack of time. There is evidence that participants prefer HIIT over continuous exertion exercise protocols, enjoy it more and are therefore more willing to exercise [6, 46, 83]. Despite these claimed advantages of HIIT, it remains a challenge to motivate people to exercise at a high intensity [28, 65] and adhere to a high-intensity exercise regimen [9, 62]. We propose using a VR exergame to enhance performance and maintain intrinsic motivation in HIIT exercise.

Evidence suggests that in traditional exercise participants employ pacing strategies that leave a significant metabolic energy reserve at the end [81]. Researchers have attempted to access this reserve by influencing participants' pacing strategy in continuous exercise through deceptive performance feedback, with equivocal results [43]. Challenging athletes with pace-setters based on previous performance levels is an established method for improving performance in traditional sports and exercise. However, it is unclear how far deception and the perception of a challenge contribute to these improvements [44, 45, 77, 86].

Immersion – the degree of involvement in a game [10] – plays an important role in motivation and enjoyment of exergaming [41]. Ijsselsteijn et al. showed that in a highly immersive exergaming environment participants reported more interest, enjoyment, perceived competence and control, as well as cycling faster [39]. In a study by Banos et al., VR increased enjoyment and enhanced attentional distraction in overweight children during exercise, motivating them to perform better [5]. Johnson et al. found that dissociation lowered the rate of perceived exertion [42]. This indicates that dissociation from exercise through VR can allow players to exert themselves more, improving performance, enjoyment and motivation.

A concept related to immersion is flow [15, 24], which is an ideal psychological state of energised focus, enjoyment and complete absorption in an activity where the skills of an individual are balanced with an adequate challenge. According to typical models of flow, challenges that are too easy lead to boredom, and challenges that are too demanding lead to anxiety. Flow has been discussed in the context of exergames [78], where flow can be subdivided into a psychological component balancing the player's perceived skill with perceived challenge ("attractiveness") and a physiological component balancing a player's fitness with the intensity of the exercise. Consideration of flow is useful when trying to improve performance while maintaining intrinsic motivation.

Some VR exercise games make use of an exercise bike, which allows players to remain seated and reduces the risk of injury or VR sickness [8, 76]. Shaw et al. found that an exergame increased enjoyment and motivation compared to conventional cycling exercise, and that the use of an HMD compared to a 2D screen led to further improvements [75]. Although exergames can be enjoyable, they are often not vigorous enough to replace traditional physical activity; "a biking exergame design requires a precise balance between interaction design and exercise physiology in order to be both engaging and beneficial to health" [36]. Game mechanics that encourage players to exercise at a higher level of intensity through rewards were found to be effective in increasing exertion levels and enjoyment [47]. Similarly, competition in exergaming, especially self competition, was found to be effective in eliciting higher levels of exercise and enjoyment [74]. However, for players with low fitness or low self-efficacy, competition in exergames can highlight their inadequacies and cause "more damage than good" [52]. Our focus is therefore on competition-based gamification techniques that intrinsically motivate players to exercise at a higher intensity.

Self modelling uses a model of an individual achieving a goal to induce higher motivation and learning of the behaviours required to achieve that goal [19]. In feedforward, the self model is created (usually by selective video editing) to exhibit an improved performance that has not yet been consistently achieved. It enables existing component behaviours to "become reconfigured as future 'new' skills or placed in a new or challenging context" [20]. It is conjectured that self modelling may be based on the activation of mirror neurons, i.e. the self model activates the neural circuits responsible for the modelled behaviour. The more similar a model is to an individual, the better it is able to activate the relevant mirror neurons; therefore a self model is better suited for feedforward than an 'other' model such as a video recording of another individual.

Feedforward effects have been reported for a number of learning, treatment and training applications [20], including applications in sports and exercise such as football [80] and power-lifting [29]. In a study comparing self modelling with 'other' (i.e non-self) modelling in beginner swimmers, participants in the self modelling condition demonstrated better performance [79]. A case study of self modelling for a professional mountain biker identified benefits including improved motivation, confidence and concentration [84]. A comparison of self observation (viewing oneself perform at current skill level) and self modelling (viewing oneself perform an improved, adaptive behaviour) showed that the latter was superior in improving children's self regulation and swimming performance [13]. A study of competitive trampolinists found that participants used video self modelling to improve their performance, with potential benefits including improved self-efficacy and motor execution [85]. These works used a static feedforward stimulus that was passively consumed, such as a video. The closest in topic and spirit to our work is a study by Gonzales et al. [34] where athletes running on a treadmill were asked to match (not surpass) a video of themselves running at an optimal stride. With the video they achieved higher time to exertion and lower oxygen consumption. Our aim is to elicit an interactive feedforward effect by using a self model which serves as a competitor, as opposed to a non-interactive video.

EXERGAME DESIGN

Our exergame is a VR racing game played riding a computer-controlled stationary exercycle and wearing an HMD; see Figure 1a. It was designed based on the principles outlined by Shaw et al. [76]. In order to provide a systematic overview, we describe the game along the dimensions of the frequently used MDA model (Mechanics, Dynamics, and Aesthetics) [38].

Mechanics: The player cycles along a straight road while avoiding slow moving trucks. In the game, the player's bike is always facing forward to avoid VR sickness due to sensory disconnect [8, 76]. In-game speed is proportional to the current pedalling cadence (in RPM) measured by the exercycle sensors. The player can move laterally by leaning her head left and right; the speed of lateral movement is proportional to the roll angle measured by the HMD sensors.

Dynamics: The gameplay follows a HIIT protocol, starting with a warm-up, followed by a number of high-intensity sprints separated by recovery phases, and finishing with a cool-down. The number of sprints, the resistance (exercycle breaking torque) and duration of each phase are configurable. During warm-up, recovery and cool-down, the resistance is low and the main gameplay objective is to avoid trucks, which are moving straight along the road. During sprints, the resistance is high and the main gameplay objective is to cycle as fast as possible. Trucks are still present but more sparsely placed. In case of a collision with a truck, the truck simply disappears without further consequence to avoid disrupting the flow of the exercise protocol and thereby to preserve the intensity of HIIT. During gameplay, the distance to the ghost, a countdown for the time remaining in the current phase and the current RPM are shown. Four seconds before a sprint starts, a message "get ready to sprint!" is displayed at the centre of the HMD.

Aesthetics: The low-intensity phases (warm-up, recovery, cool-down) aim to evoke a relaxed mood, using a sunny scene and a bright colour palette (Figure 1c). For the sprints, there is a transition to a night time scene with street lamps beside the road and cars with flashing emergency lights following the player, to evoke a sense of pressure and urgency (Figure 1d).

The exercycle was a Lode Excalibur Sport. The HMD was an HTC Vive. Both were connected to a PC running Unity with an Intel Xeon E5 2680 processor, 64 gigabytes of RAM, and two NVIDIA Titan X graphics cards running in SLI mode.

Incorporating Feedforward

The exergame can be played in three different game modes. In the *baseline* mode (B), the player's movements are recorded while they complete the configured HIIT protocol. Hence, this mode can be used to create a self model. In the *equal challenge* mode (E), a self model previously obtained in mode B is played back in the form of a "ghost" avatar (Figure 1 b-d), similar to [74]. This allows players to compete against themselves ("self competition"), resulting in a challenge equal to one of their previous performances. To reinforce that the "ghost" represents a self model, a short "self model cue" animation sequence is played at the beginning of mode E, showing the ghost with a message "This is you" in the centre of the HMD (Figure 1b). At the beginning of each sprint, the game adjusts the positions so that player and avatar start sprinting next to each other. Even if player or avatar fall behind in one of the sprints, they start the next sprint on an equal footing.

The *harder challenge* mode (H) is designed to elicit a feedforward effect. It is the same as mode E except that the resistance is increased by a constant factor. With this increase, the ghost serves as an improved self model, requiring a performance that has not yet been achieved, as the effort required to maintain the same pace as the ghost increases with the resistance. In contrast to typical video self modelling, where the feedforward stimulus is passively consumed simply by viewing it, this mode provides an interactive feedforward experience where the player competes with the improved self model.

EXPERIMENTAL DESIGN

We investigated the effectiveness of interactive feedforward in improving performance and maintaining intrinsic motivation (RQ1) using a within participants design for the independent variable *game mode* with levels baseline (B), equal challenge (E) and harder challenge (H). Participants started with B to create a self model of their performance and in E participants were asked to compete with their self model. In H we attempted to elicit a feedforward effect by, in addition to competing with the self model, increasing the resistance by 10%. This value was chosen because it is a meaningful increase in exercise intensity and was likely still achievable for many participants based on pilot testing. The order of E and H was counterbalanced. Other studies did not detect any performance differences between self competition and a baseline [74, 86], suggesting that performance in E and B will be similar. Therefore, we focused on comparing performance improvement relative to B and intrinsic motivation in E vs. H.

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Table 1: Experimental design overview. We call condition SC+H the "interactive feedforward" (IFF) condition.

Competition Framing	Resistance Awareness	Game Mode (within-participant)		
		Baseline (B)	Equal Challenge (E)	Harder Challenge (H)
Self (SC)	None (NA)	Record self model	Replay self model + self cue	Improved self model + self cue (IFF)
	Vague (VA)	Record self model	" + "may change intensity"	" + "may change intensity"
	Full (FA)	Record self model	Replay self model + self cue	" + "will be harder"
Non-Self (NSC)	None (NA)	Record "competitor"	Replay "competitor", no cue	Improved "competitor", no cue

In order to determine if the interactive feedforward effect is robust with regard to a user's awareness of the method of increasing resistance (RQ2), we used a between participants design for the independent variable *resistance awareness* with levels no awareness (NA), vague awareness (VA) and full awareness (FA). Each of the three groups followed the repeated measures design of B, E, H described above. For NA, participants were not told about the increased resistance in H, although it was likely that they would feel it. For VA, a message was displayed at the beginning of every game mode condition stating "The exergame may change the intensity of the workout to make it easier or harder". For FA, we displayed the message "The exergame will be made harder" before condition H. We compared performance and intrinsic motivation across the different levels to investigate if increasing awareness of the increased resistance influenced the effectiveness of the feedforward method in improving performance while maintaining intrinsic motivation.

To investigate differences between the feedforward effect elicited by self competition and competition with others (RQ3), we used a between participants design for the independent variable *competition framing* with levels self competition (SC) and non-self competition (NSC). Each group followed the same repeated measures design of B, E, H. For SC, the competition in E and H was framed as self competition, i.e. participants were informed that they were competing against a recording of their performance in B. We refer to SC+H as the interactive feedforward condition. For NSC, the competition in E and H was framed as competition with others, i.e. participants were informed that they were competing against a "virtual competitor". The virtual competitor was their own recording of B, exactly as in SC, but participants were not aware of this. Apart from the framing, the only difference from SC was that in NSC the self model cue was not shown. Participants were not told that the exercycle's resistance would be increased in NSC+H, i.e. no awareness (NA). Awareness of the resistance is less relevant in the context of NSC because, in contrast to SC, no expectations are set by a self model. The NSC group was compared with group SC+NA with regard to performance improvement (relative to B) and intrinsic motivation.

The overall study design is summarised in Table 1. We have four groups: SC+NA, SC+VA, SC+FA and NSC+NA. Each group uses a within participants design for game mode (B, E and H) with counterbalanced order of E and H (after recording in B). Participants were randomly assigned to the groups, with 12 participants per group. The study received ethical approval from the Research Ethics Approval Committee for Health of the University of Bath (Reference: EP 16/17 191).

Outcome Variables
To measure participants' exertion based on heart rate (HR), we used a Polar H10 chest strap sensor. For each condition, the mean of the peak HRs of the two sprints was calculated and expressed as a percentage of a participant's estimated maximum HR (HR Peak%). Based on ACSM guidelines [63], maximum HR was estimated as 220 minus age. This measure is commonly used in exercise studies to confirm participants are working at a required level of exertion. As a measure of performance, we recorded the average power output (Power) in Watts over both sprint phases in each condition, as measured by the exercycle sensors. To compensate for differences in physical fitness between participants, we considered each participant's performance in the E and H game mode against their baseline B, i.e. Power_{E-B} and Power_{H-B}, which we refer to as ΔPower in the context of game mode E or H.

To measure intrinsic motivation, we used the Intrinsic Motivation Inventory (IMI) scale [70], which has been used and validated for sports and exercise [12,55]. The IMI comprises seven subscales, but only the Interest/Enjoyment subscale measures intrinsic motivation and is considered the main self-report measure. We therefore focused on the Interest/Enjoyment subscale, while also considering the Pressure/Tension subscale, which is a negative predictor of intrinsic motivation. The scores are on a scale from 1 to 7, with 7 representing the highest intrinsic motivation or pressure/tension respectively.

To measure flow, we used the Flow State Questionnaire of the Positive Psychology Lab (FSQ) [53], which has been validated with exergames. It has two subscales: Balance of Challenges and Skills, and Absorption in the Task. We recorded the subscale scores as averages over all item scores between 1 and 5, with 5 representing the highest level of flow. We used the Immersive Experience Questionnaire (IEQ) [41] to quantify how immersive the exergaming experience was. The IEQ has been used widely in ludology, including for exergames [11]. We recorded the IEQ score as an average over item scores between 1 and 7, with 7 representing the highest level of immersion.

Exercise Protocol
A low-volume HIIT protocol suits our exergame particularly well: besides its wide applicability, appeal and health benefits, the short format mitigates typical HMD usability problems such as VR sickness, sweat and wearer discomfort [76]. Based

on ACSM guidelines for exercise [63] and related work [32, 40, 57], we used the following protocol: 60 sec warm-up, 30 sec sprint, 90 sec recovery, 30 sec sprint, 90 sec cool-down.

In the warm-up, recovery and cool-down phases, participants were instructed to cycle at a low cadence, between 65 and 70 RPM, with a low resistance of 12 Nm. The resistance during sprints was initially set to 0.4 Nm kg^{-1} based on a participant's body mass, which is in line with the resistance used for other low-volume Wingate-style protocols [40]. It was then adjusted, if necessary, for each participant in a familiarisation phase based on feedback, to enable them to perform at a "very hard" rate of perceived exertion (RPE) during all sprints while avoiding uncontrolled movements due to high cadence.

Hypotheses

Based on related work and pilot trials, we had the hypotheses:

H1 Interactive feedforward (SC+H) improves performance as measured by average power output compared to competition against a non-improved self model (SC+E) (RQ1).

H2 Interactive feedforward (SC+H) improves performance in all awareness conditions (NA, VA, FA) (RQ2).

H3 Interactive feedforward (SC+H) improves performance compared to competition with others (NSC+H) (RQ3).

H4 Interactive feedforward (SC+H) is not inferior in its effect on intrinsic motivation compared both to no competition (SC+B) and to competition with a non-improved self model (SC+E) (RQ1).

H5 Interactive feedforward (SC+H) improves intrinsic motivation compared to competition with others (NSC+H) (RQ3).

Procedure

Participants were screened using the Physical Activity Readiness Questionnaire (PAR-Q) [82]. If a participant answered 'yes' to any of the PAR-Q questions or had a resting blood pressure greater than 140/90 mmHg, they were excluded from doing the experiment. Participants were then asked to complete pre-experiment questionnaires including a demographics questionnaire and the International Physical Activity Questionnaire (IPAQ) [37]. The IPAQ estimates the volume of physical activity in Metabolic Equivalent of Task (MET) units for each group as shown in Table 2. Participants were asked to read an instruction sheet about the experiment with details about the exergame, the exercise protocol and the experiment. The instruction sheet stated either that participants would race against a recording of their own previous performance (SC) or against a "virtual competitor" (NSC). Participants were instructed to work very hard during the sprints and to maintain 65-70 RPM during the low-intensity phases. After initialising sprint resistance based on body mass, participants went through a familiarisation phase which allowed them to experience the full 5-minute protocol in the exergame and adjust the sprint resistance to their level of fitness. Participants then played the exergame in each of the three game modes, in the order BEH or BHE, with cues shown according to their resistance awareness and competition framing group. After each of the three conditions, participants were asked to complete

the IMI, FSQ and leave comments on their experience as qualitative feedback. Participants had a break of about 10 minutes between the gameplay rounds to avoid fatigue. At the end of the experiment participants were asked to complete the IEQ. The experiment took about 75 minutes.

Participants

We recruited 54 participants (35 males, 13 females; age 18-51, mean 28) through mailing lists and posters. They were a mixture of students and employees of the University of Bath. Six participants were excluded or discontinued the experiment because of high blood pressure (2), fatigue (2), VR sickness (1) or eye defects (1). All others were randomly assigned to one of the four groups, with 12 participants per group. All participants gave written, informed consent and were remunerated for their time.

RESULTS

The conditions that were compared had the same number of samples (12), for each dependent variable the variances within each condition were close enough to equal (homoscedastic) and the measurements' distributions close enough to normal to warrant an analysis of variance (ANOVA). In cases where Mauchly's test indicated a violation of sphericity for a repeated measures ANOVA, Huynh-Feldt correction was used. We used the ω^2 measure for ANOVA effect sizes [64], and all instances of 'significant' refer to 'statistically significant', taking a significance level of $\alpha = .05$.

The non-inferiority hypotheses were tested following the confidence interval (CI) approach, which is recommended practice for non-inferiority trials [51, 73]. A non-inferiority margin d was specified, which is the maximum tolerable difference between an 'old' and a 'new' treatment for the new treatment to be considered non-inferior. In our case, the 'old' treatments are B and E, and the 'new' treatment is H. If the two-tailed 95% CI of the mean difference between the treatments lies above d, then the new treatment is considered non-inferior. We chose a non-inferiority margin $d_{Enjoy} = -0.3$, based on reported characteristics of the IMI [12, 27, 39, 56, 69] which support the assumption that differences smaller than 0.3 points on the 7-point IMI Interest/Enjoyment scale are tolerable for non-inferiority.

A summary of the results is shown in Table 2. The results are illustrated in Figures 2 and 3, showing means with 95% CIs. HR Peak% is on average above 80 in all conditions, which indicates that participants were exercising to the required intensity for HIIT [63]. Independent-samples t-tests were conducted to compare all measurements made in game modes E and H between the two counterbalanced order groups, BEH and BHE. There were no significant order effects, all $|t| \leq 1.31, p \geq .20$.

A two-way repeated measures ANOVA was conducted on the effects of game mode (E and H) and resistance awareness (NA, VA and FA) for self competition (SC) on the average power output increase from baseline ΔPower (Figure 2 top-left). The main effect of game mode was significant, $F(1, 33) = 63.2, p < .001$, indicating that the harder challenge mode in self competition (SC+H) improved performance more than the equal challenge mode in self competition (SC+E)

Table 2: Summary of demographics and results for each group (mean ± std. dev.).

Competition Framing	Resistance Awareness	n	Demographics	Variable	Game Mode (within-participant)		
					Baseline (B)	Equal (E) Challenge	Harder (H) Challenge
Self (SC)	None (NA)	12	m=9, f=3 age=23±4 IPAQ=2664±1924 MET IEQ=5.74±0.65	HR Peak%	84.61±8.77	87.09±8.84	88.71±8.42
				Power	325.15±76.46	344.52±92.02	378.46±93.26
				ΔPower		19.37±23.19	53.31±26.03
				IMI Enjoyment	5.76±1.02	6.18±0.93	6.06±0.75
				IMI Tension	2.73±1.16	2.42±0.78	2.83±1.13
				FSQ Balance	4.12±0.65	3.98±0.75	4.00±0.67
				FSQ Absorption	4.13±0.59	4.19±0.65	4.30±0.50
	Vague (VA)	12	m=12, f=0 age=30±7 IPAQ=4354±2195 MET IEQ=5.34±0.46	HR Peak%	83.01±9.99	86.65±8.06	86.82±7.73
				Power	370.09±76.23	395.47±70.85	417.40±71.95
				ΔPower		25.38±28.81	47.32±32.86
				IMI Enjoyment	5.34±1.06	5.43±1.20	5.33±1.42
				IMI Tension	2.43±0.87	2.43±1.00	2.4±0.91
				FSQ Balance	4.12±0.45	4.01±0.69	3.77±0.94
				FSQ Absorption	3.71±0.45	3.81±0.60	3.63±0.52
	Full (FA)	12	m=7, f=5 age=31±9 IPAQ=2213±1102 MET IEQ=5.41±0.63	HR Peak%	84.39±9.35	87.40±9.14	87.75±9.45
				Power	309.44±92.17	312.64±92.75	340.07±92.25
				ΔPower		3.20±11.93	30.63±25.94
				IMI Enjoyment	5.98±0.69	5.70±0.89	5.60±0.93
				IMI Tension	3.30±1.26	2.78±1.27	2.71±1.20
				FSQ Balance	4.12±0.56	4.17±0.46	3.77±0.77
				FSQ Absorption	3.79±0.50	3.97±0.71	3.71±0.75
Non-Self (NSC)	None (NA)	12	m=7, f=5 age=27±6 IPAQ=2754±1176 MET IEQ=5.02±0.86	HR Peak%	85.09±6.20	88.75±5.52	87.34±5.12
				Power	267.16±80.35	274.77±84.42	289.50±93.45
				ΔPower		7.61±19.03	22.34±21.49
				IMI Enjoyment	5.25±1.06	5.21±0.91	4.58±1.08
				IMI Tension	3.52±0.98	3.95±1.19	4.03±1.40
				FSQ Balance	3.57±0.80	3.49±0.54	2.97±0.86
				FSQ Absorption	3.65±0.67	3.91±0.62	3.77±0.72

with a 'large' effect size ($\omega^2 = 0.63$, 95% CI of Cohen's d [0.88, 1.80]). This indicates that the feedforward effect was elicited in the SC+H condition and that it resulted in improved performance, therefore we accept H1. The main effect of awareness, $F(2,33) = 2.76, p = .08$, and the interaction effect, $F(2,33) = 0.99, p = .38$, were not significant. A dependent-samples t-test comparing Power for B and E in SC showed that there was a significant difference between B and E, $t(35) = 4.04, p < .001$, with a 'medium' effect size (Cohen's d=0.67).

A one-way ANOVA showed that the effect of resistance awareness (NA, VA, FA) on ΔPower in H ($Power_{H-B}$) was not significant, $F(2,33) = 2.05, p = .15$ (Figure 2 top-right). Independent-samples t-tests of the marginal means with Bonferroni correction showed that $Power_{H-B}$ was significantly positive for all levels, NA ($t = 6.49, p < .001$, 95% CI [32.59, 74.03]), VA ($t = 5.76, p < .001$, 95% CI [26.59, 68.04]) and FA ($t = 3.73, p = .002$, 95% CI [9.91, 51.36]). That is, in all awareness conditions feedforward (SC+H) led to a significant improvement in performance compared to baseline, so we accept H2.

A two-way repeated measures ANOVA was conducted on the effects of game mode (E and H) and framing (SC and NSC)

for no awareness (NA) on the power increase from baseline ΔPower (Figure 2 bottom-left). The main effect of game mode was significant, $F(1,22) = 25.97, p < .001$, indicating that a harder competitive challenge increased performance more than a challenge equal to baseline with a 'large' effect size ($\omega^2 = 0.47$, 95% CI of Cohen's d [0.49, 1.49]). The main effect of framing was significant, $F(1,22) = 7.34, p = .01$, indicating that self competition increased performance more than non-self competition with a 'large' effect size ($\omega^2 = 0.21$). The interaction effect was not significant, $F(1,22) = 4.05, p = .06$. An independent-samples t-test comparing $Power_{H-B}$ for SC and NSC (Figure 2 bottom-right) showed that SC led to a significantly higher performance, $t(22) = 3.18, p = .002$, with a 'large' effect size (Cohen's d=1.30), so we accept H3.

A two-way repeated measures ANOVA with Huynh-Feldt correction was conducted on the effects of game mode (B, E and H) and resistance awareness (NA, VA and FA) for self competition (SC) on IMI Interest/Enjoyment scores (Figure 3 top-left). The main effect of game mode, $F(1.57, 51.96) = 0.62, p = .51$, the main effect of awareness, $F(2,33) = 1.45, p = .25$, and the interaction effect, $F(3.15, 51.96) = 2.24, p = .09$, were not significant. The 95% CI of the mean difference between B and H was [-0.28, 0.26] (i.e. likely at most 0.28
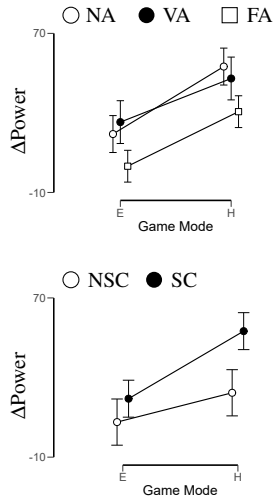
Figure 2: ΔPower (difference from baseline B) for the equal challenge (E) and harder challenge (H) conditions in different levels of resistance awareness (top-left) and in non-self (NSC) vs. self competition (SC) framing (bottom-left). ΔPower for H in different levels of resistance awareness (top-right) and competition framing (bottom-right).
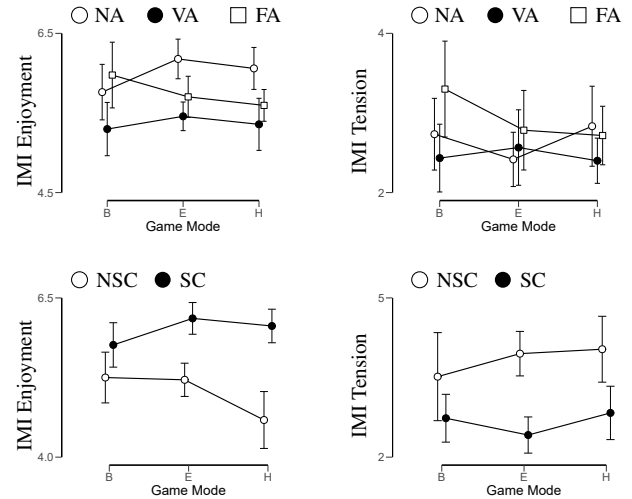

Figure 3: IMI Interest/Enjoyment (left column) and IMI Pressure/Tension (right column) scores for the baseline (B), equal challenge (E) and harder challenge (H) conditions for 1) self competition (SC) framing in different levels of resistance awareness (top row) and 2) without resistance awareness (NA) in self competition (SC) vs. non-self competition (NSC) framing (bottom row).

higher interest/enjoyment in B); the 95% CI of the mean difference between E and H was [-0.25, 0.04] (i.e. likely at most 0.25 higher interest/enjoyment in E). In both cases the lower bound is above $d_{Enjoy} = -0.3$, indicating that the feedforward effect elicited in SC+H does not worsen, within the specified non-inferiority margin, intrinsic motivation compared to no competition in the baseline mode (SC+B) and self competition in the equal challenge mode (SC+E). Therefore, we accept H4. A two-way repeated measures ANOVA was conducted on the effects of game mode (B, E and H) and resistance awareness (NA, VA and FA) for self competition (SC) on IMI Pressure/Tension scores (Figure 3 top-right). The main effect of game mode, $F(2, 66) = 1.06, p = .35$, the main effect of awareness, $F(2, 33) = 0.82, p = .45$, and the interaction effect, $F(4, 66) = 1.36, p = .26$, were not significant.

Independent-samples t-tests with Bonferroni correction were conducted to test whether the IMI Interest/Enjoyment scores of feedforward (SC+H) were above the scale midpoint 4 for all the resistance awareness levels (NA, VA and FA), i.e. whether participants were 'somewhat' intrinsically motivated according to scale labels. For NA, $t(11) = 6.83, p < .001$, VA, $t(11) = 4.50, p < .001$, and FA, $t(11) = 5.29, p < .001$, the scores were significantly above the midpoint. Independent-samples t-tests with Bonferroni correction were conducted to test whether the IMI Pressure/Tension scores of feedforward (SC+H) were below the scale midpoint 4 for all the resistance awareness levels. For NA, $t(11) = -3.71, p = .002$, VA, $t(11) = -5.09, p < .001$, and FA, $t(11) = -4.08, p < .001$, the scores were significantly below the midpoint.

A two-way repeated measures ANOVA was conducted on the effects of game mode (B, E and H) and framing (SC and NSC)

for no awareness (NA) on the IMI Interest/Enjoyment scores (Figure 3 bottom-left). The main effect of game mode was not significant, $F(2, 44) = 3.01, p < .06$. The main effect of framing was significant, $F(1, 22) = 7.80, p = .01$, indicating that interactive feedforward led to higher intrinsic motivation than competition with others, with a 'large' effect size ($\omega^2 = 0.22$). The interaction effect was significant, $F(2, 44) = 4.98, p = .01$. A dependent-samples t-test for SC+H and NSC+H showed that interest/enjoyment in SC+H was significantly greater, $t(22) = 3.88, p < .001$ with a 'large' effect size (Cohen's d=1.58). We therefore accept H5.

A two-way repeated measures ANOVA with Huynh-Feldt correction was conducted on the effects of game mode (B, E and H) and framing (SC and NSC) for no awareness (NA) on the IMI Pressure/Tension scores (Figure 3 bottom-right). The main effect of game mode was not significant, $F(1.59, 33.07) = 0.86, p = .41$. The main effect of framing was significant, $F(1, 22) = 10.80, p = .003$, indicating that interactive feedforward led to lower pressure/tension than competition with others, with a 'large' effect size ($\omega^2 = 0.29$). This supports H5. The interaction effect was not significant, $F(1.59, 33.07) = 1.13, p = .32$.

A two-way repeated measures ANOVA with Huynh-Feldt correction was conducted on the effects of game mode and resistance awareness for self competition (SC) on FSQ Balance of Challenges and Skills scores (Figure 4 top-left). The main effect of game mode, $F(1.78, 58.54) = 4.45, p = .02$ was significant with a 'small' effect size ($\omega^2 = 0.09$). The main effect of awareness, $F(2, 33) = 0.05, p = .96$, and the interaction effect, $F(3.55, 58.54) = 0.88, p = .47$, were not significant. A
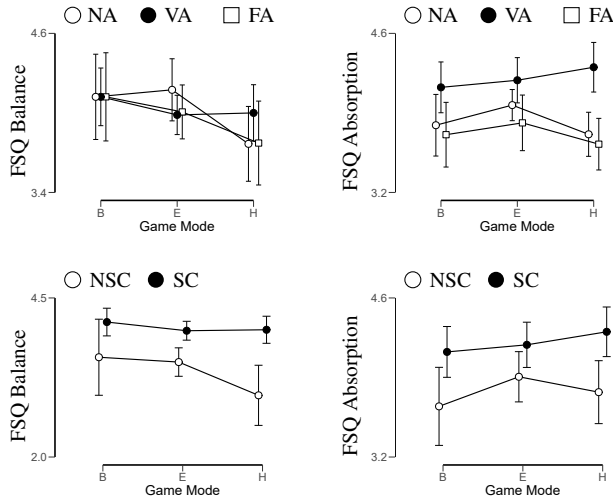
Figure 4: FSQ Balance of Challenges and Skills (left column) and FSQ Absorption in the Task (right column) scores for the baseline (B), equal challenge (E) and harder challenge (H) conditions for 1) self competition (SC) framing in different levels of resistance awareness (top row) and 2) without resistance awareness (NA) in self competition (SC) vs. non-self competition (NSC) framing (bottom row).

two-way repeated measures ANOVA was conducted on the effects of game mode and resistance awareness for SC on FSQ Absorption in the Task scores (Figure 4 top-right). The main effect of game mode, $F(2, 66) = 1.20, p = 0.31$, and of awareness, $F(2, 33) = 2.96, p = .07$, and the interaction effect, $F(4, 66) = 1.02, p = .40$, were not significant.

A two-way repeated measures ANOVA with Huynh-Feldt correction was conducted on the effects of game mode and competition framing for NA on FSQ Balance of Challenges and Skills scores (Figure 4 bottom-left). The main effect of game mode, $F(1.29, 28.27) = 2.67, p = .11$ was not significant. The main effect of framing, $F(1, 22) = 9.27, p = .006$, was significant with a 'large' effect size ($\omega^2 = 0.26$). The interaction effect, $F(1.29, 28.27) = 1.69, p = .21$, was not significant. A two-way repeated measures ANOVA was conducted on the effects of game mode and framing for SC on FSQ Absorption in the Task scores (Figure 4 bottom-right). The main effect of game mode, $F(2, 44) = 1.25, p = .30$, and of framing, $F(1, 22) = 3.86, p = .06$, and the interaction effect, $F(2, 44) = 0.66, p = .52$, were not significant.

A one-way ANOVA showed that the effect of resistance awareness (NA, VA, FA) on IEQ score was not significant, $F(2, 33) = 1.62, p = .21$ (Figure 5 left). An independent-samples t-test comparing the IET scores for SC and NSC (Figure 5 right) showed that there was a significant difference between SC and NSC, $t(22) = 2.31, p = .03$, with a 'large' effect size (Cohen's d=0.94). That is, participants felt significantly more immersed in interactive feedforward than in competition with others.
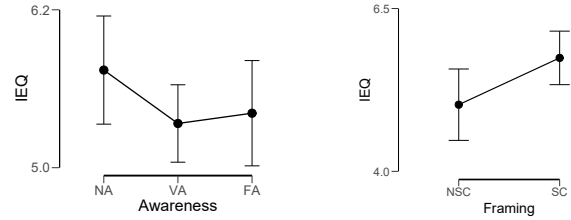

Figure 5: IEQ scores in different levels of resistance awareness (left) and competition framing (right).

Based on post-trials interviews, most participants found the gameplay experience 'immersive and fun.' Reported effects of VR were similar to those of other VR exergames [75, 76]; some participants felt discomfort because of VR sickness, the HMD's heat retention and weight on the nose. Many players noted how the ghost became their primary focus. In NSC most participants reported feelings of stress and expressed a preference for self competition. In SC participants generally reported having a more positive gameplay experience.

DISCUSSION

Our aim was to improve the performance of participants while maintaining intrinsic motivation in a VR exergame so that more people could reap the benefits of HIIT. The results showed a meaningful improvement of performance with interactive feedforward compared to competition against an unimproved self model (SC+E) (H1), with only a marginal reduction in intrinsic motivation, i.e. within a non-inferiority margin for IMI Interest/Enjoyment of $d_{Enjoy} = -0.3$ (H4). The performance results are in line with self modelling theory [19] and results about the relative efficacy of video self modelling showing current (SC+E) vs. improved behaviours (SC+H) [13]. We found a performance improvement between a baseline without competitor SC+B vs. SC+E, while other studies did not detect any performance differences between similar conditions [74, 86]. This suggests that interactive feedforward could lead to a meaningful performance improvement over an exergame without competition. At the same time, the results suggest that interactive feedforward would not be inferior with regard to intrinsic motivation compared to an exergame without competition (SC+B).

Interactive feedforward led to performance improvement in all resistance awareness conditions (NA, VA, FA) (H2). This is consistent with experiences from video self modelling where participants are usually aware of the method and the fact that the self model appears improved compared to their current performance [13, 19–21, 29, 79, 80, 84, 85]. Our results on the effect of resistance awareness indicate that interactive feedforward may not rely on deception but there could be meaningful effects that our study had insufficient power to detect. Interactive feedforward may have worked even better if participants had been more involved and aware of the method [19–21] rather than merely being aware of increased resistance.

Interactive feedforward (SC+H) was clearly superior compared to competition with others (NSC+H), in terms of improving performance (H3), intrinsic motivation (H5), flow

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(balance of challenges and skills) and immersion. The results corroborated the detrimental effect competition against others can have on intrinsic motivation [16, 68, 74]. According to feedforward theory [19] and empirical evidence [79], self models are more powerful than models of others as participants are able to identify and relate more closely to them. This is supported by frequent participant comments about relatedness ("My previous level is relevant to my condition.") and self-efficacy ("Racing myself means there is at least a good chance that I will win!"). The increase in flow and immersion may be explained by their relation to intrinsic motivation [15, 24, 39, 41].

Limitations
Confirming the efficacy of interactive feedforward more generally requires larger and longer studies with more than a single session. Here we explored only a single exergame with specific parameters. Future work could widen this exploration and address the lack of a comparison with traditional exercise. Our participants were mainly in their 20s and 30s and mostly male, which may limit the generalisability of the results. Lack of sufficient exercise is a severe problem for these age groups and they are typically familiar with video games, so they would be a suitable target group for our proposed method. There are gender differences related to physical performance [54], exercise motivations [22], gamification [48] and competitive behaviour [60] which may have influenced our results.

We took repeated measures in a single experimental session, therefore our results may have been influenced by familiarisation and fatigue. We used a familiarisation phase to mitigate the former and breaks to mitigate the latter. Our comparisons focused on conditions E and H, which were counterbalanced and showed no significant order effects. Our observations indicate that many participants were affected by fatigue near the end of the experiment. It can be argued that since B always came before E and H, it was less affected by fatigue, which may have reduced the differences in performance between B vs. E and H. Changes in game mode and framing showed fairly large effect sizes, which suggests sufficient test power. However, our study may have been underpowered for detecting effects of resistance awareness, which could be a line of future work. Increases in performance could in part be due to a Hawthorne effect. To mitigate such effects, many of the results consider contrasts between similar treatments (e.g. SC vs. NSC) as a Hawthorne would likely have affected them similarly. Participants were wearing HMDs and the IEQ results indicate that they were quite immersed in the exergame, which makes it unlikely that there was a strong awareness of the experimenter. A longitudinal field study would be the best instrument to validate the effectiveness of the method in real world conditions.

Impact and Implications for Exergame Design
Our results indicate that HIIT can be gamified effectively with interactive feedforward to help players reap the benefits of this increasingly popular type of exercise. With the proliferation of VR equipment, interactive feedforward could be implemented fairly easily in many VR exergames for cycling and other VR-safe activities such as rowing or arm crank ergometers. Our

results indicate that even when players are aware of resistance change, interactive feedforward could still work. So even if the resistance of an exercise cannot easily be increased automatically, it could be done by the player. An alternative to increased resistance may be a purely visual change such as an accelerated ghost. There are a number of exercise machines that already have some kind of pace-setting functionality. Although we have not explored interactive feedforward outside of VR, feedforward theory suggests that it may still have a positive effect. It would be fairly straightforward to add support for interactive feedforward to such existing exercise machines.

Our study highlights that competition with others in exergames can be problematic for a general population. It suggests that it can reduce both the benefits of exercise (due to lower performance) as well as desirable psychological characteristics of the game (intrinsic motivation, flow and immersion). However, many exergames include elements of competition with others. While this works well for some players our results suggest that for exergames targeted at a general population, such game mechanics may be more appropriate as optional features. Our results on framing indicate that competition against others can be replaced by self competition through interactive feedforward, with potential consequences for performance, intrinsic motivation, flow and immersion.

CONCLUSION
We proposed and evaluated interactive feedforward, a novel method to rapidly improve performance in a HIIT cycling VR exergame. Interactive feedforward is based on self competition against an improved self model of the player, such as a recording of previous gameplay. Our empirical study suggests the following conclusions, which should be considered in light of the aforementioned limitations:

1. Interactive feedforward can be effective in improving players' performance while maintaining intrinsic motivation.

2. Interactive feedforward can still work if players are aware of the increased challenge, i.e. it does not rely on deception.

3. Interactive feedforward, and self competition in general, can be superior to competition against others, leading to higher performance, intrinsic motivation, flow and immersion.

Interactive feedforward holds promise as a new method in exergames, with potential applications and opportunities in promoting positive change in people's exercise behaviour.

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