Advantages of Friend-Modelled Social Interactive Feedforward for VR Exergaming

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VR exergaming is a promising motivational tool to incentivise exercise. We present a novel VR exergaming method called social interactive feedforward. The player competes with an 'enhanced model' of one of their friends in a real-time VR environment, showing improved performance levels in a way the player can relate to. Social interactive feedforward was tested in a cycling-based VR exergame and players competed with enhanced models of themselves, their friend, and a stranger moving at the same enhanced pace. Results show that friend-modelled social interactive feedforward improves performance and intrinsic motivation the most. This indicates that the mere association of the enhanced model with their friend results in a rapid improvement in performance and motivation which implies that social feedforward was successfully elicited by using an enhanced friend's model. This widens the application of self-modelled feedforward to a wide range of social options which enables players to also reap the benefits of socialising in addition to feedforward benefits.

CCS Concepts: • **Human-centered computing → User studies**.

Additional Key Words and Phrases: Social Interactive Feedforward, Exergaming, VR, Feedforward, Performance, Intrinsic Motivation

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1 Introduction

Virtual Reality exercise controlled gaming (VR exergaming) is an intervention that involves exercising as a mode of control in a VR game. Commercial exergames such as Pokemon Go [106], Dance Dance Revolution [75], and Wii Fit [45] show some evidence of improving motivation to exercise in the short term. However, the initial excitement drops and exercise adherence wanes [78, 84]. Introducing social interaction into exergaming and enabling the players to feel a sense of belonging leads to better exercise adherence [54]. Intrinsic motivation refers to performing an activity because it is enjoyable by itself without the need for other external rewards [58]. Studies show that exergames increase intrinsic

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motivation by distracting the players from painful exercise sensations [4, 9, 35, 72, 90]. Although intrinsic motivation is an important factor in exercise adherence in the short term [56, 88, 110], its impact on long term exercise adherence is unclear and needs to be investigated further [52]. VR exergames based on an omni-directional treadmill and a flight simulator were found to be an effective tool for increasing physical activity and also meet the recommended exercise intensity for health benefits [26]. VR exergames were also found to be attractive, enjoyable, and have potential health benefits with regular use for children aged 8 to 12 [81].

Feedforward is a psychophysical training technique in which players observe an enhanced self-model resulting in rapid improvement in performance [28]. Feedforward enhances intrinsic motivation, self-efficacy, self-regulation, and performance [20]. VR exergaming is coupled with feedforward to create a more powerful exercise intervention. This is achieved by recording a player's performance to create a self-model. The speed is programmatically increased to create an enhanced self-model which exhibits previously unachieved performance levels. The enhanced self-model is then used as a competitor in the VR exergame. Since the application of feedforward in VR exergaming enables players to actively interact and train with their self-model in real time, it is called interactive feedforward. This led to improved performance while maintaining intrinsic motivation [10]. In follow up studies on interactive feedforward, Michael et al. [71] and Ioannou et al. [53] used self-modelling because previous studies showed that self-modelling is more effective than peer-modelling [29, 69, 92]. However, friend modelled interactive feedforward has not been studied and it could possibly be more effective than self-modelled feedforward as it is supported by psychological theories based on social interaction studies elaborated below. This paper discusses the introduction of a social element to interactive feedforward by using friend-modelling.

Social interaction plays a pivotal role in self-determination theory which is an important motivational theory that describes the extent to which individual behaviours are decided by oneself [27]. Applications that are designed based on self-determination theory are expected to lead to long-term intrinsic motivation [42, 87, 95]. The genesis of self-determined motivation comes from individuals' inherent tendency to cater to three basic psychological needs which are: autonomy, which refers to being the perceived source of one's own behaviour; competence, which refers to effectively managing the ongoing interaction with the social environment; and relatedness, which refers to a sense of connection and interaction with others within a community [27]. These needs are universal in nature as shown by inter-cultural studies [91]. Relatedness is defined as associating with others, to look after and provide for the needs of others and being looked after by others, to have a sense of community [13, 86, 102]. A positive association was found between intrisic motivation and perceived autonomy support from friends [109].

Several studies have found that exercising with a partner is beneficial [89, 104]. There is evidence to show that virtual social support is equally effective as face-to-face support provided that the user has the impression that the support is provided by another human via a virtual avatar [38, 59, 60]. This corroborates the media equation theory which states that users process media the same way as real-world experiences [83]. It found that the level of involvement in the virtual world was an important predictor of perceived intensity of emotions. Based on this finding we can conclude that the extent of involvement in the virtual world plays an important role in determining if the same or a different response is elicited in the user when compared to a real world interaction [38].

According to the theory of social facilitation, performance in simple tasks is enhanced by the presence of others [114]. The relationship between the players plays an important role as it impacts the social interactions in the game which can influence the social game experience. Thus, a social exergame that enables people with a pre-existing positive relationship (such as a friend) can in turn positively influence the game experience. This paper reviews various social psychology theories and discusses the important role of positive social interaction in improving exergame performance and intrinsic motivation. In particular, exergames that enable interaction with people that they have a pre-existing positive social relationships such as a friend could improve player experience [14].

Conventionally, interactive feedforward has always been tested using an enhanced self-model [10, 53, 71]. However, many studies show the effectiveness of facilitating a positive social interaction with friends in improving intrinsic motivation and performance [98, 114]. This justifies investigating friend-modelled interactive feedforward. Therefore, we define social interactive feedforward as using an enhanced model of a friend showing previously unachieved performance levels that players relate, compete and interact with at real time in a VR feedforward experience resulting in a rapid improvement in performance and intrinisic motivation. The aim of this experiment is to introduce a social element to interactive feedforward for VR exergaming by introducing an enhanced virtual model of a friend of the player as a competitor. We pair people who have roughly the same power output and we increase the resistance by 10% in both social interactive feedforward and self-modelled feedforward. Social comparison can be useful in encouraging an active life-style because studies show that people were prone to mimicking the behaviour of their peers [34, 66] and are likely to exercise when observing others around them also exercising [66].

In summary, we investigated the following research questions:

RQ1 How effective is social interactive feedforward in improving performance as measured by average power output when compared to self-modelled interactive feedforward?

RQ2 How effective is social interactive feedforward in improving intrinsic motivation when compared to self-modelled interactive feedforward?

Self modelling has been mostly used with feedforward [20, 28, 30, 31, 37, 93, 94, 101, 105]. To our knowledge, friend modelling has never previously been used in interactive feedforward. We make the following contributions:

(1) An exergaming system for social interactive feedforward in virtual reality.
(2) An empirical study comparing the efficacy of social interactive feedforward in improving exercise performance and intrinsic motivation with self-modelled interactive feedforward.
(3) A discussion of actionable recommendations for exergame designers suggesting ways to incorporate social interactive feedforward elements into exergame design.

2 Related Work

2.1 Social Facilitation vs Social Loafing

Theory of social facilitation states that behaviour in simple tasks is improved by the mere presence of others [114]. A study by Worringham et al.[113] shows that a group of runners who encountered a female facing the runner at the halfway point showed a significant acceleration when compared to the group that ran alone and the group that encountered a female seated with her back to the runner . Social loafing refers to the tendency of individuals to expend less effort when working together than when working by themselves. This detrimental effect of social loafing has been noticed in group tasks that require collective pooling of individual members' inputs and not in tasks that involve coaction in which an individual's effort is indispensable to the outcome of the task [55]. Participants were motivated to work only as hard as necessary to gain credit for good performance or to avoid blame for a bad one [49]. Another study shows that both social facilitation and loafing are complementary and results consistently showed that evaluation and coaction lead to better performance [48]. Therefore, to avoid social loafing and enhance social facilitation a task should involve coaction and should be evaluable. The effect of virtual social facilitation was explored by using a VR stationary bike and introducing competitive avatars and the results showed that it increased exercise effort among more competitive exercisers [2]. A notable difference between our study and the study by Anderson et al.[2] is that we are investigating the effectiveness of social interactive feedforward in high intensity exercising which involves enhanced interactive models of players' friends.

2.2 Social Comparison Theory, Exercise Partners, and Competition

Social comparison involves comparing oneself with others for self-evaluation, self-improvement, and self-enhancement [34, 99, 112]. The most important variables that affect social comparison are: the expertise of the person one is comparing herself to, similarity with that person, and previous agreement with that person [97]. Studies show that in conditions in which self-evaluation and self-improvement play an important role, individuals prefer to compare themselves with someone who is slightly better-off, i.e. an upward comparison [46, 107, 108, 111]. Furthermore, if the comparison dimension is a skill acquired through practice or one that increases naturally with maturity, upward comparisons are considered to be uplifting because it informs the individual that such achievements are within reach, and one feels good progressing toward the target's superior state [17]. People make upward comparisons in hopes of enhancing their self-assessments and state that it serves indirectly through self-improvement and sometimes directly by enhancing the self [22]. Self-evaluations based on comparisons with others become stronger when they compare themselves with people who are similar to them [34] specifically with regard to the dimension being evaluated [112]. Therefore, upward comparisons with people who are similar to themselves in the dimension being evaluated lead to an uplifting self-assessment potentially leading to improvement.

Studies show that exercising with friends or peers increases exercise adherence [33, 64]. Participants exercised harder when the perceived fitness level of an exercise partner was high than when it was low [80] and another study shows that exercising with a fitter exercise partner boosts a high intensity exercise session [25]. Physical activity levels among members of one activity tracking social networking site were positively associated with the physical activity levels of their connections [18] and head to head competition encourages participants to increase their performance [23].

2.3 Social Games and Exergames

Social exergames bring together the enjoyable elements of gamification and social bonding to alleviate the unpleasant effects of exercising such as fatigue and muscular pain, making it an enjoyable experience. Exergames can facilitate social play including mediated exergames [73]. The presence of a co-located co-player can significantly enhance fun, challenge, and perceived competence in the game. Social context is an integral factor of player enjoyment and should be integrated in the game [39]. Another study by Mueller et al. [74] investigated the effects of virtual co-presence of co-players they have a social relationship with. They designed a system in which spatialised audio based on heart rate would allow players to *virtually* run together. Players were paired with their friends or siblings. They concluded that social support enhances engagement with the physical activity based on a qualitative analysis of players' experience. Players reported that the system enabled them to feel co-located even though they were not together physically. They reported that in some cases it was even better than jogging together because the system enabled them to feel co-located even if their physical capabilities were different so one player didn't have to wait for the other. They also reported that social presence, which refers to the sense of being with another person, enhanced enjoyment. A study by Balnaves et al. [5] discussed the social value of the widely played social game, Farmville. It is a farming-simulator game which allows players to virtually manage a farmland by growing crops and animals. Players play Farmville despite its lacklustre aesthetics and repetitive gameplay primarily because of the social element [65]. The game fosters social interaction and allows players to feel a sense of community without having to be physically present with other players [5]. This further corroborates the importance of virtual co-presence of co-players in the gameplay.

According to a six-week study by Kaos et al.[54], people who engage in social play have an enhanced exergame adherence compared to those in individual play. The superior adherence found in social play was attributed to enabling players to feel a sense of belonging which is a crucial and universal human need [13]. Chan et al. [19] identified self-determination theory, gamification, competition and cooperation, situational interest, and social interaction as components that play an integral role in promoting adherence. Their results show that the social aspect of the exergame in particular motivates players, resulting in continued exergame play. They found that social support and communication are key mediators for encouraging behaviour change. They also found that effective player matchmaking strategies for increasing social connectedness are an important area of future research.

Bekker et al. [14] created interactive play objects that can simulate social interactions and exercise. The gameplay was influenced by behaviour theories such as the self-efficacy theory. Positive player experiences as a result of the game and motivating feedback increase self-efficacy which in turn leads to increased adherence. They found that social interaction can be evoked using a game played by multiple players and the kind of association between the players can impact the kind of social interactions that take place. This implies that the kind of relationship between the players is very important because it affects the social interactions in the game which can potentially influence the social game experience. Therefore, in our study, we use pairs of friends so that the pre-existing positive relationship can in turn positively influence the game experience.

2.4 Video Self-modelling

Modelling is the process of imitating actions and behaviour based on observational learning [6–8]. Modelling entails observing a subject in order to obtain knowledge about a certain skill. This observed information is then tried out and maintained using cognitive representation when they venture the replication of the skill. Modelling can be implemented by showing video clips of themselves or others performing the activity. This is called video modelling. Video modelling that involves using self-models is referred to as video self-modelling. A meta-analysis by Bellini et al. [15] tested the intervention, maintenance, and generalization effects of video modelling and video self-modelling interventions for children and adolescents with autism spectrum disorders. Results imply that video modelling and video self-modelling are effective intervention strategies for addressing social-communication skills, functional skills, and behavioural functioning in children and adolescents with autism spectrum disorders. A study used video modelling to educate patients about changes in health care delivery [62]. In spite of differences in research designs, clinical settings, and patient populations, the use of video modelling has potential benefits for clinical practice in facilitating knowledge acquisition, reducing preparatory anxiety, and improving self-care. Baudry et al. [12] investigated the effectiveness of video modelling in improving gymnasts' performance of the circle on a pommel horse. The modelling group received expert- and self-modelling, and performance feedback. The control group received no feedback. The results showed better performance in the modelling group than the control group. This shows that video modelling has potential in improving complex sports movements such as the double leg circle on the pommel horse. Resemblance to the model increases self-efficacy because learners are able to identify more with the model [51]. 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 [28]. Self-modelling is more effective than using peer models [29, 69, 92]. Starek et al. [93] compared the effects of self-modelling and other-modelling which refers to watching a video tape of a peer model who exhibits skills matching the player's swimming skills. Results showed participants in the self-modelling condition exhibited better performance than the ones in the other-modelling condition. However, these studies did not explore friend-modelling.

2.5 Feedforward

Feedforward is a psychophysical training technique which enables individuals to achieve a rapid improvement in performance by observing an enhanced self-model showing previously unachieved performance [29]. This ultrarapid learning in feedforward is explained within the framework of cognitive science using the neural activity called "mental time travel" [43, 96]. Mental time travel which is also referred to as autonoetic consciousness enables remembering the past and projecting or imagining the future [103]. It gives us the ability to build a sense of self. Future or past episodic memory is responsible for self-awareness, and intrinsic feelings that may impact our future actions [3] by allowing people to predict, architect, and sculpt future events [96]. A similar process called prospection is defined as the act of thinking about the future by mentally projecting ourselves into an imagined situation. Buckner et al. [16] suggest that "envisioning the future (prospection), remembering the past, conceiving the viewpoint of others and possibly some forms of navigation reflect the workings of the same core brain network". They claim that all these abilities share the same functional anatomy that includes frontal and medial temporal systems that are conventionally related to planning, episodic memory and passive cognitive states. Self-modelled feedforward is an application of prospection or future mental time travel and it trigger a behavioural response in a future context [29].

Clark et al.[20] compared two self-as-a-model interventions: enhanced self-modelling or feedforward which involved watching edited videos showing only the best performances of swimming stroke and self-observation of performance at their current skill levels. They studied the influence of the modelling interventions on self-regulation, intrinsic motivation, self-efficacy, and the physical performance. The results showed that the feedforward group consistently performed better in terms of self-regulation, self-efficacy, intrinsic motivation, and physical performance than the self observation group. Gilchrist et al. [44] investigated alleviating public speaking anxiety by using enhanced self-modelling or feedforward . Players were shown edited videos of themselves depicting confident speaking. Results showed video-self-modelling could be used as an intervention to reduce anxiety and improve public speaking performance.

An interactive adaptation of feedforward in a VR exergame (called as interactive feedforward) resulted in improved exercise performance while maintaining intrinsic motivation [10]. This work already tested interactive feedforward by including a control condition to test the absolute effectiveness of feedforward. Virtual performance augmentation implementing interactive feedforward in an immersive jump and run VR exergame showed increase in intrinsic motivation, perceived competence, and flow [53]. Flow is a state of optimal user experience while performing an activity occurring when the skills of an individual are in balance with the challenge imposed by the activity [24, 32]. A longitudinal study spanning a month implemented a new form of interactive feedforward by introducing multiple self-models. It investigated players racing against a group of self-models moving at the pace of their previous performances and one self-model projecting their future enhanced performance [71]. Results showed an improvement in performance, intrinsic motivation, and flow when compared to a non-competitive condition. In particular, introducing multiple self-models resulted in significantly higher levels of intrinsic motivation and flow with similar performance levels compared to a single self-model interactive feedforward implemented in the study by Barathi et al. [10].

Feedforward studies have always used an enhanced self-model because several studies show that self-modelling is superior to peer modelling [29, 69, 92]. However, these studies have not explored using an enhanced "friend's" model in the context of the feedforward method. Well established theories such as self-determination theory, social facilitation, and social comparison theory justify the inclusion of friend-modelling in interactive feedforward and therefore, we investigate the effectiveness of friend-modelled social interactive feedforward in this paper. Our paper builds on previous work on interactive feedforward to explore friend-modelled feedforward. We investigate the impact of friend-modelled feedforward when compared to self-modelled feedforward and stranger-modelled feedforward.

Fig. 1. The image represents social interactive feedforward implemented in a cycling based VR exergame in which the player is racing against his friend's model.

3 Exergame and Experimental Design

We used a cycling based VR exergame (Figure 1) in which the speed of the player in the VR exergame is proportional to the Revolutions Per Minute (RPM) of the stationary exercise cycle used. High Intensity Interval Training (HIIT) is an exercise protocol that involves short bursts of vigorous exercise in between periods of low-intensity exercise [40]. It is twice as time efficient while being equally beneficial or superior to low or moderate intensity exercise protocols in many health related measures [41, 63, 76]. We used a low volume HIIT exercise protocol which alternates between low intensity and high intensity phases with 60 seconds warm-up, 30 seconds sprint, 90 seconds recovery, 30 seconds sprint, and 90 seconds cool-down. Players were instructed to cycle at a speed of 65-70 RPM with 12 Nm resistance during the low intensity phases i.e. warm-up, recovery, and cool-down. They were instructed to cycle as fast as possible during the high intensity phases i.e. the sprints, with resistance of 0.4 Nm kg1 set initially based on body mass and adjusted according to player preferences during the familiarisation phase. Prompts such as the RPM, exercise protocol instructions, and timings were displayed on the game screen.

We investigated the effectiveness of using an enhanced friend's model in interactive feedforward using a counter-balanced within-participants design. Three conditions, Friend, Self, and Stranger form the levels of the independent variable Competitor after recording the baseline. Friends arrived together and one had to wait while the other player recorded their baseline model. This experiment involves three different levels and players competed with enhanced models of themselves, their friend, and a stranger who moved at the pace of their friend. To make sure players constantly associated the enhanced models to their Friend, Self, or Stranger conditions, we took photos of them to be attached to the model's back.

There is evidence to show that competitive play increases exercise performance and aggression in short bouts but cooperative play improves motivation and adherence [70]. In users with lower physical fitness levels, competition was found to have a detrimental effect by accentuating their inadequacies [70]. Therefore, to retain the good effects of competitive play and social interaction without including the negative effects, participants were made to do the study separately [67].

Both the participants recorded their exercise performance baselines separately. During the baseline, we recorded the players' performance and their friends' to create the enhanced models. In the Friend condition, we elicited a feedforward effect by, in addition to competing with the friend's model, increasing the resistance by 10%. The friend's model had a picture of their friend attached to the back to help the players associate the model to their friends. In the Self condition, we elicited a feedforward effect by, in addition to competing with the self-model, increasing the resistance by 10%. The self-model had a picture of the player attached to the back to help the players associate the model to themselves. The Stranger condition is the control condition and players were competing with a model which moved at the same speed as the friend's model under an increased resistance by 10% but had a picture of a stranger attached to it to help the players associate the model to a stranger. Participants did the study by competing with the virtual recorded enhanced self-model, friend's model, and the stranger's model individually while their friends waited outside the lab.

The players were not aware that the enhanced models in the Stranger condition and the Friend condition move at the same pace. Players were informed that they were competing with: a friend's model in the Friend condition, self-model in the Self condition and a stranger's model in the Stranger condition. A message was displayed at the beginning of Friend, Self, and Stranger conditions stating "The exergame may change the intensity of the workout to make it easier or harder". We conducted the Baseline condition first to record the speed of the enhanced models and the conditions Friend, Self, and Stranger were counterbalanced. Players cycle down a straight path while avoiding trucks during the low-intensity phases of the exergame and cycle as fast as possible during the high intensity phases with the objective of outracing the friend/self/stranger model depending on the experiment condition. The stationary exercise cycle (Figure 1) used was a Lode Excalibur Sport and the VR headset was an HTC Vive. They 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.

3.1 Outcome Variables

Our exclusion criteria were if participants answered affirmatively to any of the questions from the revised Physical Activity Readiness Questionnaire (PAR-Q) [100] or if they had a had a resting blood pressure greater than 140/90 mmHg, they were not allowed to do the user study. All our participants cleared the exclusion criteria. We recorded demographic details using a demographics questionnaire which included questions about age, gender, blood pressure, body height, weight, and body composition. They filled the International Physical Activity Questionnaire (IPAQ) questionnaire to measure their current exercise levels [47]. Players also recorded their answers to a self-reported friendship question which was a 7- point Likert scale proposed by Hays et al. [50]. 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 players, we considered each player's performance in the Self, Friend, and Stranger experimental condition against their baseline, i.e. Power (Self-Baseline), Power (Friend-Baseline), and Power (Stranger-Baseline) which we refer to as ΔPower in the context of experimental condition Self, Friend, and

Stranger respectively. We used the Intrinsic Motivation Inventory (IMI) scale [85]. In particular, we used the following subscales: IMI Enjoy, IMI Effort, IMI Pressure, and IMI Value which refer to the interest/enjoyment, effort, felt pressure and tension, value/usefulness subscales respectively. To measure flow, we used the Flow State Questionnaire's subscales: Balance of Challenges and Skills, which we refer to as Balance and Absorption in the Task, which we refer to as Absorption [68].

3.2 Procedure

The study received ethical approval from the Research Ethics Approval Committee for Health of the University of Bath (Reference: EP 16/17 191). Players were told that it was a social exergaming experiment and they were asked to partner with friends who were more or less as fit as they were. The players were informed about the experimental conditions and asked to complete the aforementioned demographics questionnaire. The players were told that the purpose of the baseline condition was to record their performance and their friend's performance for the models. Players also recorded their answers to a self-reported friendship question.

After initialising sprint resistance based on body mass, players went through a familiarisation phase which allowed them to experience the VR exergame. After players recorded their baselines, they performed the Friend, Self, and Stranger conditions in a counterbalanced order. Players performed all the conditions Friend, Self, and Stranger, in private without the physical presence of their friend to influence them. At the end of each of the conditions Friend, Self, and Stranger, players completed the IMI and Flow subscales and left qualitative feedback about their experience. Players had a break of approximately 10 minutes between the gameplay rounds to avoid fatigue. They were allowed to take longer breaks if they were tired. At the end of the experiment players were asked to comment on their experience during the different conditions. Each session took approximately 180 minutes.

3.3 Hypotheses

To summarise, self-modelled interactive feedforward has been found to rapidly and significantly improve exercise performance while maintaining intrinsic motivation [10]. Participants who viewed their virtual self model do more exercise also engaged in doing significantly more exercise [36]. A longitudinal study exploring training and competing with multiple enhanced self-models was found to significantly improve exercise performance, intrinsic motivation, and flow [71]. Studies have predominantly used self modelling in relation to interactive feedforward. However, social interaction is crucial in self-determination theory. It is a significant motivational framework that underpins the degree to which personal behaviours are self-directed [27]. This is important because applications built on self-determination theory are expected to improve intrinsic motivation [87, 95]. Having a social connection with others is one of the most important factors associated with exercise induction and adherence [57]. Social gaming plays an important role in engagement [1]. Therefore, we propose to study introducing a social connection in the form of a friend model into interactive feedforward. Based on the findings of these previous studies, we hypothesise that friend modelled interactive feedforward improves exercise performance and intrinsic motivation.

Based on related work, we had the following hypotheses:

H1 The Friend condition improves performance more than the Self condition and the Stranger condition.

H2 The Friend condition improves intrinsic motivation more than the Self condition and the Stranger condition.

Results

A summary of the results is shown in Table 1. The assumptions of analysis of variance (ANOVA) were met, so we analysed the data with repeated-measures ANOVAs using the ω^2 measure for effect sizes [77], and post-hoc tests with Holm correction for comparing a family of three. According to power analyses, the ANOVAs were able to detect medium-sized effects (Cohen's f=0.286) with a power of 0.774. They allow us to better understand the uncertainty in the test results. Because of our within-participants design, we calculated and tested repeated measures correlations using Pearson correlations. The level of significance used for all tests was $\alpha = .05$. Plots show 95% confidence intervals of the means.

3.3.1 Participants. Players were recruited through mailing lists and posters and were asked to sign up with their friends who are more or less as fit as they are. We recruited 20 players in total (15 male, 5 female, age 18-28, mean 22.5), who were students and employees of the University of Bath. We screened them with the Physical Activity Readiness Questionnaire (PAR-Q) [110] and excluded players with health risks or a resting blood pressure greater than 140/90 mmHg. All players gave written, informed consent, and were remunerated for their time. The players and their friends were of similar physical fitness levels. This is evidenced by the average of the baseline difference in the number of revolutions between the player pairs which was *mean=0.77 (std. dev.=14.86)* including the one mixed gender pair. The average self-reported friendship score was *mean=4.05 (std. dev.=0.83)* and all players reported a score of 3 or above.

3.3.2 Performance. A repeated-measures ANOVA was conducted on Competitor (Stranger, Self, and Friend) for Δ*Power*. The effect of Competitor was significant ($F(2, 38) = 7.224, p = .002^{**}$) with a 'medium' effect size ($\omega^2 = 0.067$) (Figure 2 top-left). Δ*Power* in Friend was significantly higher compared to Self ($t(19) = 2.710, p = .020^{*}$) with a 'medium' effect size (Cohen's d=0.506) and also significantly higher compared to Stranger ($t(19) = 3.663, p = .002^{**}$) with a 'medium' effect size (Cohen's d=0.683) so we accept H1. Δ*Power* in Self was not significantly higher when compared to Stranger ($t(19) = 0.953, p = .347$) with a negligible effect size (Cohen's d=0.178).

3.3.3 IMI Enjoy. A repeated-measures ANOVA was conducted on Competitor (Stranger, Self, and Friend) for *IMI Enjoy*. The effect of Competitor was significant ($F(2, 38) = 8.253, p = .001^{**}$) with a 'medium' effect size ($\omega^2 = 0.081$) (Figure 2 top-right). *IMI Enjoy* in Friend was significantly higher compared to Self ($t(19) = 2.475, p = .036^{*}$) with a 'small' effect size (Cohen's d=0.471) and also significantly higher compared to Stranger ($t(19) = 4.028, p < .001^{***}$) with a 'medium' effect size (Cohen's d=0.767) so we accept H2. *IMI Enjoy* in Self was not significantly higher compared to Stranger ($t(19) = 1.553, p = .129$) with a 'small' effect size (Cohen's d=0.296).

3.3.4 IMI Effort. A repeated-measures ANOVA was conducted on Competitor (Stranger, Self, and Friend) for *IMI Effort*. The effect of Competitor was significant ($F(2, 38) = 8.060, p = .001^{**}$) with a 'medium' effect size ($\omega^2 = 0.112$) (Figure 2 bottom-left). *IMI Effort* in Friend was not significantly higher compared to Self ($t(19) = 1.984, p = .099$) with a 'small' effect size (Cohen's d=0.459) and significantly higher compared to Stranger ($t(19) = 4.015, p < .001^{***}$) with a 'large' effect size (Cohen's d=.928). *IMI Effort* in Self was not significantly higher compared to Stranger ($t(19) = 2.030, p = .099$) with a 'small' effect size (Cohen's d=0.470).

3.3.5 IMI Pressure. A repeated-measures ANOVA was conducted on Competitor (Stranger, Self, and Friend) for *IMI Pressure* and the effect of Competitor was not significant ($F(2, 38) = 0.139, p = .871$) with no effect size ($\omega^2 = 0.0$). *IMI Pressure* in Friend was not significantly higher compared to Self ($t(19) = 0.420, p = 1.000$) with a negligible effect size (Cohen's d=.091) and was not significantly higher compared to Stranger ($t(19) = 0.065, p = 1.000$) with a negligible effect

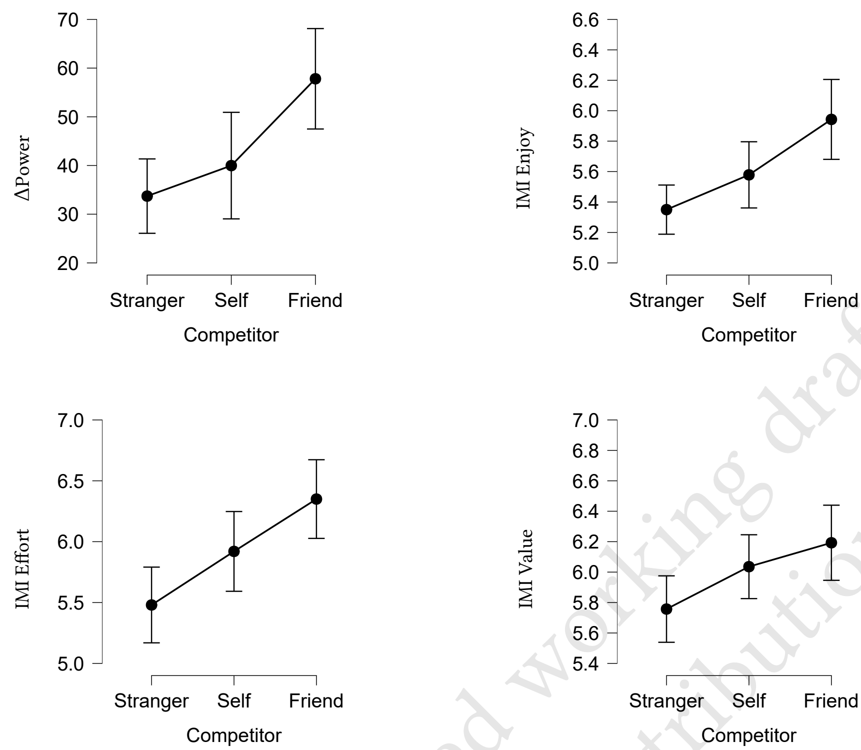

Fig. 2. ΔPower (left column) and IMI Enjoy (right column) scores for the Stranger, Self, and Friend conditions (top row) and IMI Effort (left column) and IMI Value (right column) scores for the Stranger, Self, and Friend conditions (bottom row).

size (Cohen's d=.014). *IMI Pressure* in Self was not significantly higher compared to Stranger ($t(19) = 0.485, p = 1.000$) with a negligible effect size (Cohen's d=.105).

3.3.6 IMI Value. A repeated-measures ANOVA was conducted on Competitor (Stranger, Self, and Friend) for *IMI Value*. The effect of Competitor was significant ($F(2, 38) = 4.192, p = .023^*$) with a 'small' effect size ($\omega^2 = 0.033$) (Figure 2 bottom-right). *IMI Value* in Friend was not significantly higher compared to Self ($t(19) = 1.031, p = .309$) with a negligible effect size (Cohen's d=.184) and was significantly higher compared to Stranger ($t(19) = 2.859, p = .021^*$) with a 'medium' effect size (Cohen's d=.510). *IMI Value* in Self was not significantly higher compared to Stranger ($t(19) = 1.828, p = .151$) with a 'small' effect size (Cohen's d=0.326).

3.3.7 Flow Balance. A repeated-measures ANOVA was conducted on Competitor (Stranger, Self, and Friend) for *Balance* and the effect of Competitor was not significant ($F(2, 38) = 1.709, p = .195$) with a tiny effect size ($\omega^2 = 0.007$). *Balance* in Friend was not significantly higher compared to Self ($t(19) = 0.103, p = .918$) with a negligible effect size (Cohen's d=0.018) and was not significantly higher compared to Stranger ($t(19) = 1.650, p = .321$) with a 'small' effect size (Cohen's d=0.293). *Balance* in Self was not significantly higher compared to Stranger ($t(19) = 1.547, p = .321$) with a 'small' effect size (Cohen's d=0.275).

Table 1. Summary of demographics and results (mean ± std. dev.).

Experimental Condition (within-participants)	n	Demographics	Variables	Measurement
Stranger	20	M=15, F=5	Power	370.79±88.68
		Age=22.5±3.29,	ΔPower	33.71±34.80
		BMI=22.89±2.68,	IMI Enjoy	5.35±0.91
		IPAQ=1837.7±1110.59,	Balance	3.95±0.88
		Power=337.07±83.58	Absorption	3.85±0.71
Self			Power	377.05±96.06
			ΔPower	39.98±36.93
			IMI Enjoy	5.58±0.79
			Balance	4.16±0.68
			Absorption	3.99±0.75
Friend			Power	394.88±96.57
			ΔPower	57.81±34.00
			IMI Enjoy	5.94±0.60
			Balance	4.17±0.65
			Absorption	4.29±0.57

3.3.8 Flow Absorption. A repeated-measures ANOVA was conducted on Competitor (Stranger, Self, and Friend) for *Absorption*. The effect of Competitor was significant ($F(2, 38) = 9.857, p < .001^{***}$) with a 'medium' effect size ($\omega^2 = 0.060$). *Absorption* in Friend was significantly higher compared to Self ($t(19) = 2.925, p = .012^{*}$) with a 'small' effect size (Cohen's d=0.431) and also significantly higher compared to Stranger ($t(19) = 4.356, p < .001^{***}$) with a 'medium' effect size (Cohen's d=.642). *Absorption* in Self was not significantly higher than Stranger ($t(19) = 1.431, p = .161$) with a 'small' effect size (Cohen's d=.211).

3.4 Qualitative Analysis

We asked two closed questions and one open ended question and we did a summary analysis of the answers to closed questions. The first closed question was whether participants would like to compete with a friend, themselves, or a stranger. Out of the 20 players, 13 players stated that they prefer to compete with their friends, 6 players stated that they prefer to compete with themselves, and 1 player stated that he prefers to compete with a stranger.

This is in line with our quantitative results which show that friend-modelled interactive feedforward is superior in improving intrinsic motivation when compared to self-modelled interactive feedforward and stranger-modelled interactive feedforward as intrinsic motivation is correlated with positive player experience [85]. When they were asked whether they are most likely to perform better when they are competing with a stranger, friend or themselves: 12 players answered friendly competition, 1 player answered competing with a stranger, 6 players answered self-competition, and 1 player answered both friendly competition and self-competition. These results show that the majority of the players preferred friendly competition and felt that they would perform the best when competing with a friend. This also matches our quantitative results which show that friend-modelled interactive feedforward is superior in improving exercise performance when compared to self-modelled interactive feedforward and stranger-modelled interactive feedforward. They were then asked an open-ended question asking them to comment on their preference. We highlighted comments that were interesting and added more insight into the participants' preferences. Their comments to open-ended questions asking reasons for their preference of friendly competition included phrases such as *"challenge is more personal"*, *"more* *satisfaction in a win"* and *"wanted to beat the friend the most by far"*. One player said they *"enjoyed the aspect of racing against a friend in privacy while still being competitive"* as opposed to more direct and visible forms of competition with friends. Players who preferred self-competition typically commented along the lines of *"challenging myself is the best way to track improvement"*. The player who preferred competing with a stranger commented that because he had a personal relationship with the friend he would rather compete with a random stranger who he did not care about so much.

4 Discussion

Our results indicate that social interactive feedforward is indeed effective in improving performance and intrinsic motivation compared to self-interactive feedforward. Specifically, our results indicate that even when the enhanced models move at the same pace, the mere association of the enhanced model with their friend results in a rapid improvement in performance and motivation which implies that social feedforward was successfully elicited by using an enhanced friend's model. Our study shows the perceived importance of exercising with a friend. Our findings are in line with the results of several studies that explore the benefits of exercising with a partner. Lack of exercise partner was found to be an external barrier to women participating in exercise programmes and facilities at work [104]. Exercising with a romantic partner improves exercise performance and adherence [89]. Our findings show that exercising with a friend's virtual enhanced model is also beneficial in improving performance and intrinsic motivation.

Our hypothesis was that social interactive feedforward using enhanced friends' models could improve performance and intrinsic motivation more than enhanced self-models. The results show that using an enhanced friend's model significantly improves performance when compared to an enhanced self-model with a medium effect size and significantly improves performance when compared to an enhanced stranger's model with a medium effect size (RQ1). The fact that the enhanced stranger's model and the enhanced friend's model move at the same pace with the only difference being the player's association with the enhanced model shows that the feedforward effect is elicited in the Friend condition leading to significant improvement in performance. This matches a study by Plante et al. [79] which reports that exercising with another person may be calming but more tiring because of a potential increased competition.

The results also show that players exhibited significantly higher enjoyment levels (which is the main self-reported measure of intrinsic motivation) when doing the Friend condition than doing the Self condition with a small effect size and Stranger condition with a medium effect size (RQ2). This result also shows that the player's association of the enhanced model with their friend improves enjoyment. This finding also reaffirms the results of other studies showing that inclusion of a social element of interacting with friends during a game increases enjoyment [39, 65, 73].

The results also show that the perceived effort put in by the players when doing the Friend condition is not significantly higher than the Self condition with a small effect size and significantly higher than the Stranger condition with a large effect size. This implies that even though players perform significantly better in the Friend condition than the Self condition, they do not perceive the effort put in by them to be significantly higher. This could possibly be explained by the significantly higher enjoyment levels in the Friend condition than in the Self condition leading to lesser perceived effort. The results show that the effect of competitor on perceived pressure was not significant. This contradicts our earlier finding which showed that players perceived higher pressure in the non-self competition condition. This could imply that differences in players' competitiveness could vary perceived pressure.

The results show that the balance of challenges and skills was not significantly affected by the competitor. The players show significantly higher absorption in the task in the Friend condition than in the Self condition with a small effect size and in the Stranger condition with a medium effect size. This indicates that players are more likely to enter a state of flow in the Friend condition than in the Self condition and the Stranger condition. Our findings also support the results of a study by Rackow et al. which concludes that exercising with a partner is better for receiving emotional and instrumental social support which in turn leads to better self-regulation and self-efficacy [82].

4.1 Limitations

The sample size (n=20) was relatively small, mostly male, and in their 20s, which limits the generalisability and implications of our findings. The power analysis shows that there is a 77.37% chance of detecting real improvements in performance and intrinsic motivation in the Friend Condition compared to the Self and the Stranger conditions. Longitudinal studies with larger sample sizes are required to explore our findings further. We presented only summary statistics and highlighted comments in the qualitative analysis section. We will do a detailed qualitative analysis in our future longitudinal study exploring friend-modelled interactive feedforward. Another limitation of social interactive feedforward as implemented in this study is that we studied only players who have similar fitness levels as their friends. Hence, it is unclear how well social interactive feedforward works if player pairs have different fitness levels.

Future Work and Conclusion

Broadly speaking, it would be interesting to explore how social interactive feedforward and friend modelling can be used to achieve exercise adherence. This widens the application of self-modelled feedforward to a wide range of social options which enables players to reap the benefits of socialising in addition to feedforward benefits. This method can be easily retrofitted into existing games to gain similar benefits. In our study, we use virtual avatars to represent the friend model and their performance but still manage to evoke the benefits of exercising with a partner shown in previous studies [79, 82, 89, 104]. This implies that these social benefits are also applicable in virtual world interactions.

We have designed our exergame in such a way that it integrates competitive play into the design by including a virtual recording of an enhanced friend model. This allowed us to include social interaction without including a more direct and potentially detrimental competitor. This design option could be a solution for players who have lower self-efficacy and fitness levels as it would not make them conscious of their flaws in front of others while still allowing them to enjoy indirect competitive play [70]. This can be explored by conducting further studies. Future studies could also explore further personalisation by offering the player to choose between a self-model, stranger-model, and friend model and comparing players' design choices with their personality types.

Friends of roughly similar fitness levels were asked to partcipate to avoid underwhelming or overwhelming exergaming experiences. This limitation can be addressed by tracking the player experience reflected by their affective state (emotional state) and adapting the exergame intensity to avoid unpleasant player experience. Psychophysiological measurements such as pupillometry and skin conductivity have been found to be indicators of affect in high intensity VR exergaming [11].

Future studies can explore enabling affectively adaptive VR exergaming in social interactive feedforward to overcome the limitation of using players of roughly similar fitness levels. We investigated social interactive feedforward using a single study. Longitudinal studies need to be conducted to further explore its efficacy in improving exercise adherence. We opted to help players relate to their model by sticking a photo at the back of the models. Studies have successfully further customised their models by using software tools such as Autodesk Character Generator [61] and deepfake technology [21].

We proposed and evaluated social interactive feedforward, a novel method that combines social interaction with interactive feedforward. Social interactive feedforward is based on training and competing with an enhanced model of a friend. Our empirical study suggests that social interactive feedforward can be effective in further improving players' performance and intrinsic motivation when compared to self-modelled interactive feedforward.

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