Solitary Jogging with A Virtual Runner using Smartglasses

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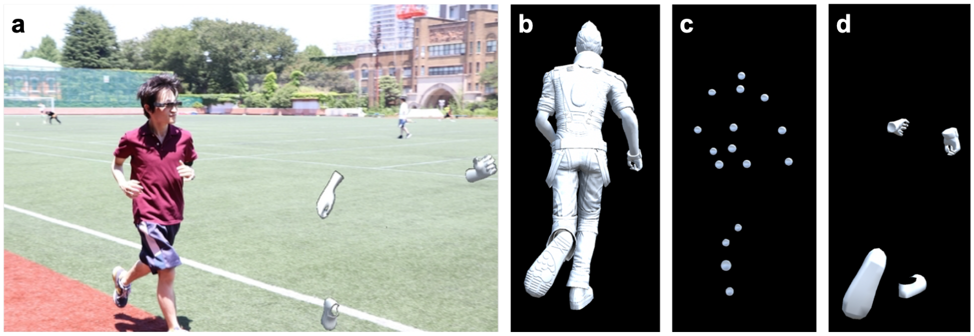

Figure 1: (a) Joggers can see a virtual runner which has each of three body visibilities: (b) full-body, (c) point-light, and (d) limb-only.

ABSTRACT

Group exercise is more effective for gaining motivation than exercising alone, but it can be difficult to always find such partners. In this paper, we explore the experiences that joggers have with a virtual partner instead of a human partner and report on the results of two controlled experiments evaluating our approach. In Study 1, we investigated how participants felt and how their behavior changed when they jogged indoors with a human partner or with a virtual partner compared to solitary jogging. The virtual partner was represented either as a full-body, limb-only, or a point-light avatar displayed on smartglasses. In Study 2, we investigated the differences between the three representations as virtual partners for casual joggers in an outdoor setting. Based on our results, we propose implications for the design of virtual runners as casual jogging partners and speculate on their relationship with human users.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality; Applied computing—Life and medical sciences—Consumer health

1 INTRODUCTION

Considering the global trend of insufficient physical activity [20], technologies for getting sedentary people motivated to exercise have taken an increasingly important role. Especially intrinsic motivation facilitates long-term adherence to physical activity [59, 62]. Intrinsic motivation, defined as behavior driven by an activity's inherent satisfactions [58], is relevant for motivation during solitary exercises.

Jogging is running at a gentle pace - a daily exercise that can be done anytime and anywhere requiring no scheduling with other individuals. Joggers may often use wearable devices to gather information and to get immediate feedback about the jogging distance, steps, pace, burned calories, and heart rate. By comparing the difference between these data and their feeling, joggers can adjust their jog to achieve set exercise goals as well as use the data to monitor their progress and gain motivation.

Group exercise has been shown a more effective way of getting motivated than exercising alone. The mere presence of others tends to affect physical activity, and individuals perform better on simple or well-rehearsed tasks with other people (*social facilitation*). For example, cyclists who competed with another cyclist increased their speed compared to when competing with a clock [74], and in the case of synchronized rowing, when training with another person the rower's pain threshold was increased compared to individual training [13]. Furthermore, even the presence of an attentive spectator can increase a jogger's pace [69, 78].

In *conjunctive tasks* [68] where the superior coworker cannot continue working on the task after a less capable member stops, such as in the case of team mountaineers, the weaker member tends to get more motivated to try harder [27]. Especially, the greatest motivational gain occurs with a slightly superior partner [42]. These phenomena are referred to as the *Köhler effect* and are caused by upward social comparison and group indispensability when performing the task [34], not the mere presence of others. That is, less capable members try significantly harder under conjunctive tasks than under additive tasks [27] where the group score is just the sum of the individual member contributions, such as in the case of tug-of-war. While conjunctive exercise with a slightly superior partner seems to provide the most benefit, for casual joggers it is difficult to always find such a rare partner and prior works have examined transforming solitary jogging into a social activity to overcome this limitation (i.e., jogging over a distance [47]). Furthermore, in times of global crises requiring efforts such as social distancing, opportunities for group exercise, sports and the use of training facilities may be scarce leaving solitary exercise the only viable option.

In this paper, we aim to explore how casual joggers feel and how their behavior changes when jogging with a virtual partner displayed on smartglasses. Since smartglasses are lighter than ordinary augmented reality (AR) glasses (e.g., Microsft HoloLens 2) and can always present virtual person's movement in the user's field of view (FOV), unlike the visual display of smartwatches, we adopted smartglasses as a device to display a virtual partner while jogging. While many joggers wear earphones and use audio-based smartphone apps, the Köhler effect requires a presentation of the partner's movement but the effect has only been verified with visual information so far (e.g., [18, 49]).

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Ensuring the jogger's safety while presenting appropriate visual information about a partner is challenging. Thus, in this work we adjust the virtual partner's body visibility based on our previous research [21, 22] in order not to obscure the jogger's FOV (Fig. 1). In summary, we investigate the following research questions:

RQ1: How do virtual runners affect joggers in terms of their motivation compared to a human runner and solitary jogging?

RQ2: Can virtual runners guide joggers' cadence to a desirable one?

RQ3: Which factors of virtual runners influence the jogger's experience?

In Study 1, participants were randomly assigned to one of three representations: a full-body avatar, a point-light avatar, or a limb-only avatar, and they jogged indoors under three conditions: alone, with a virtual partner, and with a human partner. In Study 2, participants jogged outdoors with each of the three virtual partner representations. Our results showed that jogging with virtual jogging partners even with low body visibility was rated higher in enjoyment compared to solitary jogging, and jogging with the full-body partner outdoors was more enjoyable than with the point-light or limb-only designs. This exploratory study provides implications for the design of virtual jogging partners.

2 Related Work

2.1 Social Aspect of Running

Running has a social aspect that influences runners' performance and psychological state through interactions with others. Morgan et al. identified that athlete runners use two strategies to increase their performance: association and dissociation [45]. An associative strategy focuses on their bodily sensations and adjusting the running pace, whereas a dissociative strategy focuses on the landscape and spectators to reduce boredom and pain while running. In this way, runners in dissociation are especially affected by the presence of others (i.e., social facilitation [69, 78]). Knaving et al. studied amateur runners and found that not only competition plays a role in the running experience, but that support from other runners is critical to motivation [35]. They also reported that even for runners who prefer to run alone, connection with other runners is desirable. Shipway et al. researched the running community and reported that the running group often plays an important role in providing a sense of belonging and form a place to share their running experiences [65]. Spectators' support, even if it is remote, can positively affect runners [14, 56, 79], but it can also have a negative effect depending on the runner's physical or mental state [9, 79]. Hence, in our work we focus on exploring the effects of a jogging partner that is neither a competitor nor a spectator.

Jogging is a form of exercise that can be done anywhere, anytime, but requires coordination of location and time to get together for others to participate. To address this problem, JoggingBuddy [1] is a website matching people who want to jog, offering the opportunity to run with strangers in their neighborhood. Explore the World [61] and Zwift Run [83] bring treadmill runners from around the world in virtual worlds to run together. Mueller et al. have also developed an audio-based support system that allows people who are geographically separated from each other to feel like they are running together [47]. Although significant ability difference between two people exercising together is known to decrease motivation [42], their system excludes this effect by localizing the sound source representing the partner's presence back and forth based on her/his heart rate rather than jogging distance. This method allows people to share information about how hard they are pushing against their ability to communicate with each other. While these solutions can greatly increase the number of individuals people can run with, it is not always guaranteed that they will be paired with someone who is a good match in terms of interests and abilities.

2.2 Information Representation for Assisting Running Movement

Technologies to help runners evaluate their performance are widely accepted, with many runners wearing smartphones, smartwatches and activity meters to provide feedback on their runs by presenting running pace and distance as voice notifications from apps such as Nike Run Club [51]. In this way, these feedback usually lead to assist running movement through user interpretation. However, it can be difficult especially for novice runners to determine how they could adjust their running movement based on such information representations. Adversely, the coercive way to improve running movement using electrical muscle stimulation (EMS) has been explored in previous work [25, 39]. The EMS enables quick manipulation of undesirable movement, but also runs a risk that the user may get injured if inappropriate stimulation is accidentally applied.

There are also information representations that involuntarily change the running movement. Dyck et al. found that music tempo can spontaneously impact running cadence [75]. Nylander et al. proposed Runright, a system that provides audio feedback on running movements [53]. Oliver and Flores-Mangas developed MPTrain, an automatic music selection system that determines which music to play according to predetermined running goals and physiological responses [54]. Fortmann et al. developed PaceGuard, a system that presents a rhythmic pulse beat to encourage appropriate cadence for the user [19]. Nowadays, playlists to guide people to the desired cadence are also available on popular smartphone apps of music services such as Spotify [67]. Besides, a few exergames support outdoor jogging. A smartphone app "Zombies, Run!" [71] enables usual jogging to convert into narrative-focused game experience of running away from zombies [77]. Tan et al. developed an outdoor jogging system using AR game approach in consideration of attention on the real-world actions [70]. All these systems provide audio feedback suitable for outdoor jogging, but it can be difficult to understand others' running behavior from audio stimuli alone.

2.3 Exercise with Software-based Partners

Exergames are a global trend aiming to gamify physical activity. To improve athletic performance and motivation, many exergames focusing on various exercises with virtual partners have been developed (stationary cycling [5–7, 32, 37, 40, 43, 63, 64, 66], plank [16–18], rowing [29, 49], in place running [31], and treadmill running [52]). They are intended for use in an indoor laboratory environment using screens and a virtual reality (VR) headset. However, jogging, cycling, and swimming require attention to the real environment, which makes it difficult to apply exergame's method directly to these activities.

There have been attempts to involve a robotic partner in outdoor jogging. Tominaga et al. used a display attached to an escort robot moving in front of a jogger to provide self-images [72]. On the other hand, Mueller and Muirhead proposed a method of presenting a drone as a partner for jogging which does not interfere with the perception of the surrounding environment except for the part occupied by the drone [48]. However, ensuring joggers' safety on the road should be the priority when jogging outdoors, and controlling a robot safely in a crowded environment with people and buildings is still challenging.

To solve these problems, systems that can display a software-based runner in front of a jogger using see-through AR glasses or large displays have been proposed [2, 3, 76]. However, these approaches have not yet been made commercially available for the general public to experience. On the other hand, we have been exploring the experience of jogging with a virtual runner using an optical see-through display (smartglasses) without AR functionality in terms of motivation and performance changes [21–23]. As opposed to [22] we explore the effects of three different virtual avatar designs as partners for indoor jogging, and also expand the analysis to more realistic outdoor settings [21].

2.4 Other's Avatar Representation

The effects of other's avatar representation on an individual's perception have been studied in immersive VR and AR telepresence systems. Latoschik et al. [38] explored the effect of an avatar's realism on the uncanny valley [28, 46] by comparing abstract (based on a wooden mannequin) with realistic avatars (generated from photogrammetry 3D scan methods) through gestural social interaction between self and another avatar in VR. They found that the difference between rated eeriness and attractiveness was not significant even though the real avatar's humanness was rated significantly higher. Heidicker et al. [26] studied the effect of an avatar's completeness on social presence [10] by comparing three different types of avatars: complete body with regular predefined movement, one-to-one mapping of the user's movement, and only head and hands with a one-to-one mapping of the user's movement in VR. Interestingly, they reported that the incomplete avatar body was not worse, but rather even better than the complete body with predefined movement in terms of co-presence and behavioral interdependence consisting of social presence. Yoon et al. researched the effect of avatar appearance with different levels of body part visibility (head and hands, upper body, and whole body) and two different character styles (realistic and cartoon-like) on social presence while performing remote collaboration tasks in AR [80]. They found that a realistic avatar with a whole body was the best for remote collaboration, but upper body avatar or cartoon style could be considered as a substitute depending on the collaboration context. Besides, they pointed out that the head and hands avatar should be avoided in AR remote collaboration because it could not give appropriate communicative cues such as continuous movement, gaze point, and gestures. In summary, these studies show that although a realistic full-body avatar is desirable in an AR telepresence system, an abstract avatar with low level of body part visibility could also be an alternative to a full-body avatar if the avatar can provide the necessary communicative cues.

In cases where only the general movement of a person is presented, the richness of the avatar visualization can be reduced. Johansson reported that even the movement of point lights representing the positions of major joints can be recognized as human walking, running, and dancing [33]. Kondo et al. also reported that when observing an avatar from behind with only hands and feet (white gloves and socks) moving in synchronization with the observer in VR space, the invisible body was interpolated into the transparent space between the avatar's hands and feet causing illusory body ownership [36]. This illusion was also comparable to avatars with full body visualization [36]. That is, these avatar designs which include less visual information may also be suitable for presenting simple, periodic movements in real space, such as the movements of a virtual jogging partner.

This study compares an avatar with low level of body part visibility to a full-body avatar that can reduce the area occupied by the jogger's FOV while prioritizing unobstructed attention to the surrounding environment while jogging outdoors. Since our system is not designed to be used face-to-face communication with the avatars, avatars with low level of body part visibility are also presented with the lower body.

3 Virtual Jogging Partner

To present the virtual jogging partner to experiment participants, we used smartglasses (EPSON MOVERIO BT-300, 1280 (width) x 720 (height) pixel for each eye, 69 grams) to display each avatar. The smartglasses contain a pair of organic light-emitting diode displays that enable the virtual partner to be seamlessly superimposed on the real world without paying attention to the display panes.

To determine if joggers' feeling and behavior depend on the virtual runner's appearance, we used three types of the body visibility: a full-body, a point-light, and a limb-only avatar (Fig. 1). A man who is one of the standard models of a game engine Unity was used as the full-body avatar. The point-light and the limb-only avatars were designed as a minimized visual representation of human motion to minimize obstructions in the jogger's FOV. The point-light avatar consisted of 16 point lights representing the main joints of a human. The limb-only design with only hands and feet was inspired by the research of Kondo and colleagues [36].

The virtual partner is shown to be running 10-meters ahead from the jogger's viewpoint. This is the closest distance where the virtual partner's whole body is visible considering the view angle of the smartglasses. We used the *Jog Forward* motion in the 3D animation sequences provided by Mixamo's online services [4] to generate the virtual partner's jogging motion. The virtual partner jogs at 180 steps per minute, which has been reported as an ideal running cadence to avoid injuries caused by over-striding [15]. The virtual partner stands still and starts running only when the user's motion is detected and stops running when the user slows down or stops. The user's motion and steps are detected by the smartglasses' built-in accelerometer with VR-STEP's algorithm [73], and a decision is made every second whether to show the virtual partner running or stationary.

Joggers can always see the virtual partner at the FOV regardless of their head motion. This design choice was based on our own impressions from preliminary experiments when jogging with an avatar that is localized on ground level using the built-in inertial measurement unit (IMU) sensors. This representation does not use AR technologies, and the smartglasses are used simply as a wearable display. It is possible to implement AR applications on the smartglasses using the built-in camera and IMU sensors. However, if the user moves fast, such as while jogging, the environmental recognition is delayed due to their rapid head motion. Consequently, the virtual partner would seem to run in the sky and sink into the ground leading the users to feel frustrated with the virtual partner's restless movement caused by the vigorous shaking at their eye level, insufficient sensor accuracy, and insufficient processing power. Moreover, they would easily lose sight of the virtual partner due to the overwhelmingly narrower FOV in the smartglasses compared to the human eye. Therefore, we stabilized the motion of the virtual partner without mapping it into the real world.

4 Study 1: Comparing the Effects of Jogging Partner and Body Visibility of Virtual Partner on Casual Joggers' Mental Condition and Behavior

4.1 Method

We conducted a controlled experiment to investigate how joggers feel and how their behavior changes with *jogging partner* (jogging alone, jogging with a human partner, jogging with a virtual runner) as the within-subjects factor, and three types of avatar visibility as the between-subjects variables. The participants were asked to jog three times, excluding a warm-up phase, inside a gymnasium with a lap length of about 160 meters. The order of *jogging partner* condition was counterbalanced. The participants were asked to keep wearing the smartglasses for the duration of the experiment.

Under jogging alone condition, participants were asked to simply jog for five minutes. Under jogging with a human partner condition, participants were asked to jog behind an experimenter for 5 minutes. In this condition, a 32-year-old male experimenter wearing training clothes jogged at 180 steps per minute in front of the participant to play the role of the human partner while listening to 180 beats per minute sound using headphones. The experimenter was an untrained pacesetter, however, he tried to adapt the pace to the participants while implicitly confirming a distance between them when turning a corner. Under jogging with a virtual runner condition, participants were asked to jog for 5 minutes while seeing the virtual partner on their smartglasses. While the jogging time was short, it matched the time that our target users, sedentary people, could jog comfortably rather than straining themselves and risk injury. Their jogging was recorded with a video camera.

To determine if the participants' mental condition or behavior depend on the virtual runner's body visibility, we used the *body types of the virtual partner* (full-body, limb-only, point-light avatar) as the between-subjects variables as illustrated in Fig. 1. Participants were randomly assigned to one of three groups using each virtual partner body type, respectively. Each of the three groups then followed the within-subjects design of *jogging partner* conditions described above. After each jogging condition, the participants answered a questionnaire about their jogging experience, which took less than 10 minutes for all participants. After all three sessions, we interviewed participants while they were still exhausted. The interviews were semi-structured and recorded; we focused on the participants' experience, asking questions such as: "what were the differences between the 3 conditions?" and "did the partner influence your jogging experience and if so, how?" Most interviews lasted approximately 10 minutes and the overall experiment took about one hour to complete. All interview data were transcribed, and initially analyzed by deductive content analysis to find themes related to intrinsic motivation, team perceptions, and cadence coordination. The remaining comments from the participants were open coded and analyzed using an inductive method to reveal a salient theme related to the jogging experience besides intrinsic motivation, team perceptions, and cadence coordination. The experiment was approved by the local ethics committee and conformed to the committee's guidelines and regulations.

4.2 Participants

We recruited 39 people (19 male, 20 female) aged between 21 to 58 years old (average 39.3 years) and monetary compensated them through a temp agency. To make it easy for even sedentary people to register for the experiment, the recruiting condition was specified as the ability to jog for about 30 minutes (no pace specified). All participants stated that they had normal vision and no health problems preventing them from participating in this experiment based on the results of their most recent medical examination, and agreed to take safety precautions and participate in the experiment at their own risk before completing an informed consent form. Twenty-two participants jog more than once per week. None of the participants wore corrective glasses. They were randomly assigned to one of three groups, with 13 participants per group.

4.3 Measures

To verify whether the participants' physical exercise intensity was controlled in each condition, we measured *perceived exertion* using the Rating of Perceived Exertion (RPE) scale (6=no exertion to 20=maximal exertion) [11], which is designed to estimate heart rate by multiplying response value by 10. The participants also rated their perceived workload during the jog on the six subscales in the NASA Task Load Index (NASA-TLX) on a 1 to 10 scale [24], which were averaged to create the measure of *workload* (Cronbach's α =.67).

To measure the participants' *intrinsic motivation*, we used the Intrinsic Motivation Inventory (IMI) scale [57], which has been used in several previous works on sports and exergames [12,41,82]. Similarly to previous research examining the maintenance of high intrinsic motivation with a virtual co-actor [6], we used only two of the seven subscales in this experiment: *Interest/Enjoyment* considered the self-report measure of intrinsic motivation, and *Pressure/Tension* a negative predictor of intrinsic motivation.

Five items (Cronbach's α =.91) in the IMI Interest/Enjoyment (*"I enjoyed doing this activity very much"*, *"This activity was fun to do"*, *"I would describe this activity as very interesting"*, *"I thought this activity was quite enjoyable"*, and *"While I was doing this activity, I was thinking about how much I enjoyed it"*) formed a reliable scale, and five items (Cronbach's α =.81) in the IMI Pressure/Tension (*"I did not feel nervous at all while doing this"*, *"I felt very tense while doing this activity"*, *"I was very relaxed in doing these"*, *"I was anxious while working on this task"*, and *"I felt pressured while doing these"*) formed reliable scales. The participants' ratings (1=Not at all true, 7=Very true) were averaged to create the measures of IMI Interest/Enjoyment and IMI Pressure/Tension.

To assess the participants' perceptions of the working relationship with the partner (*team perceptions*), we used a 5-item questionnaire (*"I felt I was part of a team"*, *"I thought of my partner as a teammate"*, *"I felt I was working collaboratively"*, *"I felt I was working together"*, and *"I felt I wasn't working separately"*) [17,50,55,60]. Each item was rated on a 9-point scale (1=Not at all true, 9=Very true), and these ratings were averaged to create the measure of team perceptions (Cronbach's α =.87).

To measure the participants' perceived *ability discrepancy* with the partner we used a single item questionnaire: *"How do you feel you compared to your partner?"* rated on 7-point Likert scale (1=Much less capable than my partner, 7=Much more capable than my partner) [40].

To measure the participants' level of *cadence coordination*, we counted their steps from a video recording of their jog and calculated the average steps per minute (i.e., cadence). As both the human and virtual partner were jogging at a cadence of 180, we then calculated the difference between the participants' cadence from 180 in each condition, and this difference was used as a measure of a level of cadence coordination.

5 Study1: Result

5.1 Jogging Experience with a Virtual Runner

A summary of the results is shown in Table 1. To explore our research questions, we conducted a quantitative analysis of both subjective and objective data collected during the experiment, as well as qualitative analysis of interview data. For quantitative measures we used 3 (virtual runner body visibility: full body vs. point-light vs. limb only) $\times$ 3 (jogging partner: alone, vs. human vs. virtual) Mixed ANOVAs, and non-parametric tests when the data was not normally distributed.

Perceived Exertion - RPE: The data for RPE were not normally distributed (Shapiro-Wilk, p<.05), and hence, we employed non-parametric tests for the statistical analysis. Results from a Friedman test indicated no significant effect of jogging partner on the participants' RPE ($\chi^2[1]=0.18$, $p=.92$), and results from a Kruskal-Wallis test showed no significant effect of virtual runner body visibility on participants' RPE in the virtual partner condition ($H[2]=0.17$, $p=.29$), or the human partner condition ($H[2]=0.004$, $p=.50$).

Workload - NASA-TLX: There was no significant main effect of jogging partner on the participants' NASA-TLX scores ($F[2, 72]=0.51$, $p=.60$). The main effect of virtual runner body visibility was also not significant ($F[2, 36]=0.62$, $p=.80$), and there was no significant interaction between the jogging partner and virtual runner body visibility ($F[4, 72]=0.37$, $p=.83$) on the participants NASA-TLX scores.

Intrinsic Motivation - IMI Interest/Enjoyment: Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated ($\chi^2[2]=6.28$, $p<.05$) for the IMI Interest/Enjoyment data with an estimated Huynh-Feldt epsilon of .859, and therefore,

[1] One participant could not be recorded due to the malfunction of a video camera, and we replaced the null values with the condition average for the statistical analyses.

Table 1: Summary of demographics and results for each group (mean ± std. dev.) of Study 1.

Body Visibility of Virtual Runner	n	Demographics	Variable	Jogging Partner Alone	Human	Virtual
Full-body	13	Male=6 Female=7 Age=38±12	RPE	12.31±2.29	12.38±2.02	12.15±2.23
			NASA-TLX	5.09±2.20	5.56±1.92	5.06±2.18
			IMI Enjoyment	3.91±1.60	4.69±1.16	5.32±1.11
			IMI Tension	2.77±1.53	3.31±1.67	2.82±1.72
			Team Perceptions	—	6.65±2.25	5.45±2.06
			Ability Discrepancy	—	3.54±1.13	4.15±0.90
			Cadence [spm][1]	171.13±10.71	173.21±8.13	169.64±8.94
Point-light	13	Male=7 Female=6 Age=38±13	RPE	13.27±2.65	12.58±2.16	12.04±2.33
			NASA-TLX	5.36±2.50	5.04±2.39	4.78±2.60
			IMI Enjoyment	3.75±1.53	4.85±1.38	4.68±1.25
			IMI Tension	3.46±1.83	2.82±1.68	2.69±1.45
			Team Perceptions	—	6.28±2.22	4.95±2.01
			Ability Discrepancy	—	3.00±1.22	3.54±1.13
			Cadence [spm][1]	165.55±8.66	171.94±6.74	167.01±4.84
Limb-only	13	Male=6 Female=7 Age=42±10	RPE	12.27±2.70	12.23±2.34	12.23±2.55
			NASA-TLX	4.95±2.36	5.09±2.64	4.95±2.53
			IMI Enjoyment	4.17±1.68	4.92±1.52	4.88±1.60
			IMI Tension	3.40±1.88	3.18±1.85	2.91±1.93
			Team Perceptions	—	6.82±2.44	5.42±2.73
			Ability Discrepancy	—	2.46±1.33	3.54±1.20
			Cadence [spm]	170.25±8.35	171.90±8.07	169.71±9.02

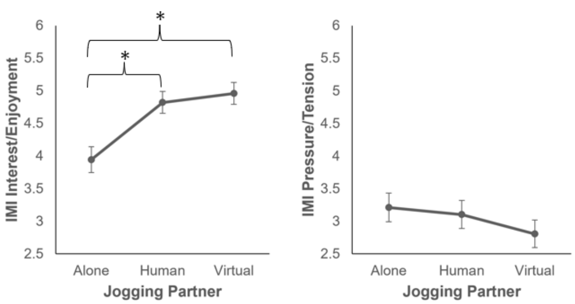

Figure 2: IMI Interest/Enjoyment and Pressure/Tension scores for jogging alone, jogging with a human partner, and jogging with a virtual runner conditions. Error bars represent the standard error of the mean.

a Huynh-Feldt correction was used. There was a significant main effect of jogging partner on the participants' IMI interest/enjoyment scores(*F[1.90, 68.25]=9.87, p<.001*) (Fig. 2, left). Post-hoc pairwise comparisons with Bonferroni correction indicated that the participants rated their enjoyment significantly higher with either a human *(M=4.82, SD=1.11, p=.012*) or an avatar partner (*M=4.89, SD=1.08, p=.001*) compared to jogging alone (*M=3.94, SD=1.45*). The enjoyment ratings between human and avatar partner were not statistically significant. The main effect of virtual runner body visibility was not statistically significant (*F[2, 36]=0.29, p=.75*), and there was no significant interaction between the jogging partner and virtual runner body visibility (*F[3.79, 68.25]=0.81, p=.63*) on the participants IMI Interest/Enjoyment scores.

Intrinsic Motivation - IMI Pressure/Tension: There was no significant main effect of jogging partner on the participants' IMI Pressure/Tension scores (*F[2, 72]=1.12, p=.33*) (Fig. 2, right). The main effect of virtual runner body visibility was also not significant (*F[2, 36]=0.46, p=.86*), and there was no significant interaction between the jogging partner and virtual runner body visibility (*F[4, 72]=0.80, p=.53*) on the participants IMI Pressure/Tension scores.

Team Perceptions: The data for Team Perceptions were not normally distributed (Shapiro-Wilk, p<.05), and hence, we employed non-parametric tests for the statistical analysis. Results from a Friedman test indicated a significant effect of jogging partner on the participants' team perceptions (χ^2*[1]=6.74, p=.009*), where the human partner (*Mdn=7.00, IQR=2.00*) was rated higher than the avatar partner (*Mdn=5.00, IQR=4.00*). Results from a Kruskal-Wallis test showed no significant effect of virtual runner body visibility on participants' team perceptions in the virtual partner condition (*H[2]=0.54, p=.77*), or the human partner condition (*H[2]=1.61, p=.45*).

Ability Discrepancy: The data for Ability Discrepancy were not normally distributed (Shapiro-Wilk, p<.05), and hence, we employed non-parametric tests for the statistical analysis. Results from a Friedman test indicated a significant effect of jogging partner on the participants' ability discrepancy (χ^2*[1]=11.64, p=.001*), where the average ability discrepancy scores were lower for human partner (*Mdn=3.00, IQR=2.00*) than the avatar partner (*Mdn=4.00, IQR=0.50*). Results from a Kruskal-Wallis test showed no significant effect of virtual runner body visibility on participants' team perceptions in the virtual partner condition (*H[2]=3.37, p=.19*), or the human partner condition (*H[2]=4.42, p=.11*).

Cadence Coordination: The data for participants' cadence coordination were not normally distributed (Shapiro-Wilk, p<.05), and hence, we employed non-parametric tests for the statistical analysis. Results from a Friedman test indicated a significant effect of jogging partner on the participants' cadence adjustment (χ^2*[1]=18.69, p<.001*), where the participants' average cadence was closer to the partner's cadence (180 steps per minute) in the human partner condition (*Mdn=15.34, IQR=11.42*) compared to the virtual partner condition (*Mdn=18.14, IQR=10.30*). Results from a Kruskal-Wallis test showed no significant effect of virtual runner body visibility on participants' cadence adjustment in the virtual partner condition (*H[2]=0.20, p=.91*), or the human partner condition (*H[2]=0.34, p=.85*).

5.2 Exploring Factors Affecting Jogging Experience with a Virtual Runner

The following sections detail the results from the deductive and inductive analysis of the post-experiment interviews. In addition to themes further explaining the results of statistical analyses on jogging experience described above, one theme emerged from the inductive analysis of remaining interview data: *desire for being encouraged*.

5.2.1 Engagement in Jogging

Twenty participants complained about boredom while jogging alone. The participants distracted themselves by paying attention to the passage of time (P1, 12, 15, 17, 21, 24, 25, 26, 31, 37), to the surrounding scenery (P12, 25, 28), or the post-workout meal (P7, 30). On the other hand, few similar comments were observed in both partner conditions (2 participants in the virtual partner condition only). Furthermore, when asked which of the conditions they felt the passage of time was the shortest, 19 participants answered when jogging with the human partner, 13 mentioned the virtual partner, and only 4 chose the alone condition: *"The time [with experimenter] went by so fast that it felt like two-thirds of the time." [P33]*

"I was in sync with his [limb-only] running tempo, so running did not become a burden or stress for me." [P25]

These results corroborated the results from our statistical analyses regarding enjoyment, and further answered our RQ1 indicating a higher motivation towards jogging itself whether jogging with a human or a virtual partner.

5.2.2 Feeling of Jogging Together

While the results of the statistical analysis showed that the human runner was rated higher in terms of team perceptions, the virtual runner also induced some level of team perceptions with the participants. In total, twelve participants reported that they regard the virtual runner as a companion, and felt like they were running together: *"I felt like someone [full-body] was running with me, but I was running by myself." [P34]*

These results further answered our RQ1, where the statistical analyses and post-experiment interviews revealed that the virtual partner can be seen as jogging partner similarly to a human partner.

5.2.3 Running Comfort

Twenty-three participants perceived the human partner as the best condition based on their criteria such as running comfort, whereas 14 participants chose the virtual partner, and five preferred the alone condition (including multiple answers): *"I can hear his [human partner's] footsteps and he is actually there, and I can just follow them." [P16]*

"With a real person, if the distance between me and the person in front of me gets a little bit bigger, I get really worried, but with that person [limb-only runner], I felt like the distance was the same." [P10]

Combined with the statistical analysis regarding cadence coordination, this result in part answered our RQ2. Overall, the participants matched the human partner's cadence more closely than the virtual partner's cadence, and coincidentally, more participants found the human partner more comfortable as a jogging partner. However, as indicated by the interview results, some participants would prefer the virtual partner as a motivator for them to run longer.

5.2.4 Desire for being encouraged

Fifteen participants wished their virtual partners would offer support, gestures of concern, and coaching: *"I think it [full-body] would have been nice if I could hear his breathing, and if there had been an occasional look back or movement of concern, I think I would have enjoyed it a little more." [P1]*

"It would be better if he [point-light runner] could show me the gap between ideal and current running form if I want to run more seriously." [P17]

In regards to our RQ3, the participants wished the virtual runners to be more interactive and offer encouragement during the jog.

6 Study 2: Comparing the Effects of Virtual Runner Body Visibility When Jogging Outdoors

6.1 Method

In Study 1, our results showed a significant difference between the virtual partner, the human partner, and no partner on the participants' mental condition or behavior, but did not show a significant difference between the body types of the virtual partner. In order to explore RQ3 in more detail (which factors of virtual runners influence the jogger's experience?), we conducted a second experiment with a within-subjects design, where the virtual avatar body type was set as the within-subjects independent variable. Moreover, participants' feedback when jogging outdoors is necessary for the practical use of our proposed system, and hence, the second experiment was conducted in an outdoor setting on a 300-meter straight sidewalk where many people usually enjoy jogging. The experiment procedure and virtual runner designs were similar to Study 1 and as depicted in Fig. 1 (full-body, point-light, limb-only). Participants were asked to jog for 5 minutes with each of the virtual partners, that is, three times excluding a warm-up phase. The order of experiencing each virtual runner body type was counterbalanced. After each condition, they answered a questionnaire about their jogging experience. After all three sessions, we interviewed the participants while they were still exhausted, similarly to Study 1. Most interviews lasted approximately 10 minutes and the overall experiment took about one hour. All interview data were transcribed, open coded and analyzed using an inductive method to reveal salient themes related to the jogging experience besides intrinsic motivation. The participants were asked to wear the smartglasses throughout the experiment.

6.2 Participants

We recruited 12 people (6 male, 6 female) aged between 21 to 57 years old (average 41.7 years) who were compensated through a temp agency[2]. The recruiting condition was set as the ability to jog for about 30 minutes (no pace specified) similarly to Study 1. The participants were casual joggers who jog on average 9 times per month and their average jogging distance is 4 kilometres for a duration of 36 minutes[3]. They reported that they have normal vision without health problems for participating in the experiment before completing an informed consent form. None of the participants wore corrective eyeglasses or participated in Study 1.

6.3 Measures

Similarly to Study 1, we also counted their cadence as *cadence coordination* and used the other questionnaires: *intrinsic motivation* (IMI Interest/Enjoyment): Cronbach's $\alpha = .92$; *intrinsic motivation* (IMI Pressure/Tension): Cronbach's $\alpha = .76$; *workload* (NASA-TLX): Cronbach's $\alpha = .74$; *team perceptions*: Cronbach's $\alpha = .87$; and *ability discrepancy*. Contrary to Study 1, all seven items in the IMI Interest/Enjoyment (*"I enjoyed doing this activity very much"*, *"This activity was fun to do"*, *"I thought this was a boring activity"*, *"This activity did not hold my attention at all"*, *"I would describe this activity as very interesting"*, *"I thought this activity was quite enjoyable"*, and *"While I was doing this activity, I was thinking about how much I enjoyed it"*) formed a reliable scale.

7 Study 2: Result

7.1 Jogging Experience with a Virtual Runner

A summary of the results is shown in Table 2. For statistical analyses, we employed one-way repeated measures ANOVAs to compare the

[2]We initially hired 13 participants but excluded the data from one male participant (31 years old) due to hardware malfunction.

[3]One male participant (37 years old) did not answer about his jogging habits.

Table 2: Summary of results for the virtual body visibility (mean ± std. dev.).

	Virtual Runner's Body Visibility		
Variable	Full-body	Point-light	Limb-only
NASA-TLX	4.51±1.52	4.96±1.74	4.68±1.40
IMI Enjoyment	4.77±1.17	3.73±1.42	4.14±1.37
IMI Tension	2.80±0.78	2.63±1.04	2.43±1.11
Team Perceptions	4.57±1.94	3.42±2.21	4.43±1.88
Ability Discrepancy	3.67±1.07	3.58±1.73	3.83±1.59
Cadence [spm]	171.92±7.14	172.33±7.86	172.33±8.95

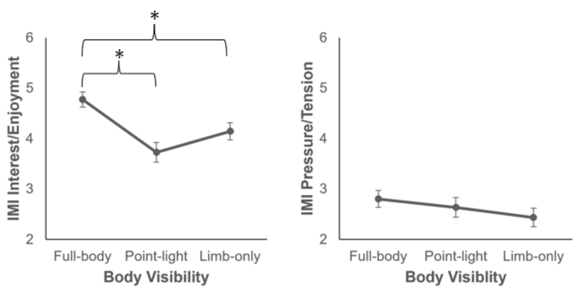

Figure 3: IMI Interest/Enjoyment and Pressure/Tension scores for jogging with a virtual full-body, point-light, and limb-only runner conditions. Error bars represent the standard error of the mean.

effects of virtual runner's body visibility on the dependent variables in the three conditions.

Workload: We observed no significant effect for NASA-TLX ($F[2,10] = 0.79, p = .48$) from one-way repeated measures ANOVA. However, when asked about their subjective perspective on the ease of running with each virtual partner, five participants chose the full-body, four participants chose the limb-only, two participants chose the point-light partner, and one participant was undecided.

Intrinsic Motivation: Results from a repeated-measures ANOVA indicated a significant effect of virtual runner's body visibility on IMI Interest/Enjoyment, $F[2,10] = 8.97, p = .006$, where the participants' rating was higher with the full-body partner compared to both the point-light partner ($p<.05$) and limb-only partner ($p<.05$) (Fig. 3, left). The difference between point-light and limb-only virtual runner body visibility was not statistically significant ($p>.05$). In contrast, we observed no significant effects for IMI Pressure/Tension ($F[2,10] = 0.98, p = .41$) (Fig. 3, right).

Team Perceptions: The data for Team Perceptions were not normally distributed (Shapiro-Wilk, $p<.05$), and hence, we employed a non-parametric test for the statistical analysis. Results from a Friedman test indicated no significant effect of the virtual runner's body visibility on participants' team perceptions ($\chi^2[2] = 3.73, p = .16$).

Ability Discrepancy: We observed no significant effects for Ability Discrepancy ($F[2,10] = 0.12, p = .89$) from one-way repeated measures ANOVA. None of the participants mentioned the discrepancy between the virtual partner and themselves in the interviews.

Cadence Coordination: The participants' average cadence was slower than the virtual partner's cadence (180 steps per minute) in all conditions. The difference between the participants' cadence and virtual partner's cadence was the largest in the full-body condition ($M = 8.08, SD = 7.45$) compared to both point-light ($M = 7.67, SD = 8.21$) and limb-only conditions ($M = 7.67, SD = 9.35$), but these comparisons were not statistically significant ($p>.05$).

7.2 Exploring Factors Affecting Jogging Experience with a Virtual Runner

The following sections detail the results from the inductive analysis of the post-experiment interviews. The analysis revealed three themes related to the jogging experience with a virtual partner that were not part of the deductive analysis described above: *attractiveness* and *synchronization.*

7.2.1 Attractiveness

The interview analysis revealed that the participants' experiences were affected by how attractive the virtual partner design was. That is, the level of visual richness may have affected how much attention the participants paid to the avatar, but at the same time they were also concerned about their safety when jogging with a rich virtual partner design.

Six participants sometimes unconsciously ignored the virtual runners. Especially limb-only and point-light runners were deprecated: "*When it was just dots or limbs, I honestly did not feel much different than usual, like just popping up in my vision and disappearing.*" *[P4]*

Four participants reported that the full-body runner attracted their attention and sometimes prevented them from checking their surroundings, making them feel unsafe. On the other hand, limb-only and point-light runners made them feel that they had better visibility: "*[The virtual runner of] hands and feet was the easiest to run because I could run while checking my surroundings.*" *[P9]*

7.2.2 Synchronization

There were five participants who matched their movements to the avatars: "*When I ran, the hands and feet in the video would run, so I'd get into a rhythm with the guy.*" *[P1]*
On the other hand, four participants also wanted the avatar to work with their motions to improve their jogging form: "*If there were a system that could detect the misalignment, it might make people think about running with more correct form.*" *[P5]*
The limb-only and the point-light avatars' motions often gave the illusion of being linked to three participants themselves: "*I felt as if it [point-light] was running along with my rhythm.*" *[P11]*
"*The limbs did not feel much like a person, but when I slowed down because I was tired, [the limbs] slowed down too.*" *[P2]*

8 Discussion

Overall, the results from our two studies suggested that virtual avatars can elicit team perceptions in casual joggers, and increase their enjoyment over solitary jogging. In outdoor settings, joggers' enjoyment was the highest with a rich full-body avatar compared to reduced point-light or limb-only avatar designs. However, our results also showed that a human is still superior to a virtual avatar as a jogging partner, and future studies should investigate ways to improve on the virtual avatar designs.

8.1 Jogging Experiences with a Virtual Runner

The results from the quantitative evaluation in Study 1 suggested that jogging with a virtual runner can be more enjoyable and more engaging than solitary jogging. The higher enjoyment measured on the IMI scale also suggests a higher level of intrinsic motivation when jogging with a virtual partner compared to solitary jogging (Fig. 2). Our results regarding improved enjoyment compared to solitary exercise also run parallel with previous exergaming literature [8,44] regardless that the virtual partner in our study could hardly interact with the participants in a real environment or in an attractive virtual world. However, comments from the participants also hinted that a short run in an unfamiliar place and in an unrealistic setting of a gymnasium may have led them to be distracted by their surroundings when running alone, whereas they only had to focus on the partner presence when running with a human or a virtual partner.

The participants perceived a greater ability discrepancy when jogging with the human partner compared to a virtual partner. This may be due to the additional cues (e.g., sound of footsteps) for recognizing the partner's performance which were not available for the virtual partner. Besides the competitive pressure, the human partner also affected the jogger's cadence, where similarly to a previous study [75] entrainment may have occurred due to the sound of footsteps. However, the participants also perceived the virtual partner as slightly superior to them, that is, even with the distance being constant and the absence of footsteps. This upward social comparison may be partially explained by one of the mechanisms of the Köhler effect, but further investigation is required.

Our results also suggested that the participants perceived their human partner more strongly as their teammate compared to the virtual partner. This result was not consistent with the results of a previous study [16] which compared exercising with low-fidelity humanoid avatars or a real human partner. As opposed to our results, this previous study did not find a significant difference between the avatar and human partner in terms of team perceptions, and the discrepancy may be explained by the experiment setting. In the study by Feltz et al. [16], the participants shared individual basic information (e.g., name, hometown, what you like to do for fun) with their partner, but in our experiment, only the human partner (experimenter) gave a self-introduction.

A virtual runner may be a suitable partner for both sedentary people who do not have exercise habits as well as casual joggers. The results from the quantitative evaluation in Study 1 suggested that the virtual runner provided enjoyment to the jogger, but did not put pressure on them or increase their perceived exertion or mental and physical workload. Results from Study 2 further suggested that the full body avatar design, as opposed to reduced limb-only or point-light avatars, lead to the highest level of enjoyment for the joggers. Moreover, jogging with the virtual runner may lead their jogging cadence to match that of the ideal cadence of the avatar, and thus, reduce the risk of injuries [15]. Comments from the post-experiment interviews in our two studies suggested that the participants often matched the movements of the avatar. Therefore, the virtual runner can be expected to encourage jogging habit while having fun.

8.2 Designing Virtual Runners as Partners for Solitary Casual Joggers

Based on our analyses from both Study 1 and Study 2, we identified two dimensions for designing virtual runners: Level of Visual Attractiveness and Synchronization in Movement. While these design dimensions should be understood as a proposal based on the initial studies, future investigations, such as longitudinal studies, may provide further insights that lead to a revision of the dimensions. In the following section, summarize the design guidelines under these dimensions.

8.2.1 Level of Visual Attractiveness

Guideline 1: Design for virtual jogging partner to balance jogger enjoyment and safety by matching body visibility to environmental conditions.

Our results suggested that joggers can adaptively choose how they view their virtual partner's body visualization in response to environmental information, thus expanding the possibilities of avatar design. Indoors, where the virtual partner was clearly visible, the participants' motivation increased even when body visibility was lowered. On the other hand, when the participants were outdoors during the day, their motivation increased when the body visibility was higher. As observed from the participants' comments, this may be due to the fact that it was not always possible to see the virtual partner outdoors during the day. When the contrast between the background environment and the virtual partner is sufficient, or when there are pedestrians or obstacles to watch, it may be possible to design a safer jogging experience by lowering the visibility. Also, in situations such as running on a well-developed running course in the middle of a sunny day, a full-body avatar can be used to make the virtual partner more visible, which can be expected to increase motivation.

8.2.2 Synchronization in Movement

Guideline 2: Design for synchronization in movement with virtual partner to improve jogging form

Some participants responded that they wanted the avatar to match their movements in order to check their performance. Interestingly, few participants in both studies also thought that the avatar moved according to their movements, and they may have unintentionally matched their cadence with that of the avatar considering that jogging is a simple rhythmic motion. Displaying the avatar movements as matching the jogger's movement is reasonable because creating an external visual image that observes oneself from another person's point of view can lead to performance improvement. For safety reasons during outdoor jogging, a motion capture system using a wearable camera (e.g., [30, 81]) or IMU sensors should be adopted.

8.3 Future Work and Limitations

In both studies, we recruited participants who "were able to jog safely for 30 minutes", that is, people who could be considered at least casual joggers. The reason for this was that our target users are casual joggers as well as sedentary people, and we aimed to recruit participants who were at least casual joggers to limit potential injuries caused by the jogging exercise. However, we could not ascertain their actual level of jogging experience, even though the participants were inquired how often they jog. Moreover, experienced joggers may provide different feedback from casual joggers and sedentary people, and while out of the scope of our research, their experiences should be examined in future works.

Different users may focus on different body parts, such as legs only or the arm swing, exclusively. In our two studies, we based the three avatar designs on previous research, but it is unclear whether these designs represent the minimal standard for inducing motivation during jogging. That is, future works should investigate, for example, whether a lower/upper body only avatar designs or showing only the footprints of an avatar would also be practical for balancing jogger motivation and safety. Furthermore, as displaying a completely opaque avatars on optical see-through displays is not possible with current technology, future works should investigate the effects of avatar opacity on joggers' experience with video see-through head-mounted displays while considering the trade-offs with user comfort and limited FOV compared to smartglasses as in our two studies.

Lastly, we employed smartglasses without AR functionality to display the virtual avatar in our two studies. Hence, presenting the jogging speed of the avatar and distance from the user were difficult to implement. In order to measure the Köhler effect beyond joggers' cadence, future works should implement these factors using smartglasses hardware with AR functionality.

9 Conclusion

We evaluated a jogging experience with a virtual runner with three body types: full-body, point-light, and limb-only avatar. The results from our two experiments showed the potential of a virtual jogging partner as a motivator for solitary casual joggers as well as sedentary people, and highlighted the trade-offs between jogger's enjoyment and safety considering the virtual partner body visibility. Based on the results of our quantitative analyses and participant interviews, we present three design guidelines for future virtual jogging partners.

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References

[1] Find a running partner. https://joggingbuddy.com/.

[2] The ghost pacer. https://ghostpacer.com/.

[3] Google glass for fitness - race yourself - virtual reality fitness motivation. https://www.youtube.com/watch?v=39W6CMpdGsM.

[4] Adobe. Mixamo. https://www.mixamo.com/.

[5] C. Anderson-Hanley, A. L. Snyder, J. P. Nimon, and P. J. Arciero. Social facilitation in virtual reality-enhanced exercise: competitiveness moderates exercise effort of older adults. *Clinical interventions in aging*, 6:275–80, 2011. doi: 10.2147/CIA.S25337

[6] S. C. Barathi, D. J. Finnegan, M. Farrow, A. Whaley, P. Heath, J. Buckley, P. W. Dowrick, B. C. Wuensche, J. L. J. Bilzon, E. O'Neill, and C. Lutteroth. Interactive feedforward for improving performance and maintaining intrinsic motivation in vr exergaming. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pp. 408:1–408:14. ACM, New York, NY, USA, 2018. doi: 10.1145/3173574.3173982

[7] A. T. Bayrak, R. Kumar, J. Tan, D. AhMu, J. Hohepa, L. A. Shaw, C. Lutteroth, and B. C. Wünsche. Balancing different fitness levels in competitive exergames based on heart rate and performance. In *Proceedings of the 29th Australian Conference on Computer-Human Interaction - OZCHI '17*, pp. 210–217. ACM Press, New York, New York, USA, 2017. doi: 10.1145/3152771.3152794

[8] R. M. Baños, P. Escobar, A. Cebolla, J. Guixeres, J. Alvarez Pitti, J. F. Lisón, and C. Botella. Using virtual reality to distract overweight children from bodily sensations during exercise. *Cyberpsychology, Behavior, and Social Networking*, 19(2):115–119, 2016. PMID: 26882326. doi: 10.1089/cyber.2015.0283

[9] T. Bi, N. Bianchi-Berthouze, A. Singh, and E. Costanza. Understanding the shared experience of runners and spectators in long-distance running events. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–13. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3290605.3300691

[10] F. Biocca, C. Harms, and J. Gregg. The networked minds measure of social presence: Pilot test of the factor structure and concurrent validity. *4th annual International Workshop on Presence, Philadelphia*, 01 2001.

[11] G. A. Borg. Psychophysical bases of perceived exertion. *Medicine & science in sports & exercise*, 1982.

[12] R. B. Clancy, M. P. Herring, and M. J. Campbell. Motivation measures in sport: A critical review and bibliometric analysis. *Frontiers in Psychology*, 8:348, 2017. doi: 10.3389/fpsyg.2017.00348

[13] E. E. A. Cohen, R. Ejsmond-Frey, N. Knight, and R. I. M. Dunbar. Rowers' high: behavioural synchrony is correlated with elevated pain thresholds. *Biology Letters*, 6(1):106–108, 2010. doi: 10.1098/rsbl.2009.0670

[14] F. Curmi, M. A. Ferrario, J. Whittle, and F. F. Mueller. Crowdsourcing synchronous spectator support: (go on, go on, you're the best)n-1. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, p. 757–766. Association for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2702123.2702338

[15] J. Daniels. *Daniels' running formula [proven programs 800 m to the marathon]*. Human Kinetics, 2005.

[16] D. L. Feltz, S. T. Forlenza, B. Winn, and N. L. Kerr. Cyber Buddy Is Better than No Buddy: A Test of the Köhler Motivation Effect in Exergames. *Games for Health Journal*, 3(2):98–105, apr 2014. doi: 10.1089/g4h.2013.0088

[17] D. L. Feltz, N. L. Kerr, and B. C. Irwin. Buddy up: the Köhler effect applied to health games. *Journal of sport & exercise psychology*, 33(4):506–26, aug 2011.

[18] S. T. Forlenza, N. L. Kerr, B. C. Irwin, and D. L. Feltz. Is My Exercise Partner Similar Enough? Partner Characteristics as a Moderator of the Köhler Effect in Exergames. *Games for Health Journal*, 1(6):436–441, dec 2012. doi: 10.1089/g4h.2012.0047

[19] J. Fortmann, M. Pielot, M. Mittelsdorf, M. Büscher, S. Trienen, and S. Boll. Paceguard: Improving running cadence by real-time auditory feedback. In *Proceedings of the 14th International Conference on Human-Computer Interaction with Mobile Devices and Services Companion*, MobileHCI '12, p. 5–10. Association for Computing Machinery, New York, NY, USA, 2012. doi: 10.1145/2371664.2371668

[20] R. Guthold, G. A. Stevens, L. M. Riley, and F. C. Bull. Worldwide trends in insufficient physical activity from 2001 to 2016: a pooled analysis of 358 population-based surveys with 1·9 million participants. *The Lancet Global Health*, 6(10):e1077 – e1086, 2018. doi: 10.1016/S2214-109X(18)30357-7

[21] T. Hamada, A. Hautasaari, M. Kitazaki, and N. Koshizuka. Exploring the effects of a virtual companion on solitary jogging experience. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 638–639, 2020. doi: 10.1109/VRW50115.2020.00170

[22] T. Hamada, M. Kitazaki, and N. Koshizuka. Social facilitation with virtual jogging companion on smartglasses. In *SIGGRAPH Asia 2018 Posters*, SA '18. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3283289.3283351

[23] T. Hamada, M. Okada, and M. Kitazaki. Jogging with a virtual runner using a see-through hmd. In *2017 IEEE Virtual Reality (VR)*, pp. 445–446, 2017. doi: 10.1109/VR.2017.7892371

[24] S. G. Hart and L. E. Staveland. Development of nasa-tlx (task load index): Results of empirical and theoretical research. In P. A. Hancock and N. Meshkati, eds., *Human Mental Workload*, vol. 52 of *Advances in Psychology*, pp. 139 – 183. North-Holland, 1988. doi: 10.1016/S0166-4115(08)62386-9

[25] M. Hassan, F. Daiber, F. Wiehr, F. Kosmalla, and A. Krüger. Footstriker: An ems-based foot strike assistant for running. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 1(1), Mar. 2017. doi: 10.1145/3053332

[26] P. Heidicker, E. Langbehn, and F. Steinicke. Influence of avatar appearance on presence in social vr. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 233–234, 2017.

[27] G. Hertel, N. L. Kerr, and L. A. Messé. Motivation gains in performance groups: Paradigmatic and theoretical developments on the köhler effect. *Journal of personality and social psychology*, 79(4):580, 2000.

[28] C. Ho, K. F. MacDorman, and Z. A. D. Pramono. Human emotion and the uncanny valley: A glm, mds, and isomap analysis of robot video ratings. In *2008 3rd ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pp. 169–176, 2008.

[29] C. P. Hoffmann, A. Filippeschi, E. Ruffaldi, and B. G. Bardy. Energy management using virtual reality improves 2000-m rowing performance. *Journal of Sports Sciences*, 32(6):501–509, apr 2014. doi: 10.1080/02640414.2013.835435

[30] D.-H. Hwang, K. Aso, Y. Yuan, K. Kitani, and H. Koike. *MonoEye: Multimodal Human Motion Capture System Using A Single Ultra-Wide Fisheye Camera*, p. 98–111. Association for Computing Machinery, New York, NY, USA, 2020.

[31] C. Ioannou, P. Archard, E. O'Neill, and C. Lutteroth. Virtual Performance Augmentation in an Immersive Jump & Run Exergame. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, pp. 1–15. ACM Press, New York, New York, USA, 2019. doi: 10.1145/3290605.3300388

[32] B. C. Irwin, J. Scorniaenchi, N. L. Kerr, J. C. Eisenmann, and D. L. Feltz. Aerobic Exercise Is Promoted when Individual Performance Affects the Group: A Test of the Kohler Motivation Gain Effect. *Annals of Behavioral Medicine*, 44(2):151–159, oct 2012. doi: 10.1007/s12160-012-9367-4

[33] G. Johansson. Visual perception of biological motion and a model for its analysis. *Perception & Psychophysics*, 14(2):201–211, Jun 1973. doi: 10.3758/BF03212378

[34] N. L. Kerr and G. Hertel. The Köhler Group Motivation Gain: How to Motivate the 'Weak Links' in a Group. *Social and Personality Psychology Compass*, 5(1):43–55, jan 2011. doi: 10.1111/j.1751-9004.2010.00333.x

[35] K. Knaving, P. Woźniak, M. Fjeld, and S. Björk. Flow is not enough: Understanding the needs of advanced amateur runners to design motivation technology. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pp. 2013–2022. ACM, New York, NY, USA, 2015. doi: 10.1145/2702123.2702542

[36] R. Kondo, M. Sugimoto, K. Minamizawa, T. Hoshi, M. Inami, and

M. Kitazaki. Illusory body ownership of an invisible body interpolated between virtual hands and feet via visual-motor synchronicity. *Scientific Reports*, 8(1):7541, dec 2018. doi: 10.1038/s41598-018-25951-2

[37] J. Koulouris, Z. Jeffery, J. Best, E. O. Neill, and C. Lutteroth. Me vs . Super (wo) man : Effects of Customization and Identification in a VR Exergame. 2020:1–16, 2020.

[38] M. E. Latoschik, D. Roth, D. Gall, J. Achenbach, T. Waltemate, and M. Botsch. The effect of avatar realism in immersive social virtual realities. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, VRST '17. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3139131.3139156

[39] K. Lu and A. Brombacher. Haptic feedback in running: Is it possible for information transfer through electrical muscle signalling? In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '20, p. 479–485. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3374920.3374976

[40] E. J. Max, S. Samendinger, B. Winn, N. L. Kerr, K. A. Pfeiffer, and D. L. Feltz. Enhancing Aerobic Exercise with a Novel Virtual Exercise Buddy Based on the Köhler Effect. *Games for Health Journal*, 5(4):252–257, aug 2016. doi: 10.1089/g4h.2016.0018

[41] E. D. McAuley, T. Duncan, and V. V. Tammen. Psychometric properties of the intrinsic motivation inventoiy in a competitive sport setting: A confirmatory factor analysis. *Research Quarterly for Exercise and Sport*, 60(1):48–58, 1989. doi: 10.1080/02701367.1989.10607413

[42] L. A. Messé, G. Hertel, N. L. Kerr, R. B. Lount, and E. S. Park. Knowledge of partner's ability as a moderator of group motivation gains: an exploration of the köhler discrepancy effect. *Journal of personality and social psychology*, 82(6):935—946, June 2002. doi: 10.1037//0022-3514.82.6.935

[43] A. Michael and C. Lutteroth. Race Yourselves : A Longitudinal Exploration of Self-Competition Between Past , Present , and Future Performances in a VR Exergame. 2020, 2020.

[44] J. Monedero, E. J. Lyons, and D. J. O'Gorman. Interactive video game cycling leads to higher energy expenditure and is more enjoyable than conventional exercise in adults. *PLOS ONE*, 10(3):1–12, 03 2015. doi: 10.1371/journal.pone.0118470

[45] W. P. Morgan and M. L. Pollock. Psychologic characterization of the elite distance runner. *Annals of the New York Academy of Sciences*, 301(1):382–403, 1977. doi: 10.1111/j.1749-6632.1977.tb38215.x

[46] M. Mori, K. F. MacDorman, and N. Kageki. The uncanny valley [from the field]. *IEEE Robotics Automation Magazine*, 19(2):98–100, 2012.

[47] F. Mueller, F. Vetere, M. R. Gibbs, D. Edge, S. Agamanolis, and J. G. Sheridan. Jogging over a distance between europe and australia. In *Proceedings of the 23nd Annual ACM Symposium on User Interface Software and Technology*, UIST '10, p. 189–198. Association for Computing Machinery, New York, NY, USA, 2010. doi: 10.1145/1866029.1866062

[48] F. F. Mueller and M. Muirhead. Jogging with a quadcopter. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pp. 2023–2032. ACM, New York, NY, USA, 2015. doi: 10.1145/2702123.2702472

[49] E. G. Murray, D. L. Neumann, R. L. Moffitt, and P. R. Thomas. The effects of the presence of others during a rowing exercise in a virtual reality environment. *Psychology of Sport and Exercise*, 22:328–336, jan 2016. doi: 10.1016/J.PSYCHSPORT.2015.09.007

[50] C. Nass, B. Fogg, and Y. Moon. Can computers be teammates? *International Journal of Human-Computer Studies*, 45(6):669–678, dec 1996. doi: 10.1006/IJHC.1996.0073

[51] Nike. Nike run club app. `https://www.nike.com/nrc-app`.

[52] M. Nunes, L. Nedel, and V. Roesler. Motivating people to perform better in exergames: Competition in virtual environments. In *Proceedings of the ACM Symposium on Applied Computing*, pp. 970–975. Association for Computing Machinery, New York, New York, USA, 2014. doi: 10.1145/2554850.2555009

[53] S. Nylander, M. Jacobsson, and J. Tholander. Runright: Real-time visual and audio feedback on running. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '14, p. 583–586. Association for Computing Machinery, New York, NY, USA, 2014. doi: 10.1145/2559206.2574806

[54] N. Oliver and F. Flores-Mangas. Mptrain: A mobile, music and physiology-based personal trainer. In *Proceedings of the 8th Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '06, p. 21–28. Association for Computing Machinery, New York, NY, USA, 2006. doi: 10.1145/1152215.1152221

[55] B. Reeves and C. Nass. *The Media Equation: How People Treat Computers, Television, and New Media like Real People and Places*. Cambridge University Press, USA, 1996.

[56] A. Romanowski, S. Mayer, L. Lischke, K. Grudzień, T. Jaworski, I. Perenc, P. Kucharski, M. Obaid, T. Kosizski, and P. W. Wozniak. Towards supporting remote cheering during running races with drone technology. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '17, p. 2867–2874. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3027063.3053218

[57] R. M. Ryan. Control and information in the intrapersonal sphere: An extension of cognitive evaluation theory. *Journal of Personality and Social Psychology*, 43(3):450–461, 1982. doi: 10.1037/0022-3514.43.3.450

[58] R. M. Ryan and E. L. Deci. Intrinsic and extrinsic motivations: Classic definitions and new directions. *Contemporary Educational Psychology*, 25(1):54 – 67, 2000. doi: 10.1006/ceps.1999.1020

[59] R. M. Ryan, C. M. Frederick, D. Lepes, R. Noel, and K. M. Sheldon. Intrinsic motivation and exercise adherence. *International Journal of Sport Psychology*, 28(4):335–354, 1997.

[60] S. Samendinger, C. R. Hill, N. L. Kerr, B. Winn, A. Ede, J. M. Pivarnik, L. Ploutz-Snyder, and D. L. Feltz. Group dynamics motivation to increase exercise intensity with a virtual partner. *Journal of Sport and Health Science*, aug 2018. doi: 10.1016/J.JSHS.2018.08.003

[61] Schwinn. Explore the world app. `https://global.schwinnfitness.com/en/app.html`.

[62] J. Schüler and S. Brunner. The rewarding effect of flow experience on performance in a marathon race. *Psychology of Sport and Exercise*, 10(1):168 – 174, 2009. doi: 10.1016/j.psychsport.2008.07.001

[63] L. A. Shaw, J. Buckley, P. M. Corballis, C. Lutteroth, and B. C. Wuensche. Competition and cooperation with virtual players in an exergame. *PeerJ Computer Science*, 2:e92, Oct. 2016. doi: 10.7717/peerj-cs.92

[64] L. A. Shaw, R. Tourrel, B. C. Wunsche, C. Lutteroth, S. Marks, and J. Buckley. Design of a virtual trainer for exergaming. In *Proceedings of the Australasian Computer Science Week Multiconference*, ACSW '16. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2843043.2843384

[65] R. Shipway, I. Holloway, and I. Jones. Organisations, practices, actors, and events: Exploring inside the distance running social world. *International Review for the Sociology of Sport*, 48(3):259–276, 2013. doi: 10.1177/1012690212442135

[66] A. L. Snyder, C. Anderson-Hanley, and P. J. Arciero. Virtual and live social facilitation while exergaming: Competitiveness moderates exercise intensity. *Journal of Sport and Exercise Psychology*, 34(2):252 – 259, 2012.

[67] Spotify. Listening is everything. `https://www.spotify.com/us/`.

[68] I. D. Steiner. *Group process and productivity*. Number . A series of monographs, treatises, and the texts in Social psychology. Academic Press, 1972.

[69] M. J. Strube, M. E. Miles, and W. H. Finch. The social facilitation of a simple task: Field tests of alternative explanations. *Personality and Social Psychology Bulletin*, 7(4):701–707, 1981. doi: 10.1177/014616728174030

[70] C. T. Tan, R. Byrne, S. Lui, W. Liu, and F. Mueller. Joggar: A mixed-modality ar approach for technology-augmented jogging. In *SIGGRAPH Asia 2015 Mobile Graphics and Interactive Applications*, SA '15, pp. 33:1–33:1. ACM, New York, NY, USA, 2015. doi: 10.1145/2818427.2818434

[71] S. to Start & Naomi Alderman. Zombies, run! `https://zombiesrungame.com/`.

[72] J. Tominaga, K. Kawauchi, and J. Rekimoto. Around me: A system with an escort robot providing a sports player's self-images. In *Proceedings of the 5th Augmented Human International Conference*, AH '14. Association for Computing Machinery, New York, NY, USA, 2014. doi: 10.1145/2582051.2582094

[73] S. Tregillus and E. Folmer. Vr-step: Walking-in-place using inertial sensing for hands free navigation in mobile vr environments. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pp. 1250–1255. ACM, New York, NY, USA, 2016. doi: 10.1145/2858036.2858084

[74] N. Triplett. The dynamogenic factors in pacemaking and competition. *The American journal of psychology*, 9(4):507–533, 1898.

[75] E. Van Dyck, B. Moens, J. Buhmann, M. Demey, E. Coorevits, S. Dalla Bella, and M. Leman. Spontaneous entrainment of running cadence to music tempo. *Sports medicine-open*, 1(1):15, 2015.

[76] Whatever. Nike unlimited stadium. `https://whatever.co/work/nike-unlimited-stadium/`.

[77] E. Witkowski. Running from zombies. In *Proceedings of The 9th Australasian Conference on Interactive Entertainment: Matters of Life and Death*, IE '13, pp. 1:1–1:8. ACM, New York, NY, USA, 2013. doi: 10.1145/2513002.2513573

[78] C. J. Worringham and D. M. Messick. Social facilitation of running: An unobtrusive study. *The Journal of Social Psychology*, 121(1):23–29, 1983. PMID: 6645421. doi: 10.1080/00224545.1983.9924462

[79] P. Woźniak, K. Knaving, S. Björk, and M. Fjeld. Rufus: Remote supporter feedback for long-distance runners. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '15, p. 115–124. Association for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2785830.2785893

[80] B. Yoon, H. Kim, G. A. Lee, M. Billinghurst, and W. Woo. The effect of avatar appearance on social presence in an augmented reality remote collaboration. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 547–556, 2019.

[81] Y. Yuan and K. Kitani. Ego-pose estimation and forecasting as real-time pd control. In *2019 IEEE/CVF International Conference on Computer Vision (ICCV)*, pp. 10081–10091, 2019. doi: 10.1109/ICCV.2019.01018

[82] Z. Zhao, A. Arya, A. Whitehead, G. Chan, and S. A. Etemad. Keeping users engaged through feature updates: A long-term study of using wearable-based exergames. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, pp. 1053–1064. ACM, New York, NY, USA, 2017. doi: 10.1145/3025453.3025982

[83] Zwift. Indoor virtual running workouts & training. `https://www.zwift.com/en/run`.