Breaking the Isolation: Exploring the Impact of Passthrough in Shared Spaces on Player Performance and Experience in VR Exergames

Zixuan Guo, Hongyu Wang, Hanxiao Deng, Wenge Xu, Nilufar Baghaei, Cheng-Hung Lo and Hai-Ning Liang

Abstract

VR exergames offer an engaging solution to combat sedentary behavior and promote physical activity. However, challenges emerge when playing these games in shared spaces, particularly due to the presence of bystanders. VR's passthrough functionality enables players to maintain awareness of their surrounding environment while immersed in VR gaming, rendering it a promising solution to improve users' awareness of the environment. This study investigates the passthrough's impact on player performance and experiences in shared spaces, involving an experiment with 24 participants that examines Space (Office vs. Corridor) and Passthrough Function (With vs. Without). Results reveal that Passthrough enhances game performance and environmental awareness while reducing immersion. Players prefer an open area to an enclosed room, whether with or without Passthrough, finding it more socially acceptable. Additionally, Passthrough appears to encourage participation among players with higher self-consciousness, potentially alleviating their concerns about being observed by bystanders. Our findings provide valuable insights for designing VR experiences in shared spaces, underscoring the potential of VR's passthrough to enhance user experiences and promote VR adoption in these environments.

Keywords: Passthrough functionality, VR exergames, shared spaces

1 Introduction

In addressing the prevalent concern of sedentary behaviors, VR exergames offer an innovative solution by integrating physical activity with immersive experiences, enhancing people's enjoyment and engagement with physical exercise [1] that can be tailored for various population groups [2–5]. While VR exergames have gained widespread popularity in private spaces, their adoption in shared spaces, such as offices, university campuses, or shopping centers, presents unique challenges. Due to the immersive nature of VR, players are isolated from their surroundings, leading to increased concerns within these environments. These concerns encompass safety worries associated with extensive movement, as well as psychological pressure and privacy issues due to the presence of bystanders [6–8].

One of the key distinctions between shared and private spaces lies in the presence of bystanders—individuals who are physically close to a VR user but cannot directly interact with their virtual environment [7, 9]. Even when simply being observed, the presence of bystanders has been shown to alter the behavior and experience of VR users [8, 10]. While some research [11] has suggested that bystanders do not significantly affect VR users, a substantial body of evidence [12–14] indicates that bystanders can indeed lead to reduced performance and a less enjoyable VR experience, primarily due to distractions and increased cognitive load.

To better assist users in utilizing VR within shared spaces, various methods [9, 10, 12, 15–20] have been proposed to heighten player awareness of the real environment, with Passthrough emerging as a promising option. Serving as a bridge between the virtual and physical worlds, Passthrough allows users to observe their immediate physical surroundings while engaged in VR activities, facilitated by a live video feed accessed through the VR headset's camera system [21, 22]. However, while previous research[9, 10, 12, 15–17] mainly delves into Passthrough aiding transitions between virtual and real environments, its impact on player performance and experience remains an ongoing area of study. The potential of Passthrough to address challenges encountered by players in shared spaces through enhanced visibility toward surroundings has yet to be fully explored.

Moreover, previous research focused on shared spaces lacks exploration into the types of spaces, the status of bystanders, and the personalities of participants, all of which are crucial factors influencing players' use of VR in these environments. Firstly, prior research [11–14] mainly focused on either enclosed rooms or open areas, where bystander behaviors differ significantly. Enclosed rooms tend to exhibit more stable behaviors (e.g., working), while open areas show greater dynamism (e.g., walking) [14, 23]. However, current research is limited to exploring different shared spaces, leading to an incomplete understanding of how these spaces and bystander states might impact VR users. Additionally, individuals' self-consciousness, or how they perceive themselves, may influence their reactions to being observed in this context [24, 25]. Those with higher self-consciousness often worry more about others' judgments and may experience increased anxiety when observed, impacting their performance and emotions [26], an aspect that has received insufficient attention in existing research.

Our work addresses these gaps by investigating how the Passthrough functionality influences player performance and experiences during VR exergaming in different shared spaces. In various Passthrough designs, Passthrough Augmented Reality (PAR) stands out as a favored and effective method, allowing uninterrupted gameplay [9], hence chosen for our experiment. We conducted a 2×2 within-subjects experiment with 24 participants, examining the effects of Space (Office vs. Corridor) and

Passthrough Function (With vs. Without). In both spatial contexts, 3 experimenters acted as bystanders with different tasks. Results indicate that Passthrough enhances gaming performance in shared spaces. Despite a potential decrease in immersion, more participants prefer using this feature in shared spaces for its perceived security and environmental awareness. Participants reported that, in comparison to enclosed spaces, they felt more socially accepted in open areas when using VR exergames, whether the Passthrough feature was enabled or disabled. This is attributed to the perception that engaging in VR exergames in enclosed spaces tends to attract prolonged attention from others. Regarding self-consciousness, we found that players with higher levels of self-consciousness perceived themselves as performing better and being more socially accepted when using Passthrough and in open spaces. This study holds significant implications for the design and implementation of VR technologies in shared spaces, as it provides insights into how Passthrough can be leveraged to create safer and more socially comfortable VR experiences.

2 Related Work

2.1 Challenges of Using VR in Shared Spaces

The widespread development of VR technology has extended its reach into shared spaces, ushering in more possibilities but also with complex challenges. The primary challenge is the presence of bystanders [8]. VR users may find themselves under social pressure, with concerns arising about how bystanders perceive their engagement with VR technology [27]. Meanwhile, the actions and reactions of VR users within the virtual environment are on full display, prompting individuals to ponder how these bystanders judge their interactions [28, 29].

Moreover, the user's detachment from the real environment gives rise to privacy concerns. In shared spaces, there exists the risk of unauthorized recording through smartphones or other recording devices from fellow occupants [10, 27]. This recording could capture the user's actions, interactions, and even their emotional responses within the VR environment, all without their consent or awareness [9, 10].

Using VR in shared spaces also introduces safety considerations. When users put on VR headsets, they become unaware of their physical surroundings, leading to a sensory disconnect from reality that can result in unintended accidents [6, 30, 31]. Due to the mismatch between the virtual world and the physical reality, users may accidentally collide with physical obstacles or other individuals [32]. Similarly, bystanders in the same spaces may encounter unpredictable behaviors from users, potentially resulting in misunderstandings or inadvertent interactions [6].

In conclusion, the integration of VR into shared spaces is accompanied by challenges related to the presence of bystanders and privacy and safety concerns. As VR technology continues to advance, addressing these challenges will be necessary to fully unleash the potential of VR for broader utilization across various environments.

2.2 Bystander Influence and Self-consciousness

Understanding the impact of bystanders on VR users is crucial for enhancing the overall usability and acceptance of VR in shared spaces. O'Hagan et al. [10] classified VR user and bystander interactions into three categories: coexisting, demoing, and interrupting. Demoing involves intentional and guided interaction, while coexisting and interrupting typically represent the bystander's interaction with the VR user during VR use. These interactions have the potential to shape the user's perception of the environment, affect their experience, and even influence their sense of privacy and safety.

Coexisting represents the most prevalent interaction scenario, encompassing behaviors like overlooking VR users, observing their activity, and direct engagement. Many studies [9, 13, 33, 34] indicate that even in scenarios where bystanders remain silent, their mere presence tends to impact VR users, often resulting in adverse effects on the users' awareness of them. For instance, Knibbe et al. [33] highlighted discomfort among VR users upon realizing the presence of silent bystanders in the room. In cognitive tasks, Rettinger et al. [13] noted that when bystanders move quietly and naturally, it substantially increases the cognitive load on VR users.

Interruptions, such as physical contact and verbal communication, have a more pronounced impact compared to coexistence, occasionally surprising VR users [10, 34, 35]. For example, Gottsacker et al. [16] suggested that interruptions might disrupt the sense of presence, affecting the sense of location and believability illusions, potentially reducing performance in virtual tasks. Moreover, the acceptability of interruptions is largely influenced by the relationship between bystanders and VR users [34].

When considering the impact of bystanders, it is essential to involve the space where bystanders interact with VR users. Many studies [11, 12, 12–14] have explored the impact of the presence of bystanders on VR users across various shared spaces, including enclosed rooms (e.g., laboratory) and open areas (e.g., hallway and plaza). For example, in a laboratory setting, McGill et al. [12] explored the presentation of bystanders in VR and found that as users become more aware of the presence of bystanders, they tend to become more distracted. Furthermore, Vergari et al. [14] suggested that more bystanders and closer proximity to VR users in parks and plazas can raise privacy and safety concerns, causing distractions, restricted movements, and embarrassment. Interestingly, they also found that using highly interactive VR applications (e.g., exergames) in shared spaces resulted in a better user experience, despite safety concerns, compared to low-interactivity applications (e.g., target selection game). In contrast to the findings of these studies, Mai et al. [11] found that users were generally comfortable with VR in both empty rooms and open areas (i.e., hallway) with bystanders. Cognitive concerns related to the presence of bystanders primarily impacted the initial minutes of the user experience.

Furthermore, accounting for self-consciousness becomes crucial in addressing bystander interactions, given its significant correlation with individual reactions [24]. Self-consciousness in our work refers to individuals' awareness of their thoughts, emotions, and actions in social contexts [25]. It entails a heightened focus on how others perceive them and concerns about social evaluation. Several studies [26, 36, 37] have explored the connection between self-consciousness and performance in various activities (e.g., sports and gaming) when individuals are in shared spaces. Generally, those with higher self-consciousness tend to experience increased anxiety and decreased performance when around others [26].

Given that coexisting is the most common type of bystander interaction, less affected by the interpersonal dynamics between bystanders and VR users, this study focuses on exploring interactions within this category. Current research generally acknowledges the adverse effects of bystanders on VR users' performance and experience. However, these studies often focus on either enclosed rooms or open areas, overlooking potential distinctions in the states of bystanders within these two types of spaces. For instance, bystanders in laboratories and offices tend to be in static working states, coexisting with VR users for extended periods in the same physical space. On the other hand, bystanders in hallways and parks are more likely to be in a dynamic state, passing by VR users while in motion. Additionally, the influence of self-consciousness on users' responses to bystanders has not been adequately considered. In shared spaces, interactions with bystanders are unavoidable, making it essential to increase users' awareness of their physical surroundings to promote VR adoption. Hence, this paper aims to investigate the potential of Passthrough functionality in addressing this scenario within two distinct shared spaces and analyzing the impact of self-consciousness.

2.3 Passthrough Functionality for Enhanced Player Awareness in VR

Enhancing users' peripheral awareness of the physical environment is crucial in shaping the social acceptance of utilizing VR in shared spaces [38]. VR's Passthrough functionality has recently emerged as a crucial component in VR systems, allowing users to observe their physical surroundings while immersed in a virtual environment. This functionality leverages the headset's built-in cameras to capture a live stereo video feed of the user's physical environment, which is then seamlessly blended with the virtual content [21, 22, 39].

Passthrough functionality addresses the issue of VR isolating users from their surrounding environment, thereby offering benefits for the use of VR in shared spaces. One of the key benefits is enhanced safety. By providing users with a live view of their physical surroundings, Passthrough enables them to avoid obstacles and individuals in their vicinity, reducing the risk of collisions and accidents [20]. Furthermore, Passthrough technology mitigates some challenges associated with bystander influence in shared spaces. It allows VR users to maintain a level of situational awareness, even while immersed in virtual content, enabling them to respond to real-world cues and interactions [40].

In previous research [9, 10, 12, 15–17], three primary approaches have been proposed to enhance player awareness of their surrounding environment through Passthrough functionality, namely Passthrough Augmented Reality (PAR), Passthrough Transparent Augmented Reality (PTAR), and Full Passthrough and Pause (FPP). These approaches are designed as follows:

- **Passthrough Augmented Reality (PAR):** This approach involves transitioning to an AR version of the game, where only essential in-game objects are retained, and the rest are replaced with the Passthrough view.
- **Passthrough Transparent Augmented Reality (PTAR):** This approach switches to an AR version of the game with added transparency to the remaining content. Only essential game objects are preserved and made transparent, while the Passthrough view replaces everything else.
- **Full Passthrough and Pause (FPP):** This method entails switching to a complete Passthrough view while simultaneously pausing the game.

O'Hagan et al.'s [9] usability assessment sheds light on the effectiveness of these three Passthrough approaches. Their findings revealed that PAR stands out as the most effective in terms of usability and user experience. Conversely, PTAR might compromise immersion and introduce distractions, while FPP is deemed less favorable due to its interruption of the immersive gaming experience.

However, these studies primarily focused on Passthrough's usability and user experience as a method for transitioning users from the virtual environment to the real world. There has been limited exploration of its impact on player performance and experience. Enhancing player visibility of the real environment and bystanders in shared spaces may hold promise for addressing the challenges mentioned earlier, but our understanding in this regard remains limited. Given the outstanding usability demonstrated by PAR in past research [9], we have chosen this approach for further in-depth investigation in this paper.

3 Exergame Application

We developed a Fruit Ninja [1]-like game using the Unity3D engine, version 2021.3.26f1. To enable the game's functionality on the PICO 4, we employed two packages provided by PICO: PICO Integration and PICO Live Preview.

We selected the VR Fruit Ninja after carefully examining the literature for the different types of exergames available. The Fruit Ninja game and its variants have been employed in many studies [41–44] related to exergaming. Outside of research, one can find this game on various platforms, including VR; as such, it is widely available and accessible, with high popularity and reception [43]. Compared to rhythm games like Beat Saber [2] or boxing games like Creed: Rise to Glory [3], VR Fruit Ninja offers simpler gameplay with vibrant visuals, which allow it to cater to a wider range of players. In addition, the gameplay requires arm movements for slicing fruits, encouraging upper body activity, and its fast-paced nature promotes increased physical activity among players [42]. Our game also affords ways to add more elements that can enrich its gameplay and encourage greater exertion levels. For example, to enhance the players' overall physical activity, we introduced flying obstacles that would move toward the players who, in turn, would need to crouch to avoid hitting

[1] https://store.steampowered.com/app/486780/Fruit_Ninja_VR/
[2] https://store.steampowered.com/app/620980/Beat_Saber/
[3] https://store.steampowered.com/app/804490/Creed_Rise_to_Glory/

them. In addition, this game affords greater flexibility to adjust the environmental context. In our case, we used a Japanese-style classroom as our virtual scene.

All parameters detailed in this section were fine-tuned through an extensive playtesting phase involving game testers of 3 different heights (160cm, 174cm, 185cm) and varied exercise backgrounds (non-exercisers, occasional, frequent). The objective of the testing phase was to ensure our game could cater to the needs of the majority of players, achieving a range from mild to moderate levels of exercise.

3.1 Rules and Logic

As shown in Figure 1, players need to use two handheld controllers to wield virtual swords in the game. Their primary objective is to slice as many fruits (i.e., watermelon, apple, and lemon) as possible while skillfully avoiding incoming bombs and obstacles. The game dynamics involve launching fruits and bombs from both the left and right sides of the player, following a parabolic trajectory that ensures they land within the player's striking range, mirroring the iconic Fruit Ninja experience.

To ensure trajectory reliability, we initially fine-tuned the gravity to 2 following input from 3 game testers of varying heights. This adjustment effectively increased the targets' airborne duration. Additionally, we calibrated the initial velocities along the X (-0.35, 0.35), Y (3, 3.5), and Z (-3, -2) axes to limit the angle variance, enabling participants to consistently hit the targets within an approximate 1-square-meter area.

The obstacle in the game is a wooden horizontal bar (Figure 1). When players wear the HMD and enter the game, this bar is automatically adjusted to the height level of the player's eyes, accommodating players of different heights. This bar travels at a constant speed of 2-3 meters per second from the same location as the fruit launch point, approaching the player. Players must quickly crouch down to avoid colliding with the obstacle and then rise back up to continue the game.

The game is designed for a total duration of 5 minutes and 12 seconds, divided into five one-minute game sequences. Brief 3-second rest intervals are thoughtfully integrated between these sequences to offer players short recovery moments. Within each minute-long sequence, players encounter 30 rapid 2-second rounds, each offering a dynamic mix of fruits and bombs. Each round presents the player with 2-4 fruits, with a bomb making an appearance approximately every 4-5 rounds. In total, there are 150 rounds, with a distribution of targets as follows: (1) watermelon: 130, (2) apple: 129, (3) lemon: 114, and (4) bomb: 35. Additionally, obstacles appear every six seconds in each one-minute sequence, totaling 50 obstacles in the game.

The frequency of target generation and the game's duration underwent rigorous testing by 3 game testers to ensure that the level of physical activity was acceptable for participants with varying exercise backgrounds. We assessed our game's usability through average heart rate (AvgHR%), calories burned, and interviews. During a game session, the AvgHR% of game testers ranged between 52% and 68%, with calorie expenditure ranging from 28 to 45. Based on the standards for heart rate zones [45] and calorie expenditure [46], our game offers a level of physical activity ranging from light to moderate intensity suitable for the majority of participants.

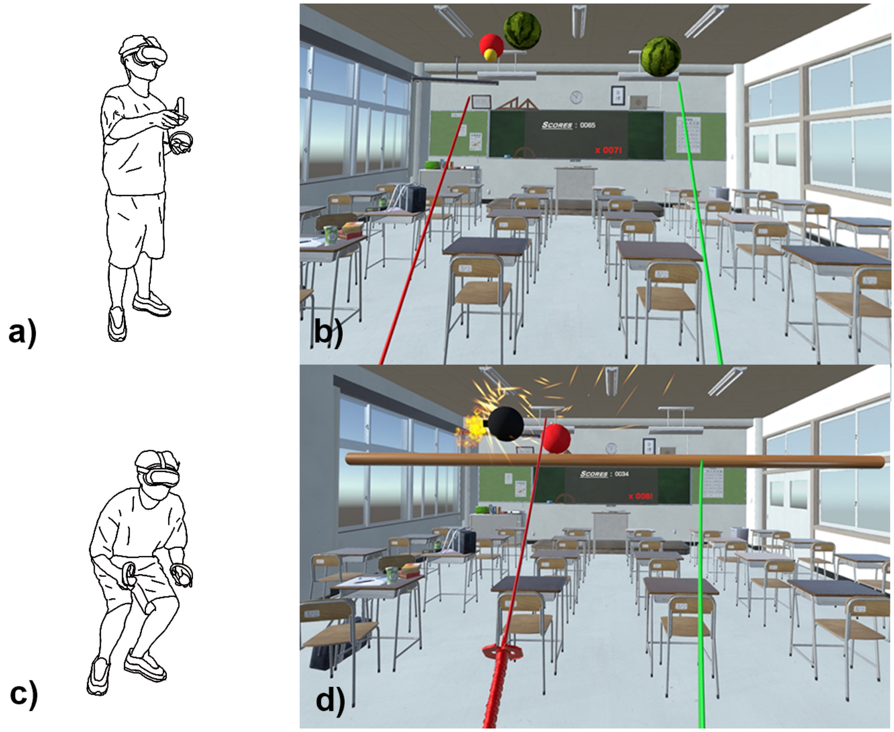

Fig. 1 (a) Players with two controllers, and (b) the corresponding fruit-slicing game scene. (c) Players crouching, and (d) the corresponding game scene with an obstacle appearing.

3.2 Scoring System

Players are awarded scores in two categories: total score and combo count. The total score represents the cumulative points earned throughout the gameplay, while the combo count keeps track of the consecutive number of sliced fruits. Slicing fruits and successfully dodging obstacles contribute corresponding points to the player's total score. Conversely, missing fruits, slicing bombs, and colliding with obstacles result in deductions from the score. Specific scoring details are provided in Table 1.

Players can view their scores on a scoring panel directly in front of them, both when the Passthrough function is turned off and on. This panel displays both the total score and the current combo count. Furthermore, in the event of a collision with an obstacle, the panel will briefly display the word "HIT" as a visual reminder to the player.

4 Experiment

4.1 Experiment Design

The study adopts a 2×2 factorial design, incorporating two independent variables: Space (Office vs. Corridor) and Passthrough Function (With vs. Without). The four conditions are as follows: (1) Office Setting with Passthrough (OS+PT), (2)

Table 1 Scoring Metrics for Total Score and Combo Count

Item	States	Total Score	Combo Count
Watermelon	Sliced	+3	+1
	Missed	-7	Reset to 0
Apple	Sliced	+5	+1
	Missed	-5	Reset to 0
Lemon	Sliced	+7	+1
	Missed	-3	Reset to 0
Bomb	Hit	-10	Reset to 0
Obstacle	Avoided	+3	/
	Hit	-3	/

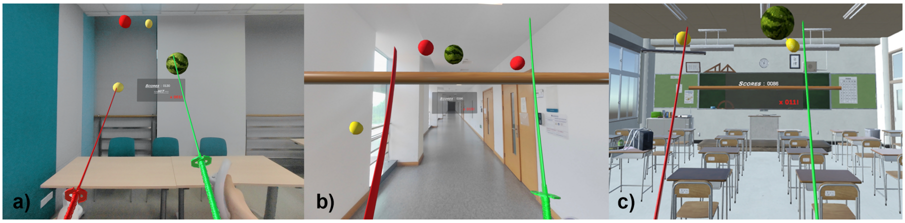

Fig. 2 (a) Office Setting with Passthrough. (b) Corridor Setting with Passthrough. (c) Game scene without Passthrough.

Office Setting without Passthrough (OS-PT), (3) Corridor Setting with Passthrough (CS+PT), and (4) Corridor Setting without Passthrough (CS-PT). We employed a balanced Latin square design to counterbalance the order of conditions. Figure 2 illustrates the virtual scene, along with the Passthrough scenes in an office and corridor.

4.2 Bystander Tasks

We utilized an empty office and a low-traffic corridor on the campus to ensure that no unrelated individuals were present during the experiment. Within each of these two spatial contexts, three trained experimenters were introduced to simulate the presence of bystanders with different tasks. Past research [10, 11] has suggested that ignoring and observing is the most common aspect of the coexisting interaction between bystanders and VR users. Similarly, Raimbaud et al. [47] employed averted gaze, directed gaze, and the transition between averted and directed gaze when investigating crowd gaze effects in VR. Building on these, we designed three tasks for bystanders: No Observation, Occasional Glance, and Continuous Observation. The experimenters did not engage in any verbal communication with the participants during the tasks. Moreover, they had no prior familiarity with any of the participants.

4.2.1 Office Tasks

As shown in Figure 3, in the office, three experimenters randomly occupied three positions in front of the participants. Their tasks are as follows:

- **No Observation:** The experimenter was in a work-like state, facing the computer, and did not observe the participants throughout the entire condition.
- **Occasional Glance:** While maintaining a work-like state with the computer, the experimenter intermittently glanced at the participants every 30-50 seconds for 2-3 seconds each time.
- **Continuous Observation:** The experimenter continuously observed the participants throughout the entire condition.

4.2.2 Corridor Tasks

As shown in Figure 3, participants were positioned to face one end of the corridor, while experimenters entered through a side door at this end and walked towards the other end, passing directly by the participants. The three experimenters appeared in a random order at approximately two minutes, three minutes, and four minutes after the start of the game. Each experimenter made a single appearance throughout the entire condition. Their tasks are outlined below:

- **No Observation:** The experimenter walked past the participants without any observation and continued his/her path without stopping.
- **Occasional Glance:** While walking past the participants, the experimenter briefly glanced at them for 2-3 seconds, then proceeded along his/her route.
- **Continuous Observation:** The experimenter paused for 20-30 seconds when walking past the participants, continuously observing them before resuming his/her path.

4.3 Measures

- ***Game Performance.*** We collected the following performance measurements: (1) game score; (2) success rate of slicing fruits and of avoiding bombs and obstacles; and (3) maximum combo count.
- ***Exertion.*** Exertion levels were evaluated through: (1) average heart rate (AvgHR%), calculated based on the mean heart rate during the section (provided by Polar OH1) and expressed as a percentage of a participant's estimated maximum HR (211-0.64 * age) [48]; (2) calories burned; and (3) the Borg Rating of Perceived Exertion (RPE) scale, ranging from 6 to 20 [49].
- ***Game Experience.*** We employed 18 items from the Player Experience of Need Satisfaction (PENS) scale [50], excluding the "Relatedness" subscale, and assessed them using a 7-point Likert scale. The four subscales we used were: (1) Competence: the player's perception of their skills and abilities. (2) Autonomy: the extent to which players would experience freedom and choice in the game. (3) Presence/Immersion: the depth of engagement that players would experience within the game. (4) Intuitive Controls: the extent to which players would feel that their choices translate smoothly into actions within the game.

- ***Social Experience.*** We assessed two experiential qualities related to players' social experience: (1) Co-presence, evaluated using 3 items from the "Co-presence" subscale of the Networked Minds Social Presence Measure [51], rated on a 7-point Likert scale. These items assessed players' perceptions of their interactions with bystanders. (2) Social acceptability, assessed through two items adapted from a study by Koelle et al. [52]. Participants were asked to rate their feelings in response to the question "How did you feel about playing this VR exergame in a shared space?" on two scales, ranging from 1 (embarrassed) to 6 (comfortable) and from 1 (annoyed) to 6 (enjoyable).
- ***Cybersickness.*** Cybersickness was assessed using the Simulator Sickness Questionnaire (SSQ) [53], which includes 16 items rated on a scale from 0 to 3, evaluating three aspects: nausea, oculomotor discomfort, and disorientation. These three sub-scores contribute to the total SSQ score, with a range of 20 to 30 indicating mild to moderate simulator sickness. Scores exceeding 40 suggest an unsatisfactory simulator experience [54].
- ***Self-Consciousness.*** Prior to the experiment, we used the Self-Consciousness Scale (SCS) [25], which comprises three subscales (private self-consciousness, public self-consciousness, and social anxiety), totaling 23 items. Each item was rated on a scale from 0 (extremely uncharacteristic) to 4 (extremely characteristic). The total self-consciousness score was calculated by summing the scores from these three subscales.
- ***Interview.*** Participants were asked to rank the four conditions and provide reasons for their rankings. Subsequently, we conducted semi-structured interviews incorporating the following questions: (1) "How do you feel the presence of bystanders impact your performance and experience during the VR exergame?"; (2) "Which bystander has the greatest impact on you? Why?"; (3) "Has Passthrough impacted your performance and experience during the VR exergame? If so, how?"; (4) "In the future, when playing VR exergames in shared spaces, would you prefer to use or not to use Passthrough? Why?" Interviews were audio-recorded and transcribed for data analysis.

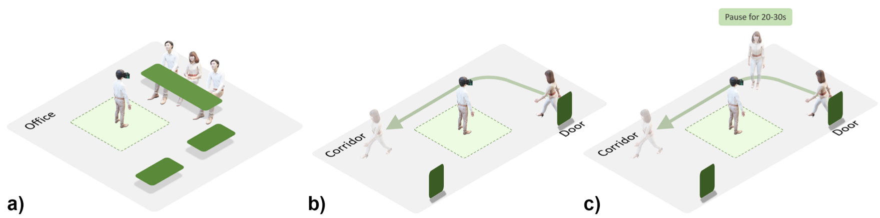

Fig. 3 (a) Bystanders' positions in Office. (b) Bystander's routine in Corridor for No Observation and Occasional Glance. (c) Bystander's routine in Corridor for Continuous Observation.

4.4 Participants

We recruited a total of 24 participants (13 females; mean age = 23.5, SD = 2.04, range = 21 to 30) through a campus-based social media platform. Among these participants, 17 had previous experience with VR HMDs, with 8 being weekly users. 20 participants had played exergames before, but only one was a regular player (weekly). In terms of their engagement in daily exercise, 9 participants exercised regularly (more than 3 hours per week), 7 were less regular (1-3 hours per week), and 8 were inactive (less than 1 hour per week). All participants volunteered for the study without compensation.

4.5 Apparatus and Setup

The experiment employed a PICO 4 as the VR device chosen for its 16MP RGB camera that enabled full-color Passthrough. To facilitate participants' extensive movements and adaptation to the complex shared environment, our exergame was fully integrated into the PICO 4. Additionally, we employed a Polar OH1 for tracking participants' heart rates and calorie expenditures. Both the office and corridor were carefully chosen to ensure sufficient space for participants, reducing the risk of collisions. Both environments were well-illuminated and isolated from external disruptions. The ambient temperature was maintained at a constant 24°C throughout the experiment via central air conditioning. Ethical approval for this study was granted by the University Ethics Committee at the host institution.

4.6 Procedure

Before the experiment began, the experimenters introduced participants to the Passthrough function, providing a brief demonstration of its activated and deactivated views to establish an initial impression. They then explained the research's objective: to investigate how Passthrough influences the experience of engaging in VR exergames in shared spaces. Participants were briefed on the two specific spaces used in the experiment, each replicated by three experimenters to simulate typical bystander scenarios. Participants were assured they would not be interrupted by the bystanders, yet they were not provided with specific details regarding the tasks assigned to the bystanders. Following this, all participants received a consent form to review and sign. Additionally, participants completed a pre-experiment questionnaire that included inquiries about demographics, such as age, gender, exercise frequency, experience with exergames and VR, as well as self-consciousness assessed via SCS [25]. Subsequently, participants were required to input their personal information, including age, gender, height, and weight, into the Polar Beat mobile application. Resting heart rate measurements were obtained using the Polar OH1 HR monitor, with participants instructed to relax and remain still for over 1 minute.

Before engaging in the formal gameplay sessions, a 3-minute training phase without Passthrough functionality was conducted. This allowed participants to practice movements and become more familiar with the equipment. For each experimental condition, participants were assisted by the experimenter in donning the Polar OH1 and HMD. The actual experiment commenced only once the participant's heart rate had returned to the resting level.

Following each condition, participants completed questionnaires to assess their exertion level (Borg RPE 6-20 [49]), game experience (PENS [50], SSQ [53]), and social experience (Networked Minds Social Presence Measure [51], social acceptability [52]). Participants rested until they felt prepared to commence the next experimental condition and their heart rates had returned to a resting level. At the conclusion of the experiment, participants underwent a semi-structured interview where they ranked the experimental conditions and provided feedback on their experiences. The entire experiment lasted approximately 50 minutes for each participant.

5 Results

We used a two-way repeated measures ANOVA (RM-ANOVA) with Space (Office vs. Corridor) and Passthrough Function (With vs. Without) as within-subjects factors. Prior to analysis, we assessed the normal distribution of the data through Shapiro-Wilks tests and Q-Q plots. We applied the Aligned Rank Transform (ART) to transform the non-normally distributed data before conducting ANOVAs. Pairwise comparisons were adjusted using the Bonferroni correction, and effect sizes were reported whenever possible (η_p^2).

Moreover, to examine the relationships between participants' self-consciousness and their performance, exertion, and experience, we conducted Pearson's bivariate correlation analyses.

5.1 Game Performance

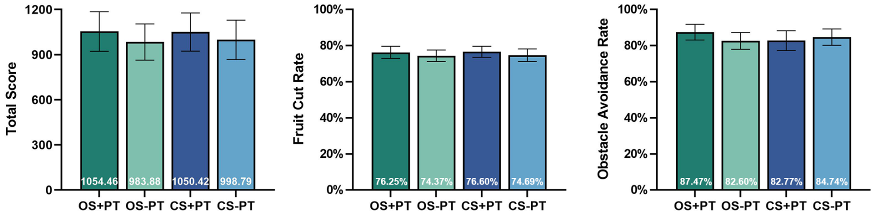

Fig. 4 Mean total score, fruit cut rate, and obstacle avoidance rate for each condition. Error bars indicate 95% confidence intervals.

Figure 4 shows the performance metrics for each experimental condition. Analyzing the data with ANOVA, we observed a significant main effect of Passthrough Function on the total score ($F_{1,23} = 5.685, p = .026, \eta_p^2 = 0.198$), while Space did not show a significant main effect ($F_{1,23} = 0.036, p = .852$), nor did their interaction ($F_{1,23} = 0.075, p = .787$). Further pairwise comparisons revealed that participants achieved higher scores with Passthrough ($M = 1052.44, SE = 57.90$) compared to without Passthrough ($M = 991.33, SE = 56.96$).

In terms of fruit cut rate, a significant main effect was found for Passthrough Function ($F_{1,23} = 7.455, p = .012, \eta_p^2 = 0.245$), while Space did not yield significant effects ($F_{1,23} = 0.190, p = .667$), and neither did the Space $\times$ Passthrough Function ($F_{1,23} = 0.000, p = .987$). Subsequent pairwise comparisons revealed that participants exhibited a higher fruit cut rate when using Passthrough function ($M = 76.4\%, SE = 0.01$) compared to when not using Passthrough function ($M = 74.5\%, SE = 0.02$).

The data for the obstacle avoidance rate did not follow a normal distribution and underwent an ART prior to conducting the RM-ANOVA. An interaction effect was observed between Space $\times$ Passthrough Function ($F_{1,23} = 5.214, p = .032, \eta_p^2 = 0.185$), but neither Space ($F_{1,23} = 0.033, p = .857$) nor Passthrough Function ($F_{1,23} = 0.163, p = .691$) yielded significant main effects. Post-hoc pairwise comparisons of the interaction effect ($p = .012$) showed participants had higher obstacle avoidance rates in OS+PT ($M = 87.5\%, SE = 0.02$) than OS-PT ($M = 82.6\%, SE = 0.02$). No significant effects were found for bomb avoidance rate, maximum combo count, or any significant correlation between participants' self-consciousness and their game performance.

5.2 Exertion

No significant main or interaction effects were observed concerning AvgHR%, calories burned, and perceived exertion via Borg RPE 6-20. Participants' AvgHR% in each condition and the corresponding calories burned were as follows: OS+PT ($M = 55.89\%, SE = 0.01$, Calories: $M = 33.33, SE = 3.45$), OS-PT ($M = 55.94\%, SE = 0.01$, Calories: $M = 34.21, SE = 3.69$), CS+PT ($M = 55.56\%, SE = 0.02$, Calories: $M = 32.92, SE = 3.23$), and CS-PT ($M = 55.72\%, SE = 0.01$, Calories: $M = 33.50, SE = 3.20$). In addition, our analysis did not reveal any significant correlations between participants' self-consciousness and their exertion.

5.3 Game Experience

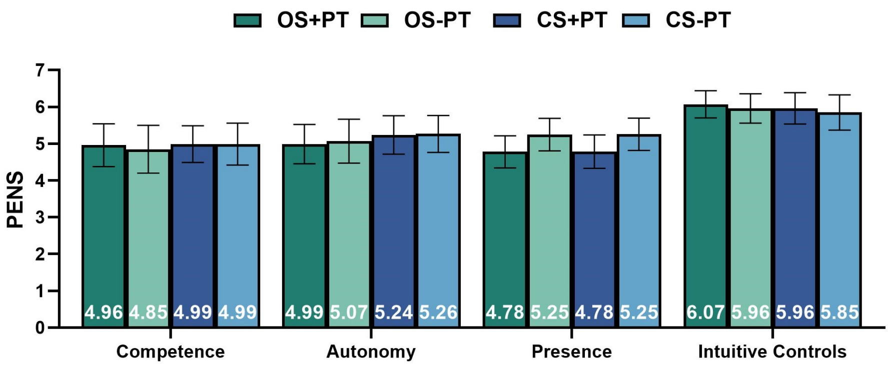

Fig. 5 PENS ratings for each condition. Error bars indicate 95% confidence intervals.

PENS ratings for each condition are displayed in Figure 5. Regarding Presence/Immersion, significant main effects were found for Passthrough Function ($F_{1,23} = 10.064, p = .004, \eta_p^2 = 0.304$), but not for Space ($F_{1,23} = 0.007, p = .932$) and Space × Passthrough Function ($F_{1,23} = 0.003, p = .960$). Participants reported a higher level of immersion when Passthrough function is not provided ($M = 5.25, SE = 0.21$) than the Passthrough function is provided ($M = 4.78, SE = 0.21$). However, no main or interaction effects were found for the other three subscales: Competence, Autonomy, and Intuitive Controls.

Furthermore, Pearson's correlation analysis revealed significant correlations between participants' self-consciousness and their perceived Competence both with Passthrough ($r = .633, p = .001$) and in the corridor ($r = .543, p = .006$). Likewise, significant correlations emerged between participants' self-consciousness and their perceived Intuitive Controls both with Passthrough ($r = .461, p = .023$) and in the corridor ($r = .477, p = .018$). No significant correlations were identified in other aspects.

5.4 Social Experience

Values for co-presence (Networked Minds Social Presence Measure) and social acceptability in each condition can be found in Figure 6. Regarding participants' perceived co-presence with other bystanders, significant main effects were observed for Passthrough Function ($F_{1,23} = 71.090, p = .000, \eta_p^2 = 0.756$), but not for Space ($F_{1,23} = 0.1.643, p = .213$) or Space × Passthrough Function ($F_{1,23} = 1.957, p = .175$). Participants reported a higher level of co-presence when using Passthrough ($M = 5.78, SE = 0.18$) compared to when not using Passthrough ($M = 2.90, SE = 0.32$).

In terms of participants' social acceptability during the experiment, we found significant main effects for Space ($F_{1,23} = 6.854, p = .015, \eta_p^2 = 0.230$), while no significant effects were observed for Passthrough Function ($F_{1,23} = 0.312, p = .582$) or Space × Passthrough Function ($F_{1,23} = 1.256, p = .274$). Participants reported a higher level of social acceptability when in the corridor ($M = 4.45, SE = 0.23$) compared to the office ($M = 3.88, SE = 0.20$).

Based on Pearson's correlation analysis results, we discovered a significant correlation between participants' self-consciousness and their perceived co-presence when Passthrough was not used ($r = .444, p = .030$). Moreover, we observed significant correlations between participants' self-consciousness and their perceived social acceptability in scenarios when using Passthrough ($r = .571, p = .004$).

5.5 Cybersickness

None of our participants had SSQ scores exceeding 30 across the four conditions: OS+PT ($M = 2.03, SE = 0.71$), OS-PT ($M = 2.18, SE = 0.74$), CS+PT ($M = 3.12, SE = 1.33$), and CS-PT ($M = 2.34, SE = 0.81$). Our analysis did not yield statistically significant results for Nausea, Oculomotor, Disorientation, or total SSQ scores.

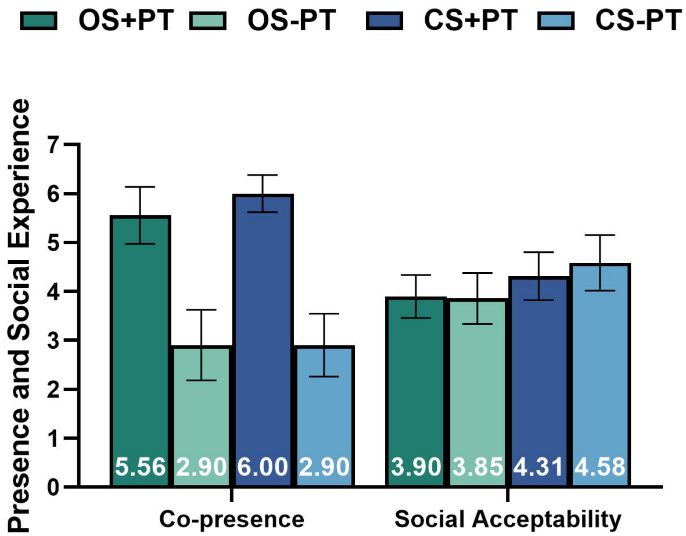

Fig. 6 Co-presence and Social Acceptability ratings for each condition. Error bars indicate 95% confidence intervals.

5.6 Interview Results

As shown in Figure 7, 9 participants favored the Corridor Setting with Passthrough (CS+PT) as their top choice, 6 preferred the Corridor Setting without Passthrough (CS-PT), 5 chose the Office Setting with Passthrough (OS+PT), and 4 favored the Office Setting without Passthrough (OS-PT). For their second-choice preferences, 10 participants leaned towards CS+PT, 5 chose CS-PT, 5 opted for OS+PT, and 4 selected OS-PT.

Regarding the reasons behind their choices, 14 participants pointed out that Passthrough *"provides a sense of security"* and P8-10, P19: *"helps in observing the positions and reactions of people around them."* Conversely, 5 participants believed that Passthrough *"breaks the immersion of VR games"* and *"seeing other people causes distraction/awkwardness."* Among the 12 participants who favored the corridor, they expressed feeling *"more free"* in this space, *"able to make large movements without worrying about collisions,"* and that *"constantly being observed by others in the office can lead to feelings of nervousness/awkwardness."* In contrast, the 5 participants leaning towards the office mentioned feeling *"more secure"* and P2, P24: *"often concerned in the corridor due to the uncertainty of people's presence."*

When asked about the impact of bystanders, 18 participants noted feeling *"distracted," "nervous," "awkward,"* and *"conscious of their reactions"* due to bystanders. In the corridor, 16 participants indicated that *"the impact of three bystanders on them was nearly equal,"* while 13 participants expressed, *"there was only a brief impact when bystanders approached."* In the office, 14 participants highlighted that Occasional Glance was more disruptive as *"it suddenly diverted their attention,"* although they *"gradually get used to Continuous Observation."*.

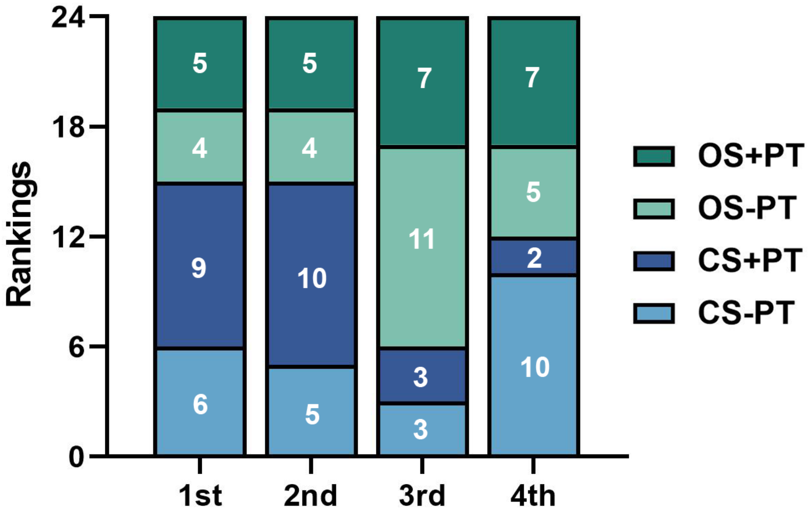

Fig. 7 Participant preference ranking for four conditions.

In contrast, 8 participants felt more *"pressured and nervous"* with Continuous Observation.

Regarding Passthrough's impact, 13 participants believed it enhanced their performance and experience by providing *"a sense of security, allowing them to navigate their surroundings confidently,"* and P2, P12, P14-15: *"creating an interesting fusion of virtual and real-world elements."* However, 6 participants felt it *"distracted them," "hindered their view,"* and *"disconnected them from the virtual content."*

In terms of future Passthrough use in shared spaces, 16 participants expressed a preference for it, citing *"a sense of security"* and *"awareness of surroundings."* On the other hand, 5 participants who did not consider using Passthrough functionality mentioned that *"there is little difference between having Passthrough or not"* and that it *"reduced the immersion of the game."*

6 Discussion

6.1 Effects of Passthrough Functionality on Player Performance and Experience in Shared Spaces

Our findings indicate that Passthrough functionality can significantly enhance player performance in shared spaces. This is likely attributed to the sense of security provided by the ability to observe the surrounding environment [17], which is supported by our qualitative data where participants reported feeling more secure and confident in their movements when Passthrough is enabled. Mansour et al. [55] emphasized the necessity of awareness systems in real-life scenarios as they can assist in safeguarding the privacy of VR users and enhancing their sense of security. In shared spaces, where safety and awareness are paramount, Passthrough appears to provide a valuable layer of reassurance, allowing users to engage in VR exergames more fully.

Furthermore, Passthrough enhances players' awareness of other bystanders, which may lead to distinct behaviors compared to when they are solely immersed in the game. Previous research suggests that the presence of others can influence an individual's performance in various activities [56–59], but whether it has a facilitating or inhibiting effect depends on various factors. Focusing on VR, Emmerich and Masuch [60] used virtual agents to simulate real human presence and observed a decline in player performance. Their study highlighted that players using VR were more significantly affected by the presence of others compared to those using an ordinary monitor. However, our findings suggest that Passthrough, by providing visual awareness, may have the potential to alleviate this inhibitory effect.

In terms of player experience, apart from immersion, there were no significant differences in other aspects of the gaming experience between using or not using Passthrough. Players experienced higher levels of immersion when Passthrough was not used, while using Passthrough allowed them to be more aware of real-world surroundings and bystanders. This aligns with previous research findings regarding the use of Passthrough as an awareness system [9, 16]. Passthrough does decrease player immersion; however, participants generally preferred conditions with Passthrough when ranking the four conditions, indicating that it did not significantly disrupt players' overall gaming experience and highlighted the value of its secure and safe functionality. Similar to previous findings regarding audio technologies [20], VR users tend to prefer technologies that enhance their awareness of bystanders during verbal interaction, regardless of the costs associated with the sense of presence.

The usability of Passthrough for transitioning between virtual and real environments has gained widespread recognition, and our findings further substantiate the advantages of prolonged Passthrough viewing in shared spaces. In studies [9, 12, 16, 40, 55] focusing on bystander interruptions, Passthrough is activated when bystanders attempt to disrupt the user's experience within the VR system. In this context, Passthrough demonstrates significant efficacy by providing users with more comprehensive visual cues and preventing sudden surprises. Our research confirms that even with limited interaction, VR users prefer using Passthrough over the long term as it helps them maintain continuous awareness of their surroundings. Despite potentially introducing a degree of compromise in player immersion, the advantage of being able to observe the real-world environment appears to position Passthrough as a potential solution better suited for shared spaces.

Additionally, considering that the Passthrough type we utilized is PAR, a technology akin to AR effects, our findings also, to some extent, demonstrate the potential applicability of AR-focused exergames in shared spaces. Ng et al. [61] extensively reviewed studies on VR and AR-based exergames, finding that VR training effectively boosts physical activity and performance, while AR research remains limited. Casual players prefer VR for its immersive experience, whereas AR's spatial awareness appeals more to certain demographics, like the elderly, aiming to reduce fall risks [62, 63]. Our research findings might offer new insights into potential applications of AR exergames.

6.2 Effects of Shared Spaces and Bystanders on Player Performance and Experience

Our study revealed that participants reported a higher sense of social acceptability in the corridor compared to the office, and they also exhibited a preference for the corridor during the interviews. In the corridor conditions, enabling or disabling Passthrough seemed to have no significant impact on participants' perception of the three types of bystanders. According to the interview results, as the bystanders were in constant motion, participants only experienced a slight sense of nervousness when the bystanders approached them. The distinction emerged in the absence of Passthrough, where participants, for safety considerations, expressed concerns about potential collisions when bystanders approached, leading them to control their movements. Conversely, with Passthrough enabled, participants felt more at ease engaging in extensive movements, experiencing a heightened sense of security in their actions.

In the office environment, participants exhibited varied awareness levels toward the three types of bystanders. Without Passthrough, akin to prior studies [9, 13, 33, 34], participants commonly felt a degree of psychological pressure when aware of others sharing the same space, despite lacking safety concerns. Moreover, due to limited visibility, participants were not entirely aware of the states of the three bystanders, yet they had a distinct sensation of being under observation. In conditions with Passthrough, participants demonstrated a noticeable awareness of bystander observation frequency. They suggested that occasional glances from bystanders seemed to have a more substantial effect on them compared to continuous observation. This suggests that sporadic or unexpected behavior may disrupt player immersion and engagement more significantly [9]. Players, however, indicated that they could adapt and become less affected by continuous observation over time.

In general, stationary bystanders in office settings often trigger tension and pressure among participants, while moving bystanders in corridors tend to elicit more safety-related concerns. Participants' preference for the corridor may be attributed to the sense of freedom and spaciousness it offers, enhancing the overall enjoyment of the experience [64]. According to the stare-in-the-crowd effect [65], individuals tend to notice and observe gazes directed toward them more frequently and for a longer duration. Therefore, when subjected to prolonged gazes in the office environment, players are more likely to perceive and be influenced by bystanders. In contrast, the dynamic aspect in the corridor may lead participants to feel less scrutinized, enabling them to engage more freely and comfortably [66, 67]. Our findings may provide an explanation for Mai et al.'s [11] finding that VR players' performance and experiences in a hallway were not significantly worse than being alone in an empty room.

Furthermore, our results indicate that Passthrough plays a constructive role in helping players navigate challenges present in both types of spaces. In corridors, Passthrough assists players in assessing their positional relationship with bystanders, thereby alleviating their concerns about collision risks. In office settings, while the ability to observe the status of bystanders may pose a distraction, confirming the status of others in the space could potentially alleviate the perceived pressure of being observed. Prior research [11–14] has often limited its experiments to a single type of shared space, neglecting the potential influence of spatial variations. In contrast, our findings illuminate how players undergo distinct experiences and responses when situated in different types of spaces, especially when interacting with bystanders in varying states.

6.3 Relationship Between Self-consciousness and Player Performance and Experience in Shared Spaces

Although players' self-consciousness appears to have no significant relationship with their performance, we found a notable association between self-consciousness and their experiences. Firstly, players with higher self-consciousness levels reported a heightened sense of capability when using Passthrough and in a corridor. Furthermore, when not using Passthrough, participants with higher self-consciousness levels were more likely to notice bystanders; when using Passthrough, they perceived a higher level of social acceptability.

Currently, using VR in shared spaces remains a challenge for many users, primarily due to worries regarding social acceptance. Introducing any new technology that demands users exhibit conspicuous or unconventional behavior in front of others raises concerns about social acceptability [68]. Individuals may hesitate to wear VR headsets due to concerns about disconnecting from reality, alongside worries about bystanders' opinions [38]. This challenge is further amplified for individuals with heightened self-consciousness.

Previous research [69, 70] has found that as self-consciousness increases, individuals tend to hyper-perceive themselves as the focus of attention in events. For instance, those with higher levels of self-consciousness are more likely to believe that others are observing them and paying attention to their performance or emotions. Consequently, when immersed in a virtual environment, these users may become more susceptible to anxiety related to the perception of being observed [70]. Passthrough functionality can provide these users with a visual means to confirm the status of bystanders, thereby reducing anxiety related to the uncertainty of others' reactions.

Overall, our results suggest that individuals with greater self-consciousness may benefit more from features that enhance their awareness of their surroundings. While many studies [11–14, 16, 18] on using VR in shared spaces rarely consider users' self-consciousness levels, our findings emphasize the significance of accounting for individual differences when designing VR experiences for shared spaces. Individual self-consciousness significantly shapes users' perceptions of abilities and social comfort, emphasizing the need to tailor features for inclusivity and an improved user experience in shared VR environments. Specifically, we highlight the potential of Passthrough in easing adaptation challenges encountered by participants with heightened self-consciousness levels while utilizing VR in shared spaces.

6.4 Limitations and Future Work

Our study provides valuable insights into how to engage players in VR exergaming within shared spaces better. However, there are several limitations to consider in interpreting our findings, which can represent potential avenues for future research. First, we exclusively utilized the PAR method in our experiment as it is widely recognized (e.g., Meta, Apple, PICO) and proven effective, serving as a representative of Passthrough functionality. Further exploration is needed to determine if other Passthrough methods align with our findings.

We primarily examined bystander interactions in the context of observation. While these were common scenarios, exploring a more extensive range of bystander interactions, including verbal communication and physical gesturing, could provide a deeper understanding of how different forms of cross-reality engagement influence VR users in shared spaces. Diversifying the range of interactions could contribute to a more comprehensive assessment of bystander effects.

To enhance the generalizability of our findings beyond the predominantly young participant demographic, future research should include individuals from diverse age groups and demographics. Different user groups (e.g., older adults [4, 71], middle-aged adults [2], and people with cognitive impairments [72]) may respond differently to shared VR spaces, and their experiences and preferences might vary significantly. By including a more diverse participant pool, we can gain a more comprehensive understanding of how shared VR spaces affect individuals across different life stages and backgrounds. Moreover, we conducted testing solely within one game application, and future work could explore other genres such as boxing, fighting, and dancing to broaden the applicability of our research findings.

Finally, our research was conducted within a controlled laboratory environment, which imposed some limitations on the duration of VR experiences and the variety of shared spaces explored. In the future, conducting field experiments that extend beyond the laboratory's confines and encompass real-world settings like shopping centers or outdoor parks can provide a more realistic assessment. Moreover, such an approach would involve a more diverse and authentic range of bystander interactions, providing a more comprehensive view of the practical implications of our research findings.

7 Conclusion

In summary, our study delved into the impact of Passthrough functionality on player performance during VR exergaming in shared spaces. The results revealed that Passthrough can enhance gaming performance while reducing the level of immersion, albeit increasing players' awareness of their surroundings and bystanders. Furthermore, our study revealed differences in VR player experiences across various shared spaces. Perceiving extended observation in enclosed environments tended to induce more psychological pressure on players, while the presence of moving bystanders in open spaces heightened concerns about safety. Players displayed a preference for open areas, deeming VR exergaming in such environments to be more socially acceptable. The Passthrough functionality, to a certain extent, proved beneficial in assisting players in coping with the distinct challenges presented in these two types of spaces. Additionally, we found that Passthrough appears to facilitate the participation of players with higher levels of self-consciousness in VR activities within shared spaces, potentially reducing their sensitivity to bystanders. By uncovering how Passthrough and spatial environments influence user performance and experiences, our research confirms the potential of Passthrough to enhance VR experiences in shared spaces. This valuable insight can guide the development of user-centric and more comfortable VR designs for shared spaces.

8 Acknowledgments

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References

[1] Zuo, M., Shen, Y.: How features and affordances of a metaverse portal engage users? evidence from exergames. Internet Research (2023)

[2] Xu, W., Liang, H.-N., Yu, K., Baghaei, N.: Effect of gameplay uncertainty, display type, and age on virtual reality exergames. In: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp. 1–14 (2021)

[3] Xu, W., Yu, K., Meng, X., Monteiro, D., Kao, D., Liang, H.-N.: Exploring the effect of the group size and feedback of non-player character spectators in virtual reality exergames. Frontiers in Psychology **14**, 1079132 (2023)

[4] Yu, K., Wen, S., Xu, W., Caon, N. Maurizio Baghaei, Liang, H.-N.: Cheer for me: effect of non-player character audience feedback on older adult users of virtual reality exergames. Virtual Reality **27**(3), 1887–1903 (2023). https://doi.org/10.1007/s10055-023-00780-5

[5] Xu, W., Liang, H.-N., Baghaei, N., Ma, X., Yu, K., Meng, X., Wen, S.: Effects of an immersive virtual reality exergame on university students' anxiety, depression, and perceived stress: Pilot feasibility and usability study. JMIR Serious Games **9**(4), 29330 (2021). https://doi.org/10.2196/29330

[6] Dao, E., Muresan, A., Hornbæk, K., Knibbe, J.: Bad breakdowns, useful seams, and face slapping: Analysis of vr fails on youtube. In: Proceedings of the 2021 Chi Conference on Human Factors in Computing Systems, pp. 1–14 (2021)

[7] Medeiros, D., Dos Anjos, R., Pantidi, N., Huang, K., Sousa, M., Anslow, C., Jorge, J.: Promoting reality awareness in virtual reality through proxemics. In: 2021 IEEE Virtual Reality and 3D User Interfaces (VR), pp. 21–30 (2021). IEEE

[8] Eghbali, P., Väänänen, K., Jokela, T.: Social acceptability of virtual reality in public spaces: Experiential factors and design recommendations. In: Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia. MUM '19. Association for Computing Machinery, New York, NY, USA (2019). https://doi.org/10.1145/3365610.3365647. https://doi.org/10.1145/3365610.3365647

[9] O'Hagan, J., Williamson, J.R., Mathis, F., Khamis, M., McGill, M.: Re-evaluating vr user awareness needs during bystander interactions. In: Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. CHI '23. Association for Computing Machinery, New York, NY, USA (2023). https://doi.org/10.1145/3544548.3581018. https://doi.org/10.1145/3544548.3581018

[10] O'Hagan, J., Williamson, J.R., McGill, M., Khamis, M.: Safety, power imbalances, ethics and proxy sex: Surveying in-the-wild interactions between vr users and bystanders. In: 2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), pp. 211–220 (2021). https://doi.org/10.1109/ISMAR52148.2021.00036

[11] Mai, C., Wiltzius, T., Alt, F., Hußmann, H.: Feeling alone in public: Investigating the influence of spatial layout on users' vr experience. In: Proceedings of the 10th Nordic Conference on Human-Computer Interaction. NordiCHI '18, pp. 286–298. Association for Computing Machinery, New York, NY, USA (2018). https://doi.org/10.1145/3240167.3240200. https://doi.org/10.1145/3240167.3240200

[12] McGill, M., Boland, D., Murray-Smith, R., Brewster, S.: A dose of reality: Overcoming usability challenges in vr head-mounted displays. In: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. CHI '15, pp. 2143–2152. Association for Computing Machinery, New York, NY, USA (2015). https://doi.org/10.1145/2702123.2702382. https://doi.org/10.1145/2702123.2702382

[13] Rettinger, M., Schmaderer, C., Rigoll, G.: Do you notice me? how bystanders affect the cognitive load in virtual reality. In: 2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp. 77–82 (2022). https://doi.org/10.1109/VR51125.2022.00025

[14] Vergari, M., Kojić, T., Vona, F., Garzotto, F., Möller, S., Voigt-Antons, J.-N.: Influence of interactivity and social environments on user experience and social acceptability in virtual reality. In: 2021 IEEE Virtual Reality and 3D User Interfaces (VR), pp. 695–704 (2021). IEEE

[15] George, C., Tien, A.N., Hussmann, H.: Seamless, bi-directional transitions along the reality-virtuality continuum: A conceptualization and prototype exploration. In: 2020 IEEE International Symposium on Mixed and Augmented

Reality (ISMAR), pp. 412–424 (2020). IEEE

[16] Gottsacker, M., Norouzi, N., Kim, K., Bruder, G., Welch, G.: Diegetic representations for seamless cross-reality interruptions. In: 2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), pp. 310–319 (2021). IEEE

[17] Von Willich, J., Funk, M., Müller, F., Marky, K., Riemann, J., Mühlhäuser, M.: You invaded my tracking space! using augmented virtuality for spotting passersby in room-scale virtual reality. In: Proceedings of the 2019 on Designing Interactive Systems Conference, pp. 487–496 (2019)

[18] Kudo, Y., Tang, A., Fujita, K., Endo, I., Takashima, K., Kitamura, Y.: Towards balancing vr immersion and bystander awareness. Proceedings of the ACM on Human-Computer Interaction **5**(ISS), 1–22 (2021)

[19] O'Hagan, J., Williamson, J.R.: Reality aware vr headsets. In: Proceedings of the 9th ACM International Symposium on Pervasive Displays, pp. 9–17 (2020)

[20] O'Hagan, J., Khamis, M., McGill, M., Williamson, J.R.: Exploring attitudes towards increasing user awareness of reality from within virtual reality. In: Proceedings of the 2022 ACM International Conference on Interactive Media Experiences. IMX '22, pp. 151–160. Association for Computing Machinery, New York, NY, USA (2022). https://doi.org/10.1145/3505284.3529971. https://doi.org/10.1145/3505284.3529971

[21] Kudry, P., Cohen, M.: Enhanced wearable force-feedback mechanism for free-range haptic experience extended by pass-through mixed reality. Electronics **12**(17), 3659 (2023)

[22] Kuo, G., Penner, E., Moczydlowski, S., Ching, A., Lanman, D., Matsuda, N.: Reprojection-free vr passthrough. In: ACM SIGGRAPH 2023 Emerging Technologies. SIGGRAPH '23. Association for Computing Machinery, New York, NY, USA (2023). https://doi.org/10.1145/3588037.3595391. https://doi.org/10.1145/3588037.3595391

[23] Chen, B., Long, J., Zheng, W., Wu, Y., Li, Z., Li, Y., Liang, H.-N.: Ar. s. space: An ar casual game for social engagement in work environments. In: 2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), pp. 842–847 (2023). IEEE

[24] Belletier, C., Normand, A., Huguet, P.: Social-facilitation-and-impairment effects: From motivation to cognition and the social brain. Current Directions in Psychological Science **28**(3), 260–265 (2019)

[25] Fenigstein, A., Scheier, M.F., Buss, A.H.: Public and private self-consciousness: Assessment and theory. Journal of consulting and clinical psychology **43**(4),

522 (1975)

[26] Wang, J., Marchant, D., Morris, T., Gibbs, P.: Self-consciousness and trait anxiety as predictors of choking in sport. Journal of science and medicine in sport **7**(2), 174–185 (2004)

[27] O'Hagan, J., Saeghe, P., Gugenheimer, J., Medeiros, D., Marky, K., Khamis, M., McGill, M.: Privacy-enhancing technology and everyday augmented reality: Understanding bystanders' varying needs for awareness and consent. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies **6**(4), 1–35 (2023)

[28] Bajorunaite, L., Brewster, S., Williamson, J.R.: Virtual reality in transit: how acceptable is vr use on public transport? In: 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), pp. 432–433 (2021). IEEE

[29] George, C., Schwuchow, J., Hussmann, H.: Fearing disengagement from the real world. In: Proceedings of the 25th ACM Symposium on Virtual Reality Software and Technology, pp. 1–5 (2019)

[30] Kenwright, B.: Virtual reality: ethical challenges and dangers [opinion]. IEEE Technology and Society Magazine **37**(4), 20–25 (2018)

[31] Hartmann, J., Holz, C., Ofek, E., Wilson, A.D.: Realitycheck: Blending virtual environments with situated physical reality. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, pp. 1–12 (2019)

[32] Simeone, A.L., Velloso, E., Gellersen, H.: Substitutional reality: Using the physical environment to design virtual reality experiences. In: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, pp. 3307–3316 (2015)

[33] Knibbe, J., Schjerlund, J., Petraeus, M., Hornbæk, K.: The dream is collapsing: the experience of exiting vr. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, pp. 1–13 (2018)

[34] O'Hagan, J., Williamson, J.R., Khamis, M.: Bystander interruption of vr users. In: Proceedings of the 9th ACM International Symposium on Pervasive Displays, pp. 19–27 (2020)

[35] George, C., Janssen, P., Heuss, D., Alt, F.: Should i interrupt or not? understanding interruptions in head-mounted display settings. In: Proceedings of the 2019 on Designing Interactive Systems Conference, pp. 497–510 (2019)

[36] Baumeister, R.F.: Choking under pressure: self-consciousness and paradoxical effects of incentives on skillful performance. Journal of personality and social

psychology **46**(3), 610 (1984)

[37] Carver, C.S., Scheier, M.F.: Self-focusing effects of dispositional self-consciousness, mirror presence, and audience presence. Journal of personality and social psychology **36**(3), 324 (1978)

[38] Williamson, J.R., McGill, M., Outram, K.: Planevr: Social acceptability of virtual reality for aeroplane passengers. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, pp. 1–14 (2019)

[39] Banquiero, M., Valdeolivas, G., Trincado, S., García, N., Juan, M.C.: Passthrough mixed reality with oculus quest 2: A case study on learning piano. IEEE MultiMedia (2023)

[40] Wang, C.-H., Chen, B.-Y., Chan, L.: Realitylens: A user interface for blending customized physical world view into virtual reality. In: Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology, pp. 1–11 (2022)

[41] Aygün, C., Çakır-Atabek, H.: Classification of exergames with different types: Perceptual and physiological responses in college students. Applied Sciences **13**(19), 10769 (2023)

[42] Huang, K.-T.: Exergaming executive functions: An immersive virtual reality-based cognitive training for adults aged 50 and older. Cyberpsychology, Behavior, and Social Networking **23**(3), 143–149 (2020)

[43] Yoo, S., Gough, P., Kay, J.: Embedding a vr game studio in a sedentary workplace: use, experience and exercise benefits. In: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, pp. 1–14 (2020)

[44] Guo, Z., Xu, W., Zhang, J., Wang, H., Lo, C.-H., Liang, H.-N.: Who's watching me?: Exploring the impact of audience familiarity on player performance, experience, and exertion in virtual reality exergames. In: 2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), pp. 622–631 (2023). IEEE

[45] Achten, J., Jeukendrup, A.E.: Heart rate monitoring: applications and limitations. Sports medicine **33**, 517–538 (2003)

[46] Letter, H.H.: Calories burned in 30 minutes for people of three different weights. https://www.health.harvard.edu/diet-and-weight-loss/calories-burned-in-30-minutes-for-people-of-three-different-weights, [Accessed 2023-12-30] (2004)

[47] Raimbaud, P., Jovane, A., Zibrek, K., Pacchierotti, C., Christie, M., Hoyet, L., Pettre, J., Olivier, A.-H.: The stare-in-the-crowd effect in virtual reality. In: 2022

IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp. 281–290 (2022). IEEE

[48] Nes, B.M., Janszky, I., Wisløff, U., Støylen, A., Karlsen, T.: Age-predicted maximal heart rate in healthy subjects: The hunt f itness s tudy. Scandinavian journal of medicine & science in sports **23**(6), 697–704 (2013)

[49] Borg, G.A.: Psychophysical bases of perceived exertion. Medicine & science in sports & exercise (1982)

[50] Ryan, R.M., Rigby, C.S., Przybylski, A.: The motivational pull of video games: A self-determination theory approach. Motivation and emotion **30**, 344–360 (2006)

[51] Harms, C., Biocca, F.: Internal consistency and reliability of the networked minds measure of social presence. In: Seventh Annual International Workshop: Presence, vol. 2004 (2004). Universidad Politecnica de Valencia Valencia, Spain

[52] Koelle, M., Ananthanarayan, S., Boll, S.: Social acceptability in hci: A survey of methods, measures, and design strategies. In: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, pp. 1–19 (2020)

[53] Kennedy, R.S., Lane, N.E., Berbaum, K.S., Lilienthal, M.G.: Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. The international journal of aviation psychology **3**(3), 203–220 (1993)

[54] Caserman, P., Garcia-Agundez, A., Gámez Zerban, A., Göbel, S.: Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. Virtual Reality **25**(4), 1153–1170 (2021)

[55] Mansour, S., Knierim, P., O'Hagan, J., Alt, F., Mathis, F.: Bans: Evaluation of bystander awareness notification systems for productivity in vr. In: Network and Distributed Systems Security (NDSS) Symposium (2023)

[56] Michaels, J., Blommel, J., Brocato, R., Linkous, R., Rowe, J.: Social facilitation and inhibition in a natural setting. Replications in social psychology **2**(21-24) (1982)

[57] Bowman, N.D., Weber, R., Tamborini, R., Sherry, J.: Facilitating game play: How others affect performance at and enjoyment of video games. Media Psychology **16**(1), 39–64 (2013)

[58] Kappen, D.L., Mirza-Babaei, P., Johannsmeier, J., Buckstein, D., Robb, J., Nacke, L.E.: Engaged by boos and cheers: the effect of co-located game audiences on social player experience. In: Proceedings of the First ACM SIGCHI Annual Symposium on Computer-human Interaction in Play, pp. 151–160

(2014)

[59] Rhea, M.R., Landers, D.M., Alvar, B.A., Arent, S.M.: The effects of competition and the presence of an audience on weight lifting performance. The Journal of Strength & Conditioning Research **17**(2), 303–306 (2003)

[60] Emmerich, K., Masuch, M.: The influence of virtual agents on player experience and performance. In: Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play, pp. 10–21 (2016)

[61] Ng, Y.-L., Ma, F., Ho, F.K., Ip, P., Fu, K.-w.: Effectiveness of virtual and augmented reality-enhanced exercise on physical activity, psychological outcomes, and physical performance: A systematic review and meta-analysis of randomized controlled trials. Computers in Human Behavior **99**, 278–291 (2019)

[62] Chen, M., Tang, Q., Xu, S., Leng, P., Pan, Z.: Design and evaluation of an augmented reality-based exergame system to reduce fall risk in the elderly. International journal of environmental research and public health **17**(19), 7208 (2020)

[63] Goumopoulos, C., Drakakis, E., Gklavakis, D.: Feasibility and acceptance of augmented and virtual reality exergames to train motor and cognitive skills of elderly. Computers **12**(3), 52 (2023)

[64] Lütke Lanfer, S.S., Becker, C., Göritz, A.S.: Well-being in open space offices: The role of office features and psychosocial working conditions. Work **68**(2), 317–332 (2021)

[65] Von Grünau, M., Anston, C.: The detection of gaze direction: A stare-in-the-crowd effect. Perception **24**(11), 1297–1313 (1995)

[66] Lefkeli, D., Tulan, D., Gürhan-Canli, Z.: Being observed in the digital era: Conceptualization and scale development of the perception of being observed. Psychology & Marketing **39**(10), 1992–2008 (2022)

[67] Aiello, J.R., Kolb, K.J.: Electronic performance monitoring and social context: Impact on productivity and stress. Journal of applied psychology **80**(3), 339 (1995)

[68] Rico, J., Brewster, S.: Usable gestures for mobile interfaces: evaluating social acceptability. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 887–896 (2010)

[69] Fenigstein, A.: Self-consciousness and the overperception of self as a target. Journal of personality and social psychology **47**(4), 860 (1984)

[70] Gilovich, T., Medvec, V.H., Savitsky, K.: The spotlight effect in social judgment: an egocentric bias in estimates of the salience of one's own actions and appearance. Journal of personality and social psychology **78**(2), 211 (2000)

[71] Xu, W., Liang, H.-N., Yu, K., Wen, S., Baghaei, N., Tu, H.: Acceptance of virtual reality exergames among chinese older adults. International Journal of Human–Computer Interaction, 1–15 (2022)

[72] Creed, C., Al-Kalbani, M., Theil, A., Sarcar, S., Williams, I.: Inclusive augmented and virtual reality: A research agenda. International Journal of Human–Computer Interaction, 1–20 (2023)