



# Cheer for me: effect of non-player character audience feedback on older adult users of virtual reality exergames

Kangyou Yu<sup>1,2</sup> · Shaoyue Wen<sup>1</sup> · Wenge Xu<sup>3</sup> · Maurizio Caon<sup>4</sup> · Nilufar Baghaei<sup>5</sup> · Hai-Ning Liang<sup>1</sup>

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## Abstract

The presence of an audience and its feedback could affect people's performance and experience during an event, especially related to sports such as tennis or boxing. Similarly, in videogames, players' gameplay could be affected if there is an audience and its feedback in response to players' performance in the environment. The inclusion of an audience with non-player characters (NPC) is common in videogames in general. However, there is a limited exploration of the use of an NPC audience in virtual reality (VR) exergames, especially focusing on elderly players. To fill this gap, this work examines the effect of an NPC audience and its associated feedback (with/without) on elderly users of VR exergames. In a user study, we used 120 NPC in a virtual audience. Results showed that the presence of the NPC audience with responsive feedback led to higher performance (with a higher success rate of performing gesture actions, more successful combinations of actions (or combos for short) performed, and more opponent's combos prevented) and better gameplay experience (with higher levels of competence, autonomy, relatedness, immersion, and intuitive controls) of elderly players. Our results can help frame the design and engineering of VR exergames that are targeted at elderly users to help them have an enhanced gameplay experience and improve their health.

**Keywords** Virtual reality · Audience feedback · Non-player characters · Exergames · Elderly users

## 1 Introduction

In the past few decades, the population of older adults has been increasing rapidly because of better living conditions and much more advanced healthcare provision. Issues related to an aging population are rapidly gaining the attention of governments and healthcare providers worldwide. According to the United Nation's World Population

Prospects 2022 report (World Population Prospects 2022), the share of the global population aged 65 years or above is projected to rise from 10% in 2022 (i.e., 771 million) to 16% in 2050 (i.e., 1.6 billion). Physical functions of these users tend to gradually deteriorate with age and can lead to many challenges and health issues (e.g., limited mobility, muscle weakness, lower motor control) for the elderly (Larsen et al. 2013). The rapidly growing number of elderly who live longer but have health issues will put healthcare services and society in general under significant stress. However, previous studies (Taylor et al. 2004; Goldspink 2005; Mikus et al. 2011) stated that the most common reason for the loss of the physical function of the elderly is an unhealthy inactive lifestyle. Although regular exercise could improve their health, reduce the risk of many diseases, balance energy consumption and expenditure, and control weight gain (Warburton et al. 2006), many elderly still experience a lack of motivation to exercise. The situation has worsened with the COVID-19 pandemic since exercising in public outdoor or indoor places (e.g., gyms) for the elderly could involve a higher risk, than young adults (Guan et al. 2020; Lai et al. 2020), to be infected by the COVID-19 and

✉ Hai-Ning Liang  
haining.liang@xjtlu.edu.cn

<sup>1</sup> Department of Computing, Xi'an Jiaotong-Liverpool University, Suzhou, China

<sup>2</sup> Department of Computer Science, The University of California, Santa Barbara, Santa Barbara, CA, USA

<sup>3</sup> DMT Lab, Birmingham City University, Birmingham, UK

<sup>4</sup> School of Management of Fribourg, University of Applied Sciences and Arts Western Switzerland (HES-SO), Fribourg, Switzerland

<sup>5</sup> School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, QLD, Australia

experience significantly more symptoms, and even higher mortality (Guan et al. 2020; Chen et al. 2020). Thus, the space for exercising has been reduced, and this leads to a focus on individual and home-based activities, which can involve games.

Exergames have been used to address physical inactivity in the past decade because they could provide players with enjoyable and playful gameplay while at the same time exercising (Mellecker et al. 2013). Prior work has confirmed that elderly players can gain health benefits from playing exergames (e.g., improved quality of life (Konstantinidis et al. 2016), balance skills (Yang et al. 2020), and improved cognitive functions (Moreira et al. 2021); more can be found in Xu et al. (2020)).

Spectator audiences are always an important and integral part of public events, such as sports games. In such events, the presence of an audience and its feedback (or lack of it) could result in positive or negative effects on players' performance. The social facilitation theories suggest that the presence of an audience can affect people's performance and experience during an event (Aiello and Douthitt 2001; Bond and Titus 1983; Ducheneaut et al. 2006). Similarly, in videogames, virtual audiences, usually made of non-player characters (NPC), are often included in the gaming environment and can be considered an important gameplay element in sports videogames (e.g., NBA 2K,<sup>1</sup> FIFA<sup>2</sup>). There is some research exploring the social facilitation effect of an NPC audience in virtual reality (VR) games (Bolton et al. 2014; Strojny et al. 2020). However, there has been little research investigating the effect of NPC audiences on players' performance and experience in VR exergames. To our knowledge, there has been no prior research that has looked at the effect of audience and its feedback on elderly users playing VR exergames. This work aims to fill this gap and help find guidelines that can frame the design and engineering of such games for an increasingly more important population segment, older adults.

Rapid advances in immersive VR technology, especially in the form of inexpensive head-mounted displays (HMDs), have introduced new affordances and features to games that can improve immersion, gameplay experience, and enjoyment. For VR exergames, players can have additional gameplay capabilities and experiences that combined with an enhanced level of immersion make these games more interesting, enjoyable, and effective in promoting health outcomes (Xu et al. 2021, 2020, 2019) and can improve players' intrinsic motivation to play such games (Xu et al. 2021). Prior research has confirmed that playing exergames in VR are more immersive and challenging than a 50-inch

TV display (Xu et al. 2020) and can lead to better performance (Xu et al. 2021). In addition, playing exergames in VR can increase their motivation to do physical activities in general (Ioannou et al. 2019). These findings have been confined to younger players. For elderly players, while one recent paper has found that there is a general tendency for elderly users to accept VR exergames as part of their regular exercise regime (Xu et al. 2023), research linking VR exergames and older adult users are still largely underexplored. Much less is known about how these users will perceive an NPC audience 'watching' them play a competitive exergame, and the feedback it provides based on their actions.

In short, this study aims to fill an unexplored space by investigating the effect of NPC audience feedback on the elderly's performance and experience in VR exergames. More specifically, we want to investigate the following two Research Questions (RQ):

*RQ1*: How would the presence of an NPC audience without reactive feedback (i.e., non-reactive to the player's performance) affect older adult users' performance and experience in VR exergames?

*RQ2*: How would the presence of an NPC audience with reactive feedback affect older adult users' performance and experience in VR exergames?

To answer these two questions, we run an experiment with 20 older adult participants who played a VR exergame under three conditions (no audience, audience with no feedback, and audience with reactive feedback). Our results show that an audience without feedback has no significant effect, but an audience with positive feedback can lead to improved performance and a better gameplay experience. These results can form the basis to frame the design and engineering of VR exergames that are tailored for older adult users.

## 2 Related work

### 2.1 VR exergames

With the increasing popularity of VR HMDs, several commercial VR exergames have been developed to provide users with a way of exercising that is fun and engaging. For instance, Virtual Sports<sup>3</sup> allow players to perform full-body movements or gestures to play different sports. In FitXR,<sup>4</sup> users are required to perform either arm-based movements (e.g., weave, uppercuts, and jab) or full-body dance movements following the music rhythm. Other commercial games like Gym Masters<sup>5</sup> follow a similar playing style as FitXR.

<sup>1</sup> <https://nba.2k.com/>.

<sup>2</sup> <https://www.ea.com/en-gb/games/fifa/fifa-23>.

<sup>3</sup> <https://www.vrgamerankings.com/virtual-sports>.

<sup>4</sup> <https://fitxr.com/>.

<sup>5</sup> <https://www.oculus.com/experiences/quest/3568106689962388>.

These types of games leverage the increased level of immersive experience and natural, richer body-based gestures afforded by VR HMDs.

Likewise, research-based exergames have been proliferating. For instance, Bolton et al. (2014) presented a bicycle-based VR exergame and found it increases immersion and provides a more natural experience. KIMove (Xu et al. 2019) requires players to hit fruits floating in midair using their arm movements and step on blocks moving toward them on the ground using their feet. Ioannou et al. (2019) designed and implemented a VR game in which the player is required to run or jump over obstacles and avoid hitting other obstacles, like trucks. VirusBoxing (Xu et al. 2020) employs a similar playing style as FitXR but uses high-intensity interval training (HIIT) to reduce playing time but still allow players to achieve a high level of exercise and exertion. Another exergame, GestureFit (Xu et al. 2021), requires players to perform different body gestures to release attacks to fight against an opponent, a monster-like creature, and make defense moves in a stadium-like environment, akin to a one-to-one fighting match.

Prior research on VR exergames has tended to emphasize the design of bodily gestures and movements. However, VR exergames involve other aspects that can be also important to providing a good gameplay experience and leading to improved performance, which in turn help users attain greater benefits. One such aspect is the presence of an audience and its feedback in response to players' actions.

## 2.2 Effect of age on game perception

Different age groups tend to perceive a game or elements of a game differently. For example, fun is a powerful motivator for young children (John et al. 2006), while teenagers and young adults may have a stronger sense of competitiveness and challenge-driven motivations (Subramanian et al. 2020). In the contrast, a recent paper (Xu et al. 2023) reports that older adult players emphasize the need to have some level of social interaction and have some type of feedback provided to them when playing VR exergames.

Subramanian et al. (2020) found that young people prefer rewarding experiences, but the elderly prefer something that is beneficial to their health. Younger people are more attracted to appealing graphics and music that is suitable for the theme, but older people prefer slower games that have guided feedback that could help them complete the game in a shorter time (Subramanian et al. 2020). In addition, as users grow older, their appreciation of the pleasure brought by games increases, their satisfaction with autonomy increases, and their appreciation of ability decreases, especially after a certain threshold is reached (Birk et al. 2017). In other words, young adults prefer games that are more challenging to show their abilities to their peers, but older adults prefer

games that are interesting, beneficial to their health, and can be played with and discussed with their peers (Birk et al. 2017; Xu et al. 2023).

In short, older adult users tend to value playing games based on benefits to their health and have a need to have a social aspect to the games, particularly some degree of feedback to their actions. One way of providing such feedback is through the use of an NPC audience that is responsive to their actions.

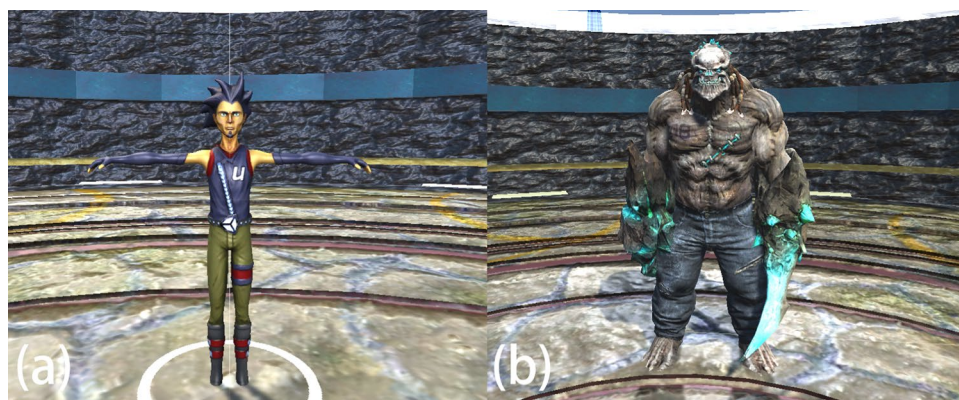
## 2.3 Health benefits of exergames to older adult users

In general, exergames are an effective tool to bring health benefits (both mental and physical) to elderly users (Xu et al. 2020) and older adults are aware that exergames could help maintain or even improve their health (Bird et al. 2015). For instance, a study (Peng et al. 2020) investigated the effects of exergames on older adults' physical performance and showed that exergames had a significant advantage over the control group, who went to multi-component exercise intervention focused on physical and cognitive training, in terms of lower-extremity strength and flexibility, aerobic endurance, dynamic balance, and agility. Rendon et al. (2012) stated that the elderly have better balance and postural stability when exercising using Nintendo Wii exergames. Yu et al. (2020) found that exergames are effective in improving cardiopulmonary endurance and leg muscle strength. In addition, exergames can be used to improve endurance (Bruno Morbeck et al. 2017) among the elderly. A detailed review of the health benefits of older adult users playing exergames can be found in Xu et al. (2020). In short, while it is clear that exergames can bring many benefits to elderly users, it is unknown if VR exergames, in particular, can bring the same benefits and if controlling feedback from a virtual audience can have an impact on their performance and preference for such games.

## 2.4 Effect of audience feedback

The social cognitive theory (Bandura 1997, 1982, 2001) suggests that receiving encouraging messages motivate people to increase their effort in performing better, which can result in positive effects, such as attaining higher levels of self-efficacy. This feedback often serves to provide individuals with support for their efforts and continue performing the task over a period despite physical and mental challenges. When this feedback is full of encouragement and support, it can be used to indicate to people that they are performing well and making good progress (Ilgen et al. 1979). Deci et al. (1999) reported that supportive feedback could lead to more positive exercise experiences and outcomes. More specifically, receiving supportive feedback during physical activity could result in better

**Fig. 1** Two pictures of avatar characters of the VR exergame: **a** the player's character and **b** the opponent's character, a monster-looking character



performance, increased competence, and intrinsic motivation (Escarti and Guzman 1999; Gernigon and Delloye 2003; Bindarwish and Tenenbaum 2006).

For video games, participants reported that they had more positive gameplay experiences such as greater enjoyment, more motivation for future play, higher self-efficacy, and better game ratings when receiving feedback based on their performance during gameplay (Peng et al. 2012). Kappen et al. (2014) showed that both positive and negative feedback could lead to better game engagement for players than an audience that could not provide any feedback. Also, in Kim and Timmerman (2018), it has been suggested that players had a better exergame experience if they received more supportive feedback. In addition, Haller et al. (2019) found that virtual spectator feedback could lead to better participants' performance and higher heart rates. To date, previous work has effectively stated the effect of feedback on exergames. However, they mainly used the feedback provided by a real human. While Haller et al. (2019) has provided some evidence of the positive effect of virtual audience feedback, this research is preliminary and limited to a cycling VR game and participants ( $N = 6$ ) aged 21 or 22. To our knowledge, the effect of feedback from a virtual audience has not been investigated in detail in gesture-based VR exergames for both general audiences and especially older adult users.

In this research, we evaluated the effect of an NPC audience with and without reactive feedback on players' actions in a gesture-based VR exergame focusing on elderly users. Both visual and audio feedback was used because prior work indicated that feedback delivered via multiple channels (e.g., visual and audio) could contribute to greater enjoyment and energy expenditure (e.g., see (Kim et al. 2014)).

## 3 Experiment

### 3.1 Exergame application

#### 3.1.1 Implementation

The VR exergame was developed in house using Unity 3D (version 2019.4.22f1). Players would control a character (see Fig. 1a) fighting against an opponent using body movements, which were captured using a Microsoft Kinect 2. The game used a first-person perspective and required players to perform gestures to release (magical) attacks to fight against an opponent, in our case a monster-like looking character, which was placed 10 meters in front of the player's view and controlled by a computer program (see Fig. 1b).

#### 3.1.2 Game task

Participants were required to fight against the monster by performing different gesture-based movements to release magical attacks to take life/health points (HP) off the monster and do defense moves to protect against the monster's attacks. Players were required to defeat the opponent monster's three lives (1500 HP for three lives in total) to finish the game.

#### 3.1.3 Gameplay

As shown in Fig. 3, the player would begin with 100 HP while the monster with 500 HP. The monster could perform four moves, including two walk actions (move leftward and move rightward) and two attack actions (punch



**Table 1** Description of each gesture move (or skill) by the player and the monster, with instructions for how to perform the gesture, features, and requirements

Name	Performer	Instruction of the gesture	Function of the move	Cooldown
Push	Player	Single hand pushing	An attack move that inflicts 10 HP damage to the opponent on the pushing direction	3 s
Psi	Player	Raise two arms up	A ranged attack move that deals 10 HP damage	3 s
Squat	Player	Performing a squat	A ranged attack move that deals 30 HP damage	5 s
Zoom	Player	Stretching two arms out	A defense move that releases a sphere to protect the user for 2 seconds and heals 20 HP if it could successfully defend the player from the monster's attack	3 s
Punch	Monster	Right hand punch	An attack move that inflicts 10HP damage to the player on the punching direction	3 s
Squat	Monster	Performing a squat	A ranged attack move that deals 30 HP damage	5 s

See also Fig. 2 for pictures of an elderly user performing each gesture and their representation in the exergame environment

and squat). The monster would perform one of these four actions randomly every 2 s. Players could perform four movements, three attack movements, and one defensive movement. To design the moves so they fit the game scenario and are tailored to the elderly, we relied on the literature on VR exergames to frame them. Table 1 shows a summary of the gesture-based skill movements and their corresponding functions and requirements. To show their suitability for elderly players, we followed a participatory design approach that involved two elderly users in the iterative testing and refinement of the parameters of the movements. For example, for *Squat*, we made sure that the required body movement to enact the gesture would not make an elderly user fall off-balance. Figure 2 shows screenshots of the final moves performed by an elderly user, how they are represented in the player avatar, and the visuals used to show their effect during gameplay.

In addition, to make the game more engaging and unpredictable, we included features such as uncertainty elements to the game, which could make an exergame more engaging and increase the exercise level (Thomas et al. 1993; Xu et al. 2021). For instance, we included the false-attack feature, where the monster would have 20% chances to perform false-attack moves that were designed to trick players to perform a defensive move, thus eliciting additional gestures to be performed. Moreover, both of players and the opponent have 15% chances to make a (1) *Critical Attack* which would cause 50% more damage, or (2) *Miss*, which would lead to no damage to the opponent. Like the gesture, we tested all the features of the game with the two elderly users to make sure that they were easy to understand and could lead to a positive experience.

In addition, the game provided players with both visual and audio feedback in response to their moves to give a fuller range of sensory experiences, just like any typical game.

### 3.2 Evaluated conditions

To provide a more natural setting to have an audience, we set the game to be in a stadium-like environment, with the middle area as the fighting arena and the NPC audience placed around it. We derived 2 conditions, both using an audience of 120 NPC, with one providing feedback based on the players' moves and one do not provide any feedback. A third condition without an audience was also included as the benchmark condition. Figure 4 shows an example of each condition, which is briefly described below:

- *No audience* (NA): as Fig. 4a shows, this condition was the control condition to investigate the players' performance when NPC audience and their feedback were both absent.
- *Audience with no feedback* (NF): as Fig. 4b shows, this condition included 120 NPC in the audience, but they would not react to either the player's or the monster's performance.
- *Audience with feedback* (WF): as Fig. 4c shows, this condition had the same number (120) of NPC in the audience as NF. In contrast to NF, the NPC supporters (90 for the player and 30 for the monster) would cheer up for either the player or the monster with three types of animations (i.e., standing up, jumping, clapping their hands) to show their support visually. Also, applause sounds mixed with cheering and hand clapping were provided as a form of audio support. These feedback elements were triggered by the following: (1) *Encouraging*: the player's supporters (90 NPC) would cheer up when the player performed five successful consecutive actions based on combinations of attack and defensive moves. (2) *Discouraging*: the opponents' supporters (30 NPC) would cheer up when the monster performed three successful consecutive actions that could be a combination of attacks, defense moves, and false-attacks (that is, fake moves intended to trick the oppo-



**Fig. 2** Pictures of each gesture move (or skill) from top to bottom (push, psi, squat, and zoom) as performed by an elderly user (left column: a, d, g, j), their avatar representation (middle column: b, e, h, k) and the visual effect in the game (right column: c, f, i, l)

nent into doing a defensive move). The 90/30 split of supporters of the player and the monster was designed to simulate how sports games behave in real-life, where typically the home team would have more supporters than the visiting team. In our case, after consulting with our two elderly playtesters, they thought that this proportion was good and that the higher proportion of supporters given to the player gave them a better feeling than for example a 50% split or assigning more supporters to the monster.

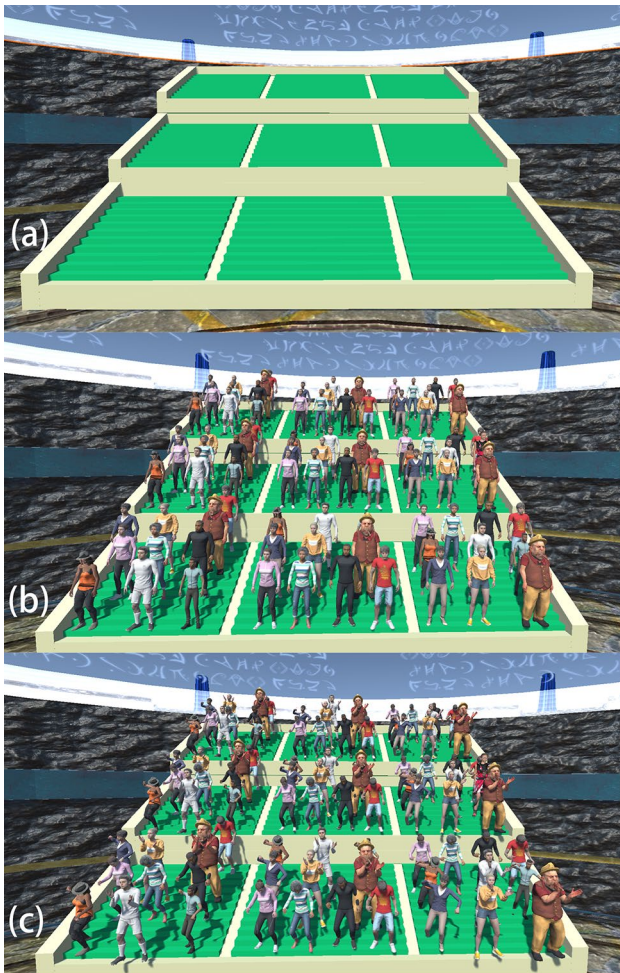
### 3.3 Experimental design

The experiment followed a within-subjects design with one factor—*Audience Feedback*, which is evaluated with a baseline condition, where no audience and feedback were provided during gameplay. The order of these three conditions was counterbalanced in the experiment.

We collected the following data to assess our participants' gameplay performance, experience, exertion, and overall thoughts:



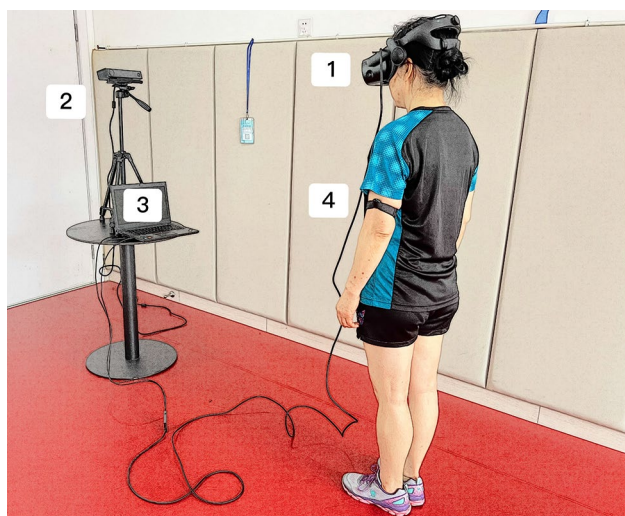
**Fig. 3** A first-person perspective screenshot of the game scenario from the players' viewpoint



**Fig. 4** Conditions evaluated in our experiment: **a** NA: no NPC audience, **b** NF: NPC audience with no feedback, and **c** WF: NPC audience with feedback when feedback is triggered. **b** and **c** Show 90 NPC in the game scenario; there are other 30 NPC on another audience stand in the scenario

- *Player performance*: (1) game completion time: time taken by the player to kill the three lives of the monster using gesture-based body movements; (2) the success rate of gesture moves; (3) players' combinations (Combos): five consecutive successful actions based on a combination of attack and defense moves—in other words and similar to typical fighting games, Combos simply represent a combination of successful actions/movements; and (4) Monster's Combos: three consecutive successful actions that can be a combination of attack, defense, and false-attack moves.
- *Player experience*: the player experience was measured by the Player Experience of Need Satisfaction (PENS) scale (Ryan et al. 2006), which has 21 items and covers 5 subscales (Competence, Autonomy, Relatedness, Immersion, and Intuitive Controls). The Competence scale reflects aspects of how capable the players felt. The Autonomy scale indicates the extent to which players experienced freedom and choice in the game. The Relatedness scale assesses the extent to which players feel connected to “other players in the game” (e.g., in our case, other players be the virtual audience). The Presence/Immersion scale is related to emotional engagement in the game. The Intuitive Controls scale indicates the degree to which players found that they could translate their choices into in-game actions.<sup>6</sup> In addition, cybersickness was assessed by a 9-item Virtual Reality Sickness Questionnaire (VRSQ) (Kim et al. 2018), which covers oculomotor and disorientation. VRSQ was developed and adapted for VR based on the original

<sup>6</sup> Please note authors using PENS do not have permission to publish the individual items of the questionnaire. For more details, visit their official website <https://immersyve.com/> to register and access the detailed description of each item.



**Fig. 5** A picture of the exergame, apparatus, and experimental setup: (1) an HP Reverb G2 Omnicept, (2) the Microsoft Kinect 2, (3) a laptop, and (4) the Polar OHI

Simulator Sickness Questionnaire (commonly known as SSQ) (Kennedy et al. 1993).

- *Exertion*: the perceived exertion level of the exergame was evaluated by (1) the average heart rate percentage (avgHR%) expressed as a percentage of the average heart rate across the session divided by a participant's estimated maximum heart rate (the equation is  $\text{avgHR} = 211 - 0.64 \times \text{age}$ ) (Nes et al. 2013), (2) calories burned (which was measured by Polar Beat), and (3) Borg RPE 6–20 scale (Borg 1982).
- A brief structured interview with open-ended questions targeting their experience and performance toward the use of NPC-based audience and their feedback in the game. The questions were: “Overall, what did you think about the design of the NPC audience and their feedback on performance?,” “What did you like about the design of the NPC audience and their feedback on performance?,” and “What did you not like about the design of the NPC audience and their feedback on performance?” The answer could be provided verbally or written, depending on the participants' preference.

### 3.4 Apparatus and setup

Figure 5 shows the experimental setup, which consisted of (1) an HP Reverb G2 Omnicept<sup>7</sup> which was the VR HMD used in the experiment; (2) a Microsoft Kinect 2 was used to track the players' movements; (3) a laptop with an i7 CPU, 16GB RAM, and Nvidia Quadro P5200 GPU that powered

the HMD and run the application; and (4) a Polar OH1 that was used to monitor players' heart rate (HR).

The experiment was conducted in a well-illuminated indoor room that could not be seen from the outside. The room temperature was controlled by an air conditioner that regulated the temperature to 24°C during the experiment. To ensure the safety of participants, the experiment was conducted under the observation and supervision of an experimenter. While there had not been a positive case of COVID-19 in the city the experiment took place, we followed extra precautions and safety guidelines (e.g., the participant and researcher stood at a safe distance from each other; cleaning and sanitation of the devices before and after each use) (Spittle et al. 2021). This research was reviewed and approved by the University Ethics Committee of the host institution.

### 3.5 Participants

Twenty (20) community-dwelling older adults (12 males and 8 females) with an average age of 66.25 (SD = 1.45) were recruited from a typical community center where elderly adults would gather regularly. All of them reported that they had no experience with VR HMDs and exergames before. They all had normal or corrected-to-normal vision and declared themselves to be physically fit. The inter-pupillary distance of the headset was adjusted for each participant to have the best visual experience.

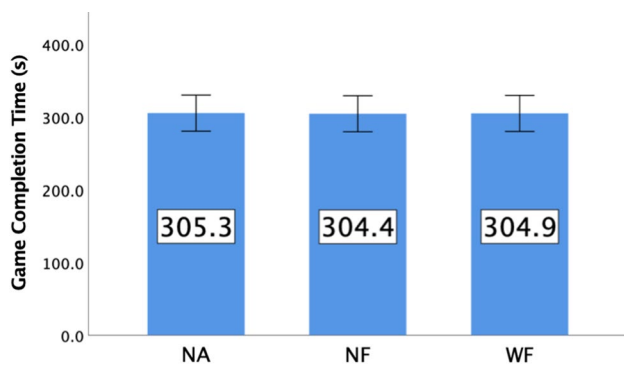
### 3.6 Procedure

Before the experiment started, participants were required to complete a pre-experiment demographic questionnaire (e.g., age, gender, experience with exergames and VR HMDs) and the Physical Activity Readiness Questionnaire (Thomas et al. 1993), which was used to ensure they were physically well enough to participate in the experiment. Then, a researcher gave a detailed description of the experiment. After, participants would sign the consent form to participate in the experiment voluntarily. Then, the researcher would assist them to enter their personal anonymized information (i.e., age, gender, weight, and height) into the Polar Beat mobile app.

Before each condition, the experimenter would help participants wear the Polar OH1 and HMD (i.e., an HP Reverb G2 Omnicept). Participants would only start the experiment when their HR reached the resting HR level. For each condition, there was a training phase to help players practice their movements and become familiar with the wearable devices. This phase was followed by formal gameplay sessions in the corresponding game condition. After each condition, they needed to complete three questionnaires [i.e., PENS (Ryan et al. 2006), VRSQ (Kim et al. 2018), and Borg RPE 6–20 (Borg 1982)] and then, rested until they felt ready to go to

<sup>7</sup> <https://www.hp.com/us-en/vr/reverb-g2-vr-headset.html>.





**Fig. 6** Results of players' performance for Game completion time in seconds

the next condition and had a resting level HR. At the end of the experiment, they would be asked to complete a post-experiment interview, rank the conditions, and share their thoughts on the three conditions. Overall, the whole experiment took around 40 min for each participant.

## 4 Results

We used the Shapiro–Wilks tests and Q-Q plots to check the normality distribution of the data. For normally distributed data, we used one-way repeated-measures ANOVAs (RM-ANOVA) with Audience Feedback [(1) no audience at all, (2) audience with no feedback, (3) audience with feedback] as the within-subjects variable. For data that were not normally distributed, we applied the Aligned Rank Transform (ART) (Wobbrock et al. 2011) to first transform the data and then, applied the one-way RM-ANOVA to analyze the data. We used Bonferroni corrections for all pairwise comparisons, and we report the effect size whenever feasible ( $\eta_p^2$ ).

### 4.1 Player's performance

**Game completion time** The Game Completion Time data were not normally distributed and were transformed by ART (Wobbrock et al. 2011) before using the one-way RM-ANOVA. An ANOVA test found that Audience Feedback ( $F(2, 57) = 0.060, p = 0.942, \eta_p^2 = .302$ ) did not have a significant effect on Game Completion Time (see Fig. 6).

**Success rates of push** A one-way RM-ANOVA revealed that Audience Feedback had a significant effect on the success rate of Push ( $F(2, 57) = 11.694, p < 0.001, \eta_p^2 = 0.285$ ). Post hoc analysis suggested that participants had a higher success rate of Push when there is an NPC audience, and they reacted to their performance (i.e., the WF condition led to better performance than NA and NF (both  $p < 0.001$ )).

)). See Fig. 7a for the success rate of Push under each condition.

**Success rates of Psi** Details of the success rates of Psi can be found in Fig. 7b. A one-way RM-ANOVA reported that Audience Feedback had a significant effect on the success rate of Psi ( $F(2, 57) = 4.006, p < 0.001, \eta_p^2 = 0.355$ ). Post hoc tests revealed that participants had a higher success rate of Psi when the audience and its feedback were both provided (i.e., the WF condition led to better performance of Psi than both NA and NF ( $p < 0.001$ )).

**Success rates of Squat** The one-way RM-ANOVA indicated that Audience Feedback had a significant effect on the success rate of Squat ( $F(2, 57) = 21.296, p < 0.001, \eta_p^2 = 0.421$ ). As shown in Fig. 7c, participants had a higher success rate of Squat in WF than NF and NA conditions (post hoc tests showed both  $p < 0.01$ ).

**Success rates of Zoom** Our ANOVA test suggested that Audience Feedback had a significant effect on the success rate of Zoom ( $F(2, 57) = 8.237, p = 0.001, \eta_p^2 = 0.219$ ). Post hoc tests suggested that WF led to better performance of Zoom than NA and NF (both  $p < 0.001$ ). As shown Fig. 7d, participants had a better performance of Zoom when the audience was present and feedback was provided.

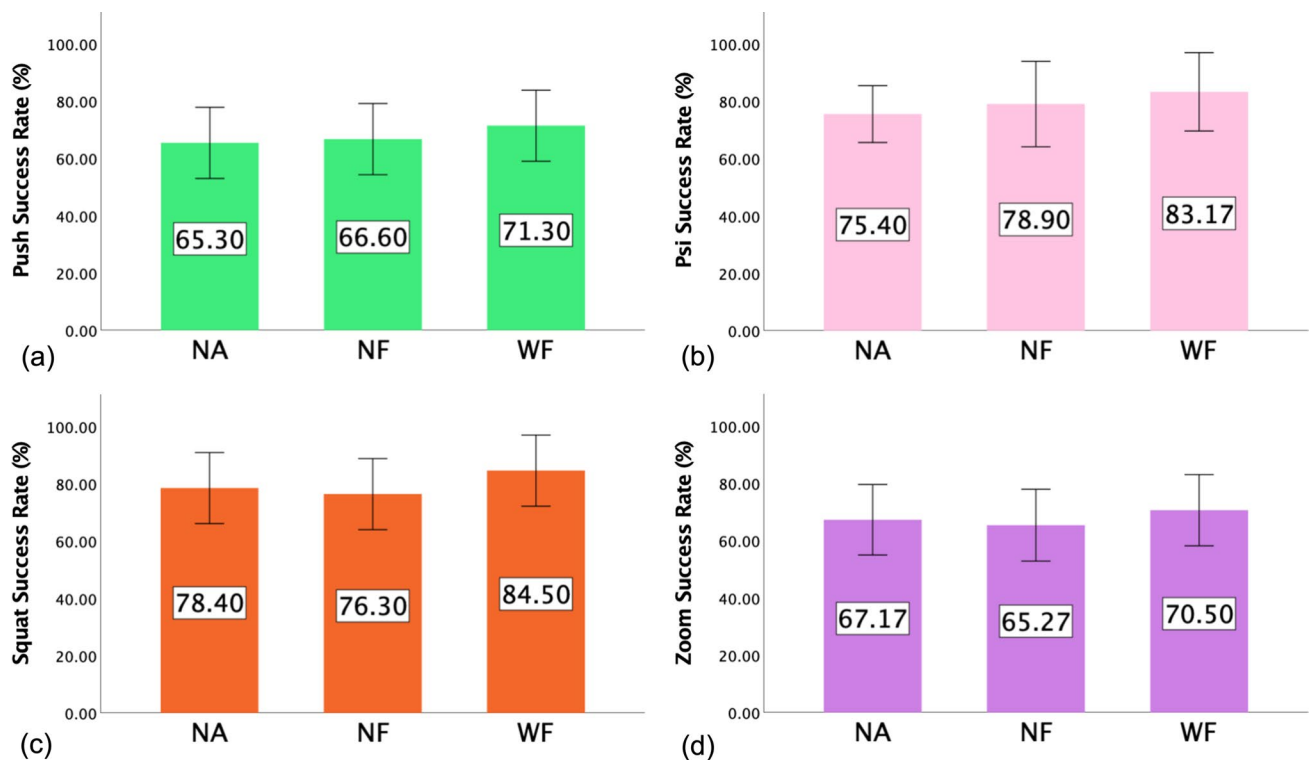
**Participants' Combos** The one-way RM-ANOVA reported that Audience Feedback had a significant effect on participants' performance of Combos ( $F(2, 57) = 31.716, p < 0.001, \eta_p^2 = 0.519$ ). Post hoc tests suggested that participants performed more Combos when the NPC audience and their feedback were both presented (i.e., WF led to better performance of Combos than NA and NF (Both  $p < 0.001$ ); see Fig. 8a).

**Monster's Combos** A one-way RM-ANOVA reported that Audience Feedback had a significant effect on the Monster's Combos ( $F(2, 57) = 37.853, p < 0.001, \eta_p^2 = 0.563$ ). As Fig. 8b shows, the monster performed fewer combos, or the participants prevented the monster from doing combos when the NPC audience and their feedback were provided ( $p < 0.001$ ).

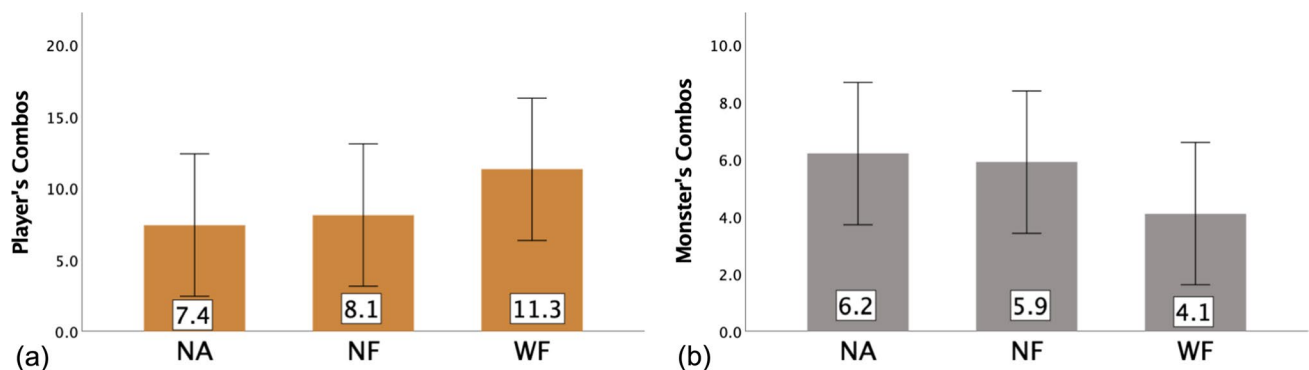
### 4.2 Participants' experience

Figure 9 shows the results of participants' feedback on each condition for Competence, Autonomy, Relatedness, Immersion, and Intuitive Controls.

**PENS: competence** A one-way RM-ANOVA reported that Audience Feedback had a significant effect on the feeling of Competence ( $F(2, 57) = 46.479, p < 0.001, \eta_p^2 = 0.620$ ). As can be seen in Fig. 9a, participants had a greater feeling of Competence when the NPC audience and reactive feedback were provided (i.e., WF led to better competence ratings for players than NA and NF (both  $p < 0.001$ )).



**Fig. 7** Results of players' performance for **a** Push success rate, **b** Psi success rate, **c** Squat success rate, and **d** Zoom success rate



**Fig. 8** Performance results of **a** Player's Combos and **b** Monster's Combos

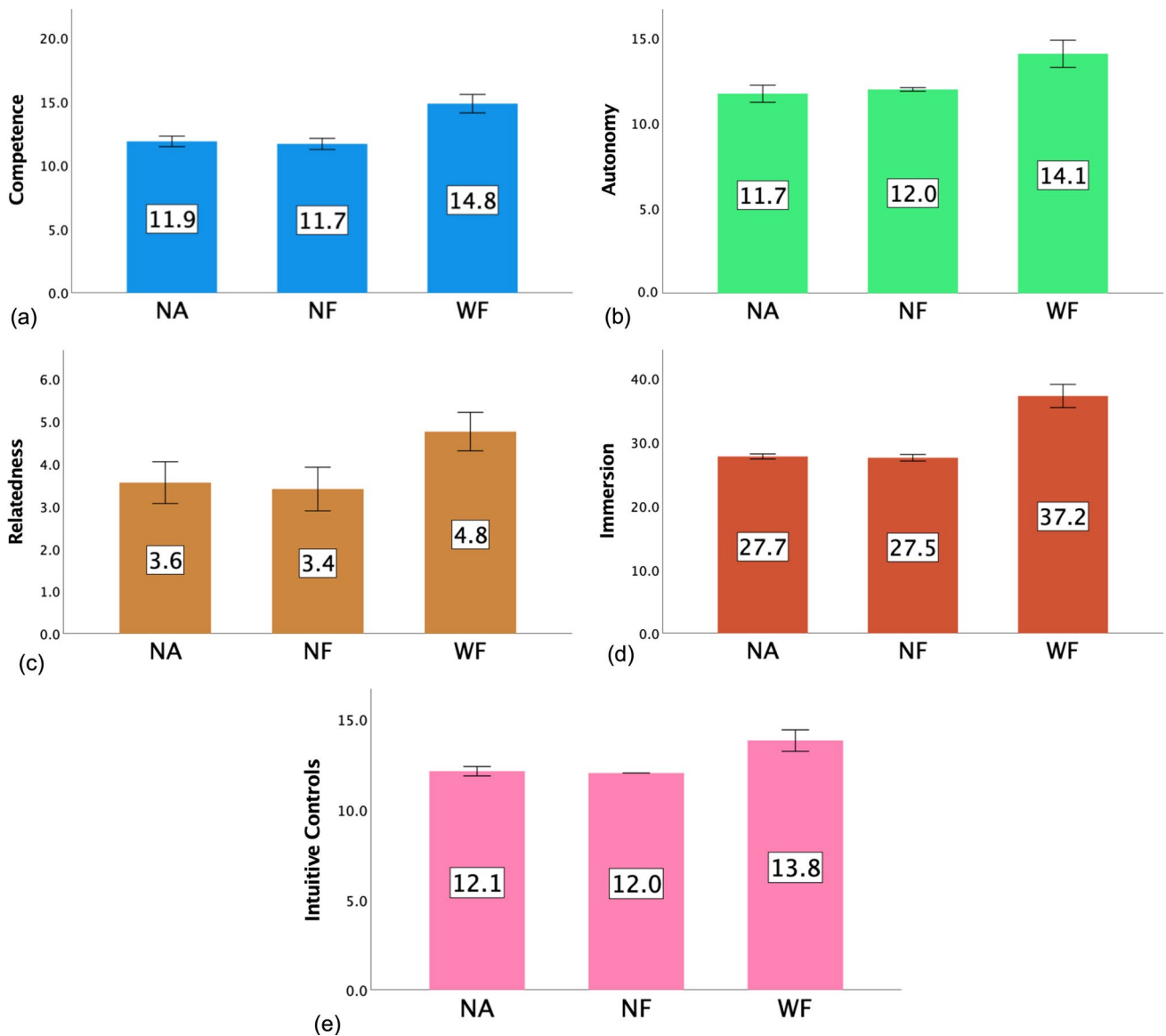
**PENS: autonomy** A one-way RM-ANOVA indicated that Audience Feedback had a significant effect on the feeling of Autonomy ( $F(2, 57) = 24.316, p < 0.001, \eta_p^2 = 0.560$ ). Post hoc tests suggested that WF led to greater Autonomy feeling for players than NA and NF conditions ( $p < 0.01$ ). Figure 9b shows the Autonomy scores under each condition.

**PENS: relatedness** Fig. 9c shows the feeling of Relatedness score under each condition. ANOVA tests showed that Audience Feedback had a significant effect on the feeling of Relatedness ( $F(2, 57) = 10.149, p < 0.001, \eta_p^2 = 0.663$ ). Post hoc analysis indicated that participants had better relatedness feeling when the NPC audience and their feedback were

present (i.e., WF led to better relatedness feeling for players than NA and NF ( $p < 0.01$ )).

**PENS: immersion** A one-way RM-ANOVA reported that Audience Feedback had a significant effect on the feeling of Immersion ( $F(2, 57) = 108.661, p < 0.001, \eta_p^2 = 0.792$ ). We found that participants were more immersed in WF than NA and NF conditions ( $p < 0.001$ ), which Fig. 9d also shows.

**PENS: intuitive controls** Fig. 9e shows the rating for Intuitive Controls among all conditions. Our ANOVA results suggested that Audience Feedback had a significant effect on Intuitive Controls ( $F(2, 57) = 31.530, p < 0.001, \eta_p^2 = 0.525$ ). Post hoc test



**Fig. 9** Results of players' experience for **a** competence, **b** autonomy, **c** relatedness, **d** immersion, and **e** intuitive controls

shows that participants achieved a higher level of intuitive controls in WF than NA and NF conditions (both  $p < 0.01$ ).

**VRSQ: cybersickness** Cybersickness was not detected among all participants as our results showed that all items from VRSQ were rated as 0 (i.e., None) across all conditions.

### 4.3 Perceived exertion

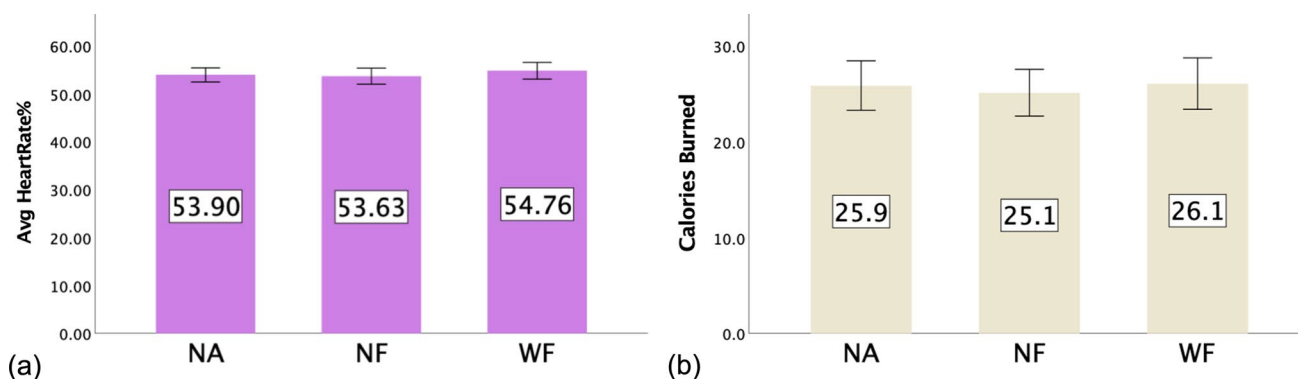
We could not observe any significant effect of Audience Feedback on avgHR% ( $F(2, 57) = 0.587, p = 0.559, \eta_p^2 = 0.220$ ) and Calories burned ( $F(2, 57) = 0.168, p = 0.846, \eta_p^2 = 0.306$ ). Figure 10 shows the detailed score for each measurement. As for the

Borg ratings, all participants rate “no exertion at all” for all conditions.

### 4.4 User ranking and feedback

All participants ( $N = 20$ ) ranked the WF condition (an NPC audience with feedback) as the best option among the three conditions. There was a mix of votes between NA (no NPC audience and no feedback) and NF (has NPC audience but provided no reactive feedback) as their second-best choice: 11 participants voted for NF as their second preferred condition with the remaining 9 voted for NA as their second preferred condition.





**Fig. 10** Results of players' experience for **a** average heart rate (avgHR%) and **b** calories burned

In the following description, the twenty participants were labeled as P1-P20. Overall, 13 participants perceived the design of the NPC-based audience and their feedback in the VR exergame as “*interesting/good*” (P1, P4–6, P9–12, P14–17, P20). They believed that having an NPC audience providing feedback, reacting to their moves, and cheering for them made the exergame “*more enjoyable and competitive*” (P1, P5–6, P9, P14, P16–17, P20). In addition, many participants stated that the design of a supportive NPC audience's feedback could make them realize that their performances were good and made them feel more satisfied with their performance (P1, P5–6, P9, P14, P16–17, P20)—that is, self-gratification and self-belief were stronger with reactive feedback.

Regarding the elements of the design of the audience and its feedback in the VR exergame that they liked, in general, they appreciated the presence of the audience and their feedback: “*I felt like a real fighter to attack the monster because there are my own supporters*” (P1, P4, P6, P14, P20). Some of them also thought that having two audiences, one for the player and another for the monster, were a good idea. “*Having audiences to support both me and the opponent is a good idea, it makes the fighting process more competitive*” (P1, P14, P20). Others liked that “*the audience have varied reactions to their performance*” (P5, P15).

Regarding the elements that they disliked, most participants disliked the condition of the NPC audience with no feedback, since they thought an NPC audience without feedback was “*not natural*” and “*a little bit strange*” (P2–3, P7–8, P18–19). On the other hand, some participants dislike the limited supportive feedback animations (P2–3, P7, P18). They suggested that we could employ more types of animations. They also discussed the appearance of the NPC audience (P4, P6, P12–14, P20); for instance, they suggested that we could add NPC that look like their friends and acquaintances because they believe having familiar faces in the audience would make them more comfortable and encourage them to perform even better.

Our interview data also showed that some participants want to have the chance to customize the gestures according to their capability. Male participants, for example, wanted to have more difficult gestures to give them more intensive exercises. A few said that it would have been good if they could create their own gestures, for example, based on yoga, tai-chi, or traditional dance moves.

## 5 Discussion

In this work, we aimed to explore design features that could help elderly users to improve their performance and gameplay experience in VR exergames. Specifically, we investigated the use of an NPC audience and its feedback that reacted to the movements of both the player and its opponent in the virtual environment.

Based on the results from the user study, we found that players had better performance in terms of success rates of gestures and quality performance (combinations of successful actions) when the NPC audience is present and reactive feedback is provided. Players' success rates of gestures (e.g., Push, Psi, Squat, Zoom) were higher in WF (i.e., the condition with an NPC audience with feedback) than in NA (i.e., the condition with no audience) and NF (i.e., the condition with an audience but no reactive feedback). In addition, results showed that players performed more Combos and prevented more Combos from the monster in WF. Similarly, when the audience reacted to participants' performance in WF, they also had a better gameplay experience than in either NA or NF. More specifically, participants had an improved gameplay experience in terms of competence, autonomy, relatedness, immersion, and intuitive controls.

Social cognitive theory (Bandura 1997, 1982, 2001) argues that people can be motivated to increase their effort to complete a task and have higher levels of self-efficacy when they receive supportive and encouraging messages. Moreover, encouraging audience feedback based on players'

performance has been used to inform the recipients that their performances are improving and have achieved a standard (Ilgen et al. 1979), which in turn can result in positive outcomes, like better performance and experience (Escarti and Guzman 1999; Fitzsimmons et al. 1991; Kim and Timmerman 2018). Our findings are aligned with previous work, because the NPC audience with feedback can provide players with affirmative and supportive messages, which helped improve their performance (i.e., success rates of gestures and quality performance) and experience (in terms of competence, autonomy, relatedness, immersion, and intuitive controls) in the VR exergame. In addition, our results show that this effect can be created for elderly users who do not often seek to engage with new technology, such as VR (Xu et al. 2023). Therefore, these findings could answer *RQ2*: presenting audience and their reactive feedback can positively affect players' performance and experience, including those who are of more advanced age.

We also observed that there were no significant differences in game completion time across conditions. In addition, according to the statistical analysis, we only found that players had better performance (i.e., success rates of gestures and quality performance) and more positive game experience (i.e., competence, autonomy, relatedness, immersion, and intuitive controls) when there was an NPC audience and its feedback, which aligns with the results of a previous short study with young users in a VR cycling game (Haller et al. 2019), which found that an NPC audience improved their participants' performance. However, the presence of an NPC audience without reactive feedback had no significant effect on the elderly's performance and experience which answers *RQ1*.

Regarding the result of the exertion, our results showed that there is no significant difference in calories burned and  $\text{avgHR\%}$  between conditions. This finding seems somewhat contrary to what we had expected, as prior research seems to indicate that feedback from an NPC audience could motivate players to make more efforts on their tasks to improve their performance and experience and increase the heart rate (Haller et al. 2019)—i.e., increase their exertion level. To find an explanation for this finding, we cross-checked our data. For instance, the results of the Borg RPE 6–20 questionnaire point to a low level of total perceived exertion of all three conditions (i.e., no exertion at all). Furthermore, some participants commented in the interview that they thought the level of difficulty and the intensity of the movements were not that high, and so, they did not feel too tired during the experiment. As such, one main reason that the audience and feedback condition did not lead to a greater level of exertion is that the design of our gestures suited to the physical capabilities of the elderly users, and this shows that the participatory design with two elderly playtesters was helpful to find the right parameters and requirements for these

movements. Had we included more difficult movements requiring lower body motions and jumps like other research exergames aimed at younger user groups (e.g., Ioannou et al. (2019); Xu et al. (2020)), the exertion level could have been higher but it could have impacted the elderly users' perception of the exergame and might put them into risk due to physical capability.

## 5.1 Recommendations for the design VR exergames for the elderly

From our results, we have been able to distill the following two main recommendations together with specific design guidelines for developing VR exergames targeting the elderly.

### 5.1.1 Include an audience and feedback that reacts to players' movements in VR exergames

Based on our findings, including an audience (even composed of generic NPCs) and its feedback reacting to the players' movements can improve the performance and enhance the gameplay experience for elderly players. Therefore, we suggest including an audience and providing positive feedback whenever the elderly players are making good progress, for instance, (1) when their performance has achieved a certain level (e.g., a number of successful movements in a row), (2) when their performance has resulted in good outcomes (e.g., taking the lead in rounds won), and (3) when their performance has prevented the opponent from performing well (e.g., blocking an opponent's action). In addition, according to the qualitative feedback from participants, we observed that the number of NPC models for the audience and the number of embedded audio and visual feedback are two other factors that need to be taken into account; in general, more models and a diverse range of visual and audio feedback would be needed.

Previous work has shown that different age groups have different perceptions of the same elements in a game (John et al. 2006; Subramanian et al. 2020; Birk et al. 2017). Thus, we also suggest using those types of NPC audience models and feedback which are more easily understandable and preferred by older adults in VR exergames. One way to achieve this, as suggested by some participants, is to include characters who look like their friends, family members, or acquaintances, which has been also shown to lead to positive feelings in other VR training scenarios (e.g., in giving presentations (Monteiro et al. 2020, 2023)). In addition, it may be suitable to include other practices and cultural elements familiar to the elderly users (e.g., for elderly users in some East Asia countries, such as Japan or China, having big drums in the audience can bring positive feelings because

drums are used in events like weddings, dragon boat festival, or other celebrations, and even football matches).

### 5.1.2 Gesture customization or adaptive exertion level for older adult users

Prior work (Xu et al. 2020) showed that high-intensity movements could lead to some benefits when exercising. Based on our findings, we observed that the presence of an NPC audience and its feedback has no significant effect on players' perceived exertion level. According to the analysis of the gestures and comments from participants, it seems that the intensity and the complexity of each movement are not high enough to result in significant differences. The following solutions could be adopted depending on the exertion requirement of the exergame. When all movements can achieve the desired exertion of the exergame, possible solutions are (1) providing the players with a list of movements and enabling them to select their preferred gestures, or (2) allowing the players to customize the gestures; both approaches could lead to a better and more personalized experience. When some movements cannot achieve the desired exertion level but are necessary to help players reach a certain exertion level, a possible approach is to apply an adaptive exertion level (e.g., automatically changing the intensity and requirement of a movement/gesture, such as squatting lower and closer to the ground for it to be counted as a successful move in more advanced levels) for each participant based on each individual's physical ability level, exercise demands, and performance in the game.

### 5.2 Limitations and future work

There are some limitations in this work, which can also serve as directions for future work. One limitation is related to the audience in that we only involved three types of cheering motions (i.e., standing up, jumping in place, clapping their hands) and only one type of sound feedback (a mixture of cheering and hand clapping). Future work could (1) involve more types of cheering motions-hands up, thumb up, hitting drums, waving flags, and more sounds-singing songs, and screaming; (2) adjust the length/frequency of the cheering to make them dynamic; (3) add facial expressions to the audience as a type of performance feedback; and (4) add other cultural elements that older adult users are familiar with or fond of hearing.

In addition, our study only employed 10 character models and, while our participants did not have any issues with the relatively homogeneous audience, future work can involve more models with more diverse cultural and

physical features to see if they have the same effect on players' performance and gameplay. As some participants indicated, models could even be based on their family members, friends, or acquaintances. Current machine learning techniques can generate 3D faces by using a single image of the user (Deng et al. 2019), similar technology has already been used in games such as football manager.<sup>8</sup> Similarly, the models could be famous characters from movies of whom older adults are fans.

## 6 Conclusion

In this work, we examined the effect of the presence of an audience based on non-player characters (NPC) and its reactive feedback on older adult users of virtual reality (VR) exergames. We focused on their performance, gameplay experience, perceived exertion, and subjective preference. Our results lead to two important observations for the type of exergame used in our research: (1) the presence of a virtual audience but without feedback has no impact on elderly users in VR exergames; (2) providing NPC audiences and their reactive feedback are useful in improving older adult players' performance, resulting in higher gesture success rates, more successful combos performed, and more opponent's moves prevented by the players, and gameplay experience (in terms of competence, autonomy, relatedness, immersion, and intuitive controls). Most importantly, having audience feedback responding to players' actions has a higher impact on players than simply providing an audience without any responsive supportive feedback, particularly in the context of older adult players. From these results, we provided two recommendations that can help to design future VR exergames that can motivate improved performance and gameplay experience of elderly users, a rapidly growing user group across many countries.

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**Availability of data and materials** Data and related materials are available upon reasonable request to the corresponding author.

### Declarations

**Conflict of interest** There are no conflicts of interest to report.

<sup>8</sup> <https://www.footballmanager.com/games/football-manager-2023>.



**Ethical approval** The study was categorized as Low-Risk Research (LRR) research, conducted according to the guidelines regulating LRR projects, and approved by the University Ethics Committee at Xi'an Jiaotong-Liverpool University.

**Consent to participate** Participants consented to participate in the study on a voluntary basis.

**Consent for publication** All authors read the paper and agreed for it to be submitted for review and publication.

## References

- Aiello J, Douthitt E (2001) Social facilitation from triplatt to electronic performance monitoring. *Group Dyn* 5(3):163–180. <https://doi.org/10.1037/1089-2699.5.3.163>
- Bandura A (1982) Self-efficacy mechanism in human agency. *Am Psychol* 37(2):122–147. <https://doi.org/10.1037/0003-066x.37.2.122>
- Bandura A (1997) Self-efficacy: the exercise of control. *J Cogn Psychother* 13(2):158–166. <https://doi.org/10.1891/0889-8391.13.2.158>
- Bandura A (2001) Social cognitive theory of mass communication. *Media Psychol* 3(3):265–299. [https://doi.org/10.1207/S1532785XMEP0303\\_03](https://doi.org/10.1207/S1532785XMEP0303_03)
- Bindarwish J, Tenenbaum G (2006) Metamotivational and contextual effects on performance, self-efficacy, and shifts in affective states. *Psychol Sport Exerc* 7(1):41–56. <https://doi.org/10.1016/j.psychsport.2005.04.001>
- Bird M-L, Clark B, Millar J, Whetton S, Smith S (2015) Exposure to “exergames” increases older adults’ perception of the usefulness of technology for improving health and physical activity: a pilot study. *JMIR Ser Games* 3(2):8. <https://doi.org/10.2196/games.4275>
- Birk MV, Friehs MA, Mandryk RL (2017) Age-based preferences and player experience: a crowdsourced cross-sectional study. In: Proceedings of the annual symposium on computer-human interaction in play. CHI PLAY ’17. Association for Computing Machinery, New York, pp 157–170. <https://doi.org/10.1145/3116595.3116608>
- Bolton J, Lambert M, Lirette D, Unsworth B (2014) Paperdude: a virtual reality cycling exergame. In: CHI ’14 extended abstracts on human factors in computing systems. CHI EA ’14. Association for Computing Machinery, New York, pp 475–478. <https://doi.org/10.1145/2559206.2574827>
- Bond CF, Titus LJ (1983) Social facilitation: a meta-analysis of 241 studies. *Psychol Bull* 94(2):265–292. <https://doi.org/10.1037/0033-2909.94.2.265>
- Borg GA (1982) Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 14(5):377–381
- Chen N, Zhou M, Dong X, Qu J, Gong F, Han Y, Qiu Y, Wang J, Liu Y, Wei Y, Xia J, Yu T, Zhang X, Zhang L (2020) Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: a descriptive study. *The Lancet* 395(10223):507–513. [https://doi.org/10.1016/S0140-6736\(20\)30211-7](https://doi.org/10.1016/S0140-6736(20)30211-7)
- De Queiroz BM, Borgatto AF, Barbosa AR, Guimarães AV (2017) Exergame vs. aerobic exercise and functional fitness of older adults: a randomized controlled trial. *J Phys Edu Sport* 17(02):740–747. <https://doi.org/10.7752/jpes.2017.02112>
- Deci EL, Koestner R, Ryan RM (1999) A meta-analytic review of experiments examining the effects of extrinsic rewards on intrinsic motivation. *Psychol Bull* 125:627–668. <https://doi.org/10.1037/0033-2909.125.6.627>
- Deng Y, Yang J, Xu S, Chen D, Jia Y, Tong X (2019) Accurate 3d face reconstruction with weakly-supervised learning: From single image to image set. In: 2019 IEEE/CVF conference on computer vision and pattern recognition workshops (CVPRW). IEEE Computer Society, Los Alamitos, pp 285–295. <https://doi.org/10.1109/CVPRW.2019.00038>
- Ducheneaut N, Yee N, Nickell E, Moore R.J (2006) “Alone together?”: exploring the social dynamics of massively multiplayer online games. In: Proceedings of the SIGCHI conference on human factors in computing systems. CHI ’06. Association for Computing Machinery, New York, pp 407–416. <https://doi.org/10.1145/1124772.1124834>
- Escarti A, Guzman JF (1999) Effects of feedback on self-efficacy, performance, and choice in an athletic task. *J Appl Sport Psychol* 11(1):83–96. <https://doi.org/10.1080/10413209908402952>
- Fitzsimmons PA, Landers DM, Thomas JR, van der Mars H (1991) Does self-efficacy predict performance in experienced weightlifters? *Res Q Exerc Sport* 62(4):424–431. <https://doi.org/10.1080/02701367.1991.10607544>. (PMID: 1780566)
- Gernigon C, Delloye J-B (2003) Self-efficacy, causal attribution, and track athletic performance following unexpected success or failure among elite sprinters. *Sport Psychol* 17(1):55–76. <https://doi.org/10.1123/tsp.17.1.55>
- Goldspink DF (2005) Ageing and activity: their effects on the functional reserve capacities of the heart and vascular smooth and skeletal muscles. *Ergonomics* 48(11–14):1334–1351. <https://doi.org/10.1080/00140130500101247>
- Guan W-j, Ni Z-y, Hu Y, Liang W-h, Ou C-q, He J-x, Liu L, Shan H, Lei C-l, Hui D, Du B, Li L-j, Zeng G, Yuen K-Y, Chen R-c, Tang C-l, Wang T, Chen P-y, Xiang J, Li S-y, Wang J-l, Liang Z-j, Peng Y-x, Wei L, Liu Y, Hu Y-h, Peng P, Wang J-m, Liu J-y, Chen Z, Li G, Zheng Z-j, Qiu S-q, Luo J, Ye C-j, Zhu S-y, Zhong N-s (2020) Clinical characteristics of coronavirus disease 2019 in China. *New Engl J Med* 382(18):1708–1720. <https://doi.org/10.1056/NEJMoa2002032>
- Haller JC, Jang YH, Haller J, Shaw L, Wünsche BC (2019) Hiit the road: Using virtual spectator feedback in hiit-based exergaming. In: Proceedings of the Australasian computer science week multi-conference. ACSW 2019. Association for Computing Machinery, New York. <https://doi.org/10.1145/3290688.3290752>
- Ilgel D, Fisher C, Susan M (1979) Consequences of individual feedback on behavior in organizations. *J Appl Psychol* 64:349–371. <https://doi.org/10.1037/0021-9010.64.4.349>
- Ioannou C, Archard P, O’Neill E, Lutteroth C (2019) Virtual performance augmentation in an immersive jump and run exergame. In: Proceedings of the 2019 CHI conference on human factors in computing systems. CHI ’19. Association for Computing Machinery, New York, pp 1–15. <https://doi.org/10.1145/3290605.3300388>
- Kappen D.L, Mirza-Babaei P, Johannsmeier J, Buckstein D, Robb J, Nacke L.E (2014) Engaged by boos and cheers: the effect of co-located game audiences on social player experience. In: Proceedings of the 1st ACM SIGCHI annual symposium on computer-human interaction in play. CHI PLAY ’14. Association for Computing Machinery, New York, pp 151–160. <https://doi.org/10.1145/2658537.2658687>
- Kennedy RS, Lane NE, Berbaum KS, Lilienthal MG (1993) Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. *Int J Aviat Psychol* 3(3):203–220. [https://doi.org/10.1207/s15327108ijap0303\\_3](https://doi.org/10.1207/s15327108ijap0303_3)
- Kim J, Timmerman CE (2018) Effects of supportive feedback messages on exergame experiences: a mediating role of social presence. *J Media Psychol* 30(1):29–40. <https://doi.org/10.1027/1864-1105/a000175>
- Kim SYS, Prestopnik N, Biocca FA (2014) Body in the interactive game: How interface embodiment affects physical activity and

- health behavior change. *Comput Hum Behav* 36:376–384. <https://doi.org/10.1016/j.chb.2014.03.067>
- Kim HK, Park J, Choi Y, Choe M (2018) Virtual reality sickness questionnaire (vrsq): motion sickness measurement index in a virtual reality environment. *Appl Ergonom* 69:66–73. <https://doi.org/10.1016/j.apergo.2017.12.016>
- Konstantinidis EI, Billis AS, Mouzakidis CA, Zilidou VI, Antoniou PE, Bamidis PD (2016) Design, implementation, and wide pilot deployment of fitforall: an easy to use exergaming platform improving physical fitness and life quality of senior citizens. *IEEE J Biomed Health Informat* 20(1):189–200. <https://doi.org/10.1109/JBHI.2014.2378814>
- Lai C-C, Liu YH, Wang C-Y, Wang Y-H, Hsueh S-C, Yen M-Y, Ko W-C, Hsueh P-R (2020) Asymptomatic carrier state, acute respiratory disease, and pneumonia due to severe acute respiratory syndrome coronavirus 2 (sars-cov-2): facts and myths. *J Microbiol, Immunol Infect* 53(3):404–412. <https://doi.org/10.1016/j.jmii.2020.02.012>
- Larsen LH, Schou L, Lund HH, Langberg H (2013) The physical effect of exergames in healthy elderly—a systematic review. *Games Health J* 2(4):205–212. <https://doi.org/10.1089/g4h.2013.0036>. (PMID: 26192224)
- Mellecker R, Lyons EJ, Baranowski T (2013) Disentangling fun and enjoyment in exergames using an expanded design, play, experience framework: a narrative review. *Games Health J* 2(3):142–149. <https://doi.org/10.1089/g4h.2013.0022>
- Mikus C, Oberlin D, Libla J, Taylor A, Booth F, Thyfault J (2011) Lowering physical activity impairs glycemic control in healthy volunteers. *Med Sci Sports Exerc* 44(2):225–31. <https://doi.org/10.1249/MSS.0b013e31822ac0c0>
- Monteiro D, Liang H-N, Li H, Fu Y, Wang X (2020) Evaluating the need and effect of an audience in a virtual reality presentation training tool. In: *Computer animation and social agents*, pp 62–70. [https://doi.org/10.1007/978-3-030-63426-1\\_7](https://doi.org/10.1007/978-3-030-63426-1_7)
- Monteiro D, Wang A, Wang L, Li H, Barrett A, Pack A, Liang H-N (2023) Effects of audience familiarity on anxiety in a virtual reality public speaking training tool. *Universal Access in the Information Society*. <https://doi.org/10.1007/s10209-023-00985-0>
- Moreira NB, Rodacki ALF, Costa SN, Pitta A, Bento PCB (2021) Perceptive-cognitive and physical function in prefrail older adults: exergaming versus traditional multicomponent training. *Rejuven Res* 24(1):28–36. <https://doi.org/10.1089/rej.2020.2302>
- Nes BM, Janszky I, Wisløff U, Støylen A, Karlsen T (2013) Age-predicted maximal heart rate in healthy subjects: the hunt fitness study. *Scand J Med Sci Sports* 23(6):697–704. <https://doi.org/10.1111/j.1600-0838.2012.01445.x>
- Peng W, Lin J-H, Pfeiffer KA, Winn B (2012) Need satisfaction supportive game features as motivational determinants: an experimental study of a self-determination theory guided exergame. *Media Psychol* 15(2):175–196. <https://doi.org/10.1080/15213269.2012.673850>
- Peng H-T, Tien C-W, Lin P-S, Peng H-Y, Song C-Y (2020) Novel mat exergaming to improve the physical performance, cognitive function, and dual-task walking and decrease the fall risk of community-dwelling older adults. *Front Psychol* 11:9. <https://doi.org/10.3389/fpsyg.2020.01620>
- Rendon AA, Lohman EB, Thorpe D, Johnson EG, Medina E, Bradley B (2012) The effect of virtual reality gaming on dynamic balance in older adults. *Age Ageing* 41(4):549–552. <https://doi.org/10.1093/ageing/afs053>
- Ryan RM, Rigby CS, Przybylski A (2006) The motivational pull of video games: a self-determination theory approach. *Motiv Emot* 30(4):344–360. <https://doi.org/10.1007/s11031-006-9051-8>
- Sherry JL, Greenberg BS, Lucas K, Lachlan K (2006) Video game uses and gratifications as predictors of use and game preference. In: *Playing video games: motives, responses, and consequences*, 1st edn. Lawrence Erlbaum Associates Publishers, Hillsdale, pp 248–262, Chap. 15. <https://doi.org/10.4324/9780203873700-18>
- Spittle B, Xu W, Frutos-Pascual M, Creed C, Williams I (2021) Socially distanced: Have user evaluation methods for immersive technologies changed during the covid-19 pandemic? In: *2021 IEEE international symposium on mixed and augmented reality adjunct (ISMAR-Adjunct)*, pp 415–420. <https://doi.org/10.1109/ISMAR-Adjunct54149.2021.00094>
- Strojny PM, Dużmańska-Misiarczyk N, Lipp N, Strojny A (2020) Moderators of social facilitation effect in virtual reality: co-presence and realism of virtual agents. *Front Psychol*. <https://doi.org/10.3389/fpsyg.2020.01252>
- Subramanian S, Dahl Y, Skjæret Maroni N, Vereijken B, Svanæs D (2020) Assessing motivational differences between young and older adults when playing an exergame. *Games Health J* 9(1):24–30. <https://doi.org/10.1089/g4h.2019.0082>. (( PMID: 31532235))
- Taylor AH, Cable NT, Faulkner G, Hillsdon M, Narici M, Van Der Bij AK (2004) Physical activity and older adults: a review of health benefits and the effectiveness of interventions. *J Sports Sci* 22(8):703–725. <https://doi.org/10.1080/02640410410001712421>
- Thomas S, Reading J, Shephard R (1993) Revision of the physical activity readiness questionnaire (PAR-Q). *Can J Sport Sci* 17(4):338–45
- United nations department of economic and social affairs: World Population Prospects 2022: summary of results. Technical Report UN DESA/POP/2022/TR/NO.3, New York (2022). [https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022\\_summary\\_of\\_results.pdf](https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf). Accessed 24 Jan 2023
- Warburton DER, Nicol CW, Bredin SSD (2006) Health benefits of physical activity: the evidence. *CMAJ: Can Med Assoc J* 174(6):801–809. <https://doi.org/10.1503/cmaj.051351>
- Wobbrock JO, Findlater L, Gergle D, Higgins JJ (2011) The aligned rank transform for nonparametric factorial analyses using only Anova procedures. In: *Proceedings of the SIGCHI conference on human factors in computing systems*. CHI '11. Association for Computing Machinery, New York, pp 143–146. <https://doi.org/10.1145/1978942.1978963>
- Xu W, Liang H-N, Baghaei N, Wu Berberich B, Yue Y (2020) Health benefits of digital videogames for the aging population: a systematic review. *Games Health J* 9(6):389–404. <https://doi.org/10.1089/g4h.2019.0130>
- Xu W, Liang H-N, He Q, Li X, Yu K, Chen Y (2020) Results and guidelines from a repeated-measures design experiment comparing standing and seated full-body gesture-based immersive virtual reality exergames: within-subjects evaluation. *JMIR Ser Games* 8(3):17972. <https://doi.org/10.2196/17972>
- Xu W, Liang H-N, Zhang Z, Baghaei N (2020) Studying the effect of display type and viewing perspective on user experience in virtual reality exergames. *Games Health J* 9(6):405–414. <https://doi.org/10.1089/g4h.2019.0102>. (PMID:32074463)
- Xu W, Liang H-N, Baghaei N, Ma X, Yu K, Meng X, Wen S (2021) Effects of an immersive virtual reality exergame on university students' anxiety, depression, and perceived stress: pilot feasibility and usability study. *JMIR Ser Games* 9(4):29330. <https://doi.org/10.2196/29330>
- Xu W, Liang H-N, Yu K, Wen S, Baghaei N, Tu H (2023) Acceptance of virtual reality exergames among Chinese older adults. *Int J Hum-Comput Interact* 39(5):1134–1148. <https://doi.org/10.1080/10447318.2022.2098559>
- Xu W, Liang H-N, Ma X, Li X (2020) Virusboxing: A hiit-based vr boxing game. CHI PLAY '20. Association for Computing Machinery, New York, pp 98–102. <https://doi.org/10.1145/3383668.3419958>
- Xu W, Liang H-N, Yu K, Baghaei N (2021) 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. CHI '21. Association for Computing Machinery, New York. <https://doi.org/10.1145/3411764.3445801>
- Xu W, Liang H-N, Yu Y, Monteiro D, Hasan K, Fleming C (2019) Assessing the effects of a full-body motion-based exergame in virtual reality. In: Proceedings of the 7th international symposium of Chinese CHI. Chinese CHI '19. Association for Computing Machinery, New York, pp 1–6. <https://doi.org/10.1145/3332169.3333574>
- Yang C-M, ChenHsieh JS, Chen Y-C, Yang S-Y, Lin H-CK (2020) Effects of kinect exergames on balance training among community older adults. *Medicine* 99(28):21228. <https://doi.org/10.1097/MD.00000000000021228>
- Yu T-C, Chiang C-H, Wu P-T, Wu W-L, Chu I-H (2020) Effects of exergames on physical fitness in middle-aged and older adults in

Taiwan. *Int J Environ Res Public Health*. <https://doi.org/10.3390/ijerph17072565>

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