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Social Balance Ball: Designing and Evaluating an Exergame That Promotes Social Interaction between Older and Younger Players

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ABSTRACT

As the population ages rapidly, there is a strong focus on the healthy aging of older adults. A central part of healthy aging is keeping people connected in later social life. Exergames are recommended as one of the coping strategies to help improve health and quality of life in older adults. In our study, we developed an exergame called Social Balance Ball to engage older and younger people to play together, encouraging social interaction between generations. From May to July 2021, we evaluated this exergame in Shanghai, China, performing a user experiment with 18 unfamiliar young-old pairs under three test conditions (virtual player, mediated human player, and co-located human player). To evaluate the exergame, our main findings demonstrated that participants felt significantly perceived social interaction in mediated play and co-located play than in virtual play. Overall, older participants perceived significantly higher social interaction than younger participants. In this study, we contribute (1) empirical research findings on how the Social Balance Ball exergame enhances social interaction in generations; (2) design implications for informing future design and development of social exergames.

1. Introduction

The global population is aging rapidly; between 2015 and 2050, the proportion of older adults will almost double (WHO, 2021). Globally, people aged 60 or older are growing faster than in other age groups (WHO, 2019). As the population ages, there is often a greater focus on the healthy aging of older adults. As defined by WHO (2020), healthy aging is "the process of developing and maintaining the functional ability that enables well-being in older age." Physical well-being is an important part of healthy aging, and fall is one of the greatest threats to the physical health of older adults (WHO, 2014), and fall prevention strategies, such as balance training have been shown to be effective in reducing the rate and risk of fall in older adults (Gillespie et al., 2012). Another part of healthy aging involves keeping social connections, which are central to older adults' well-being (Macdonald et al., 2021). The power of a social network can "enhance a senior's longevity, quality of life, protect against functional decline and promote resilience" (WHO, 2015). However, as people age, they become more likely to reduce social interaction and almost unavoidably feel lonely. Emotional and social isolation in older adults can be caused by many factors, such as the loss of family and friends, poor health, and reduced income (Zhang et al., 2017). Social trends, such as less intergenerational living and less community cohesion also play a role (Bernard, 2013). Additionally, in recent years, due to the ongoing impact of the COVID-19 pandemic, older adults are advised to maintain social distancing and stay at home or in institutions most of the time. They lack physical activities and cannot see friends and family members as usual. Such a situation exacerbates the social loneliness of older adults, adversely affecting their physical and mental health.

To address these aging-related issues, an exergame [i.e., the combination of exercise and video games (Bogost, 2007)] is recommended as a coping strategy to help improve the health of older adults, especially during the COVID-19 quarantine period (Viana & De Lira, 2020). As stated by Loos and Kaufman (2018), while exergaming is universally loved and has benefits for mental health and physical activity of older adults, it remains unclear whether the outcomes of exergaming interventions have a strong evidence base. The majority of previous studies focused on examining the efficacy of the exergames in improving balance and reducing the risk of falls in older adults (Clark & Kraemer, 2009; Garcia et al., 2018; Pisan et al., 2013). For example, Clark and Kraemer (2009) investigated the effect of a commercial exergame to address balance dysfunction in older adults in a nursing home who were at risk for falls. Pisan et al. (2013) developed the Microsoft-Kinect-based step training system to predict the loss of balance for older adults under cognitive load. Garcia et al. (2018) evaluated a fall prevention game's compliance, fun, and ease of use to determine its suitability for use as an unsupervised home training tool for older adults. However, all of these balance training

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exergames are designed to be played alone. Older adults like playing with other people in a social context (Loos & Kaufman, 2018; Loos & Zonneveld, 2016; Villani et al., 2017). Additionally, a narrative literature review (Loos, 2017) found that social interaction is one of the most important factors in older adults playing exergames.

Thus, improvements in well-being should not be limited to older adults' physical or cognitive health but must also extend to the social domain (Rice et al., 2013). For this research purpose, we conducted an empirical study that focuses uniquely on the social dimension of the exergame (including social interaction, social connectedness, emotional state, etc.). Generally, intergenerational interactions consist of two types: (1) older people interact with younger people in the family, or (2) interact with unfamiliar younger people (Salehzadeh Niksirat et al., 2022). Unlike most existing research studies regarding social intergenerational family entertainment (Fuchsberger et al., 2012; Khoo et al., 2009; Salehzadeh Niksirat et al., 2022), our design purpose is to enhance social interaction among unfamiliar older and younger people. As reported by Thang (2006), family interactions reduce due to lifestyle and family structure changes, which fosters new synergies in intergenerational exchanges between non-family age groups. Thus, we focus on evaluating strangers (rather than family members), motivated by an interest in understanding how the exergame can be leveraged in community practice to encourage social interaction.

In our study, an exergame called Social Balance Ball was implemented to engage older and younger people to play together. We examine the impact of the Social Balance Ball on the mental and social well-being of older and younger participants to understand how this exergame can best promote social interaction between generations. We use three different modes to test the level of social presence of the co-player as a determinant of player experience. Thus, the system was implemented with three conditions: (1) virtual player, (2) mediated human player (i.e., participants played online), and (3) co-located human player (i.e., participants played face-to-face). In the virtual player mode, the counterpart's game avatar appears on the game interface but two remote human players do not play together. In fact, in this mode, two remote players control the game independently, while in the mediated human player mode, two remote players use their own Social Balance Balls to control the game avatar to play together. Virtual player mode is a control condition in which there is no social interaction between two human players. A within-subjects study of 36 participants, including 18 older and 18 younger participants, was conducted in Shanghai, China, from May 2021 to July 2021. We compared three working modes of Social Balance Ball in terms of social presence, social connectedness, and emotional state. Our work can contribute to the HCI research community in two main ways:

1. Empirical evidence suggests that balance training exergames in social settings, whether online or in-person, can have positive effects on intergenerational interactions between unfamiliar younger and old players;
2. Our findings also aid in HCI design and shed light on innovations in intergenerational balance training systems that promote physical, mental, and emotional well-being in older adults.

In this article, we investigate the primary research question about how the Social Balance Ball exergame affects intergenerational interactions. More specifically, we are interested in which specific factors can influence intergenerational interactions in social balance training games, such as different social modes, different perceptions of older and younger people, or the impact of gender on exergames. All of these have rarely been discussed in previous studies. We, therefore, address the following four sub-research questions:

RQ1: How does the Social Balance Ball impact the social interaction of all players in three conditions?

RQ2: Do older and younger players perceive social interaction differently in this exergame?

RQ3: Does gender affect the perceived social interaction of players in this exergame?

RQ4: How do the findings from this study inform us about designing exergames in a social context?

For **RQ1**, **RQ2**, and **RQ3**, we presented three relevant hypotheses in the experimental design:

H1: All players perceive significantly different social interactions under the three different modes of the Social Balance Ball.

H2: Older and younger players perceive significantly different social interactions in the Social Balance Ball exergame.

H3: Male and female players perceive significantly different social interactions in the Social Balance Ball exergame.

For **RQ4**, we use semi-structured interviews to gather qualitative feedback from all players on their attitudes, perceptions, and design recommendations for the Social Balance Ball.

2. Related work

2.1. Older adults and balance training exergames

Exergames have the potential to facilitate long-term exercise for older adults. Traditional balance training includes booklets or videos demonstrating training procedures, but it lacks feedback that older adults do not know their performance and the effects of the training. Nowadays new technologies, such as immersive VR/AR experiences have been applied to older adults, showing potential for fall prevention or balance training. Rings et al. (2020) implemented the VR exergame for fall prevention and found it promising in motivating exercise. Promising results were also found in an experiment involving older adults and therapists using an exergame aimed at stroke rehabilitation (Donker et al., 2015). Older adults thought the exergame facilitates their training, while therapists mentioned the effectiveness and ease of use. Nawaz et al. (2014) assessed older adults' user experience and preference of the exergames, in which older adults indicated the motivational effects of the exergame, and they expected the exergame to provide challenging tasks and present the qualities of their exercise. Some researchers also focused on the long-term usage of the exergame and found that older adults playing the exergame are more likely to reach the exercise requirements and adhere to the training plan compared to those who used the traditional balance training (Uzor & Baillie, 2014). One of the reasons is that exergames can provide feedback about training to keep older adults' confidence in the process and appeal to them with visual feedback, such as interesting gaming (Brickwood et al., 2016). Additionally, among the many advantages brought by exergames, social interaction of the exergames still needs to be studied. For example, Pecchioni and Osmanovic (2018) revealed connections between social interaction and the long duration of gameplay in the generic games. To achieve an improvement in long-term balance training, social interaction should be considered in such an exergame. In particular, older adults showed more exercise intentions while playing exergames with younger people (Xu et al., 2016). They may also look forward to social interaction with younger generations because it will make them feel young and energetic, and they consider young people are more aware of the present society and trending (Fuchsberger et al., 2012; Leung et al., 2012). Thus, exergames providing proper feedback can make the training more rewarding while social interaction of the game facilitates long-term gameplay.

2.2. Social exergames

Social exergames have many advantages. Caro et al. (2018) found that pre-existing positive relationships, such as friendships positively affect physical activity levels of players when playing social action-based games compared to strangers, and this effect increases when more game actions are amplified. However, the level of overall physical activity declined after four weeks. Rooksby et al. (2015) developed a mobile application called Pass the Ball to enable a turn-taking mechanism. Based on a "*research through design*" approach, they found that taking turns can increase the level of enjoyment, communication, and social interaction between players. In addition, many previous studies have explored how exergames can facilitate social play in computer-mediated environments (Mueller et al., 2009, 2010), and how social elements can be incorporated into exergames to increase game engagement (Mueller et al., 2017). Mueller et al. (2009) discussed how social interaction and exergames complement each other to achieve a win-win situation. They conducted a qualitative case study to show that a social exergame supported by varying intensities of exertion activity can convey meaning to players in a social setting. Mueller et al. (2010) conducted a qualitative study with a social exergame "Table Tennis for Three." They found a significant theme: anticipation, the idea that the physical actions of other players create anticipation for the development of the game, which is an important part of social exergames. While considering physical interaction, Mueller et al. (2017) focused on the dimension of bodily interplay: parallel and interdependent play in the social exergame and its affect on players' experiences. By studying different coupling of bodily interplay dimension, they offered tools and guidance for designing social exergames with better gaming experience. This section discusses the benefits of social exergames, which can provide opportunities for new ways of intergenerational interaction.

2.3. Intergenerational games

Intergenerational interaction is a promising way to promote an active lifestyle (Flora & Faulkner, 2007), improve moods (Newman et al., 1995), self-esteem (Kessler & Staudinger, 2007), and life satisfaction in older adults (Kessler & Staudinger, 2007; Powers et al., 2013), as well as strengthen family bonds (Bengtson, 2001). Intergenerational ties can increase well-being by providing older adults opportunities to feel young, rediscover their abilities, and share joy with younger generations (Zhang et al., 2017). As digital devices have become a core part of everyday life (Bogost, 2007; Sarachan, 2012), intergenerational games get increased attention in HCI. For example, Costa and Veloso (2016) pointed to the potential of digital games to strengthen intergenerational interactions, such as bridging intergenerational gaps, fostering a sense of togetherness, and stimulating intergenerational awareness.

Most studies explored intergenerational games based on family relationships (e.g., father-son, grandmother, and granddaughter) as it is the most common type of intergenerational relationship (Salehzadeh Niksirat et al., 2022). Pecchioni and Osmanovic (2018) investigated the potential of cooperative video gameplay to establish or restore intergenerational family relationships. Findings suggested that intergenerational games as a shared activity positively impacted family relationships by increasing relationship closeness between grandparents and grandchildren. Fuchsberger et al. (2012) developed a novel online-intergenerational game for geographically separated grandparents and grandchildren to enhance family ties. Furthermore, Cantwell et al. (2012) designed and implemented a prototype for intergenerational exergaming. It offers personalized difficulty levels so that old and young can work better together or compete against each other.

A growing number of HCI studies also explored the benefits of playing such games in non-family user groups. Xu et al. (2016) studied the effects of exergames on older adults' exercise intentions. They conducted a three-week experiment to compare the effects of playing the exergame among young-old and old-old conditions. Findings demonstrated that older adults in the young-old condition felt more motivated to play the exergame than those in the old-old condition. Zhang et al. (2017) recruited five intergenerational pairs to play two Wii games and record their gameplay and conversations. During game sessions, older participants acted as students, followers, and storytellers, while younger participants acted as teachers, leaders, encouragers, and caregivers. Their conversations were analyzed by the Conversation Analysis (CA) method which is a systematic analysis of social interaction. In this method, social interactions are recorded in the form of video, then researchers construct detailed transcriptions from the recordings containing both verbal and non-verbal conduct. After transcription, patterns of interaction can be found by inductive analysis. Based on the analysis, the researchers identify models to describe these patterns to enhance or replace initial hypotheses. Findings revealed that cooperative gameplay could promote intergenerational interactions and prosocial behaviors of participants. Seaborn et al. (2019) developed two versions of intergenerational games to test young-old pairs. They found that intergenerational shared activity can promote engagement and empathy between older adults and young people.

This section highlights the value of playing cooperative exergames between old and young, especially in the non-family setting. Studies mentioned above have investigated various video games and exergames in the intergenerational context. However, designing balance training exergames for intergenerational pairs is still missing. Thus, our study focuses on the design and implementation of the balance training exergame and the effects of the exergame on intergenerational interactions.

3. Methodology

3.1. System implementation

3.1.1. Tangible interaction

The initial version of the Social Balance Ball was created by a student design team. As suggested by Morat et al. (2019), an unstable surface was helpful for balance training and motor skills relevant to preventing falls. Therefore, the prototype in our study used an unstable surface to provide better balance training and other features like visual feedback to appeal to older adults to play for the long term. Detailed descriptions of design concepts and system implementation have been reported in a previous study (Kaisar et al., 2021). Here, we briefly introduce the prototype design. The user can control a digital game by using the Social Balance Ball. The prototype consists of one acrylic layer (5 mm thick) on the top for the user to step on, which is laser cut to roundness ($\Phi = 460$ mm), with a foot-shaped non-slip mat indicating the right position for standing. The prototype includes an Arduino microcontroller, a blue-tooth device, a gyroscope, and a portable battery. To ensure the safety of older adults, a bracket with two armrests is added to the system. In a revised version, we use a mature accelerometer (WT901BLE5.0C) to increase the accuracy of the interaction for a good user experience. The accelerometer is attached beneath the acrylic board and connects to the computer with a wire. The computer sharing screen with the big TV screen can provide a good gaming experience. Figures 1 and 2 present the structure of the Social Balance Ball and system overview, respectively.

3.1.2. User interface design

Game design has three modes consisting of virtual play, mediated play, and co-located play. Despite the difference in modes, the workflows are similar. Firstly, choose a mode

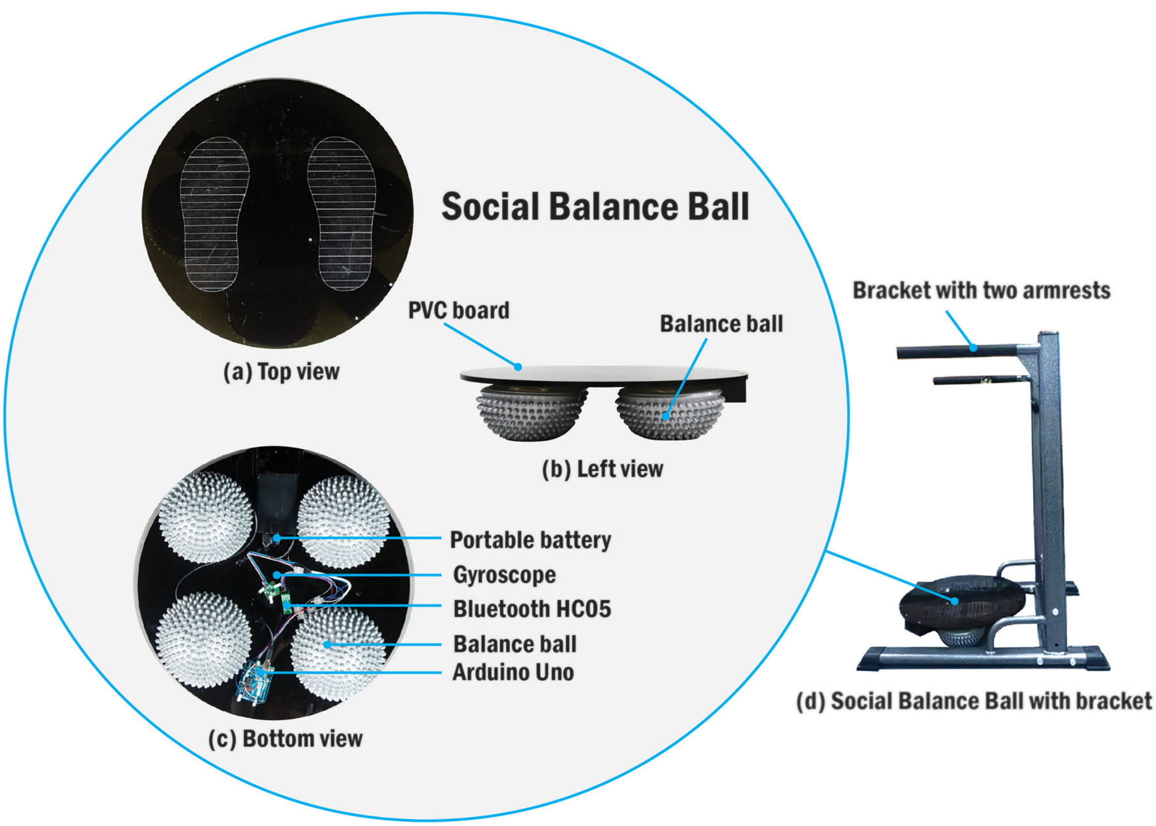

Figure 1. The structure of the Social Balance Ball: (a) top view, (b) left view, (c) bottom view, and (d) Social Balance Ball with bracket (revised based on Kaisar et al., 2021, 2022).

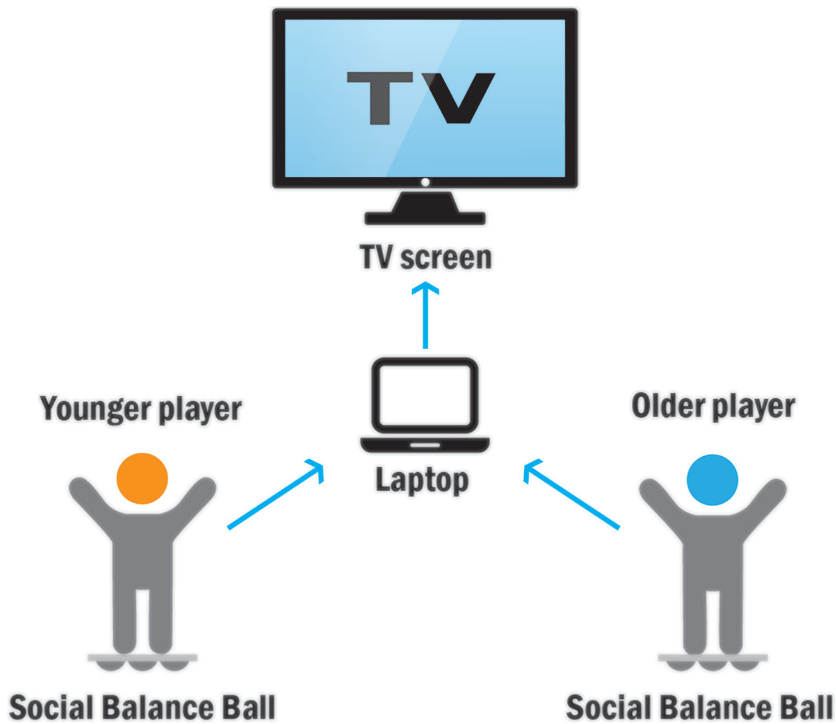

Figure 2. System overview.

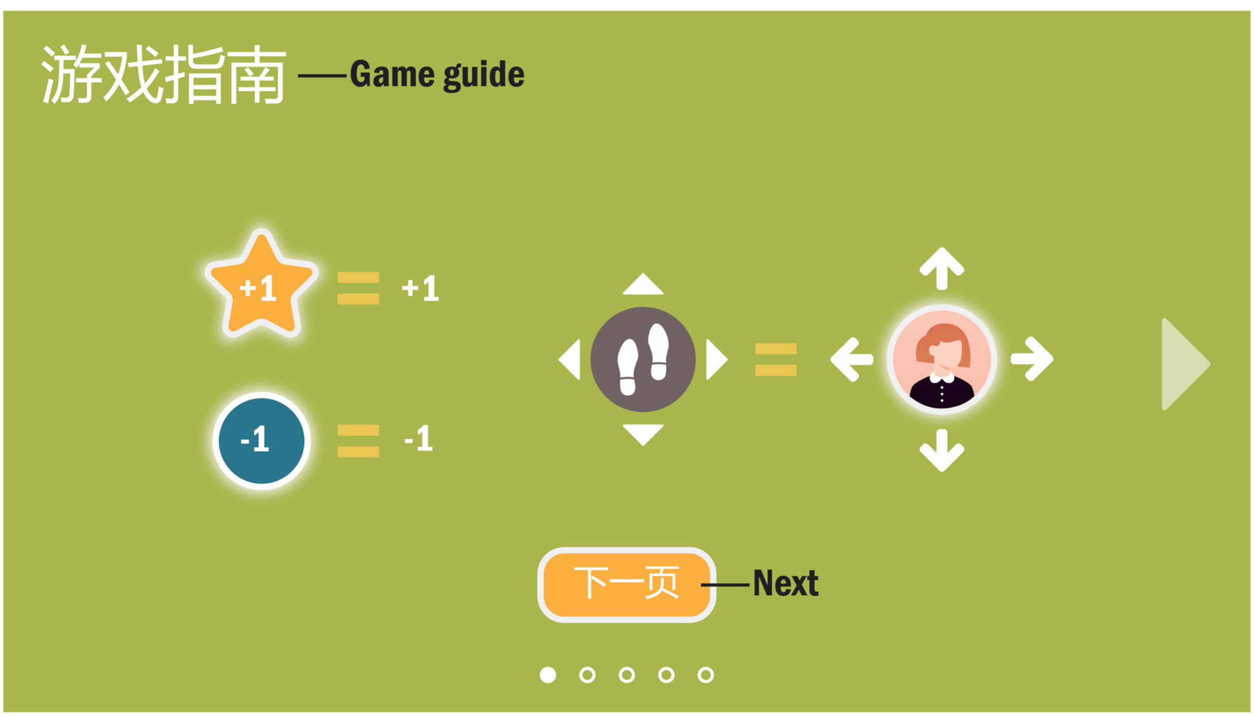

Figure 3. The user interface of the game guide.

and a game avatar. Secondly, think of a name for the team (i.e., in mediated play and co-located play) or the player (i.e., in virtual play), then there is a guide to introduce the game's basic control. Finally, the game begins, and the performance is given. Background music runs throughout the game; whenever a team gains or loses points, there is the corresponding audio feedback.

The graphic guide (Figure 3) at the beginning of the game suggests the simple binding between the avatar and the tangible device. When a player steps on the board and tilts the board direction forward, the game avatar moves vertically upward on the 2D screen, and vice versa. Similarly, when the player tilts to their left or right, the avatar moves correspondingly. In mediated play and co-located play, the team is made up of an older adult and a young person who needs to think of a name for their team, while in virtual play, the player takes a name for themselves. Therefore, in the end, the performance of the exergame is attached to the team or the player.

3.1.2.1. Virtual play. Two participants play the exergame in different places. They know each other's existence because the counterpart's avatar appears in the bottom left corner of the digital game's interface. There is no elastic rope connecting them. In the virtual play, the player controls the avatar to collect the point for themselves.

3.1.2.2. Mediated play and co-located play. Both modes share the same digital user interface: the white elastic rope between two avatars indicates a solid social bonding between two participants during exergaming (Figure 4). The mechanism is that two players form an area with the elastic rope which connects their avatars. While players increase the area, the possibility of getting points is similar to losing them. Two participants can use the Social Balance Ball to control the distance between two avatars. Then they will control the game avatars cooperatively to collect as many points as they can in the given time (6 min). Anyone with two avatars or the white elastic rope that touches the big yellow five-pointed star (BYS) will get three points for the team score (total score). Otherwise, the big dark-blue solid circle (BDC) is the opposite of the BYS. In addition, there are a little yellow five-pointed star (LYS) and a little dark-blue solid circle (LDC). When the game ends, the result of their performance and rank compared to other teams are given (Figure 5). The total score and smiling faces are calculated based on the following rationale:

$$\text{Total Score} = \text{N(BYS)} * 3 + \text{N(LYS)} - \text{N(BDC)} * 3 - \text{N(LDC)}$$

$$\text{N(Smile Face)} = \text{N(BYS)} - \text{N(BDC)}$$

This article focuses on the cooperation genre of exergame, and there should be an indicator of cooperation performance (Sakai et al., 2016). Therefore, the algorithm of the total score combined with the elastic band is designed such that to reflect the cooperation performance. Two players cannot get too close or too far, and this requires two players to cooperate. Because there is an elastic band between two players, and together they form an area that collects or loses points when encountered with correspondent UI elements (BYS, LYS, BDC, LDC).

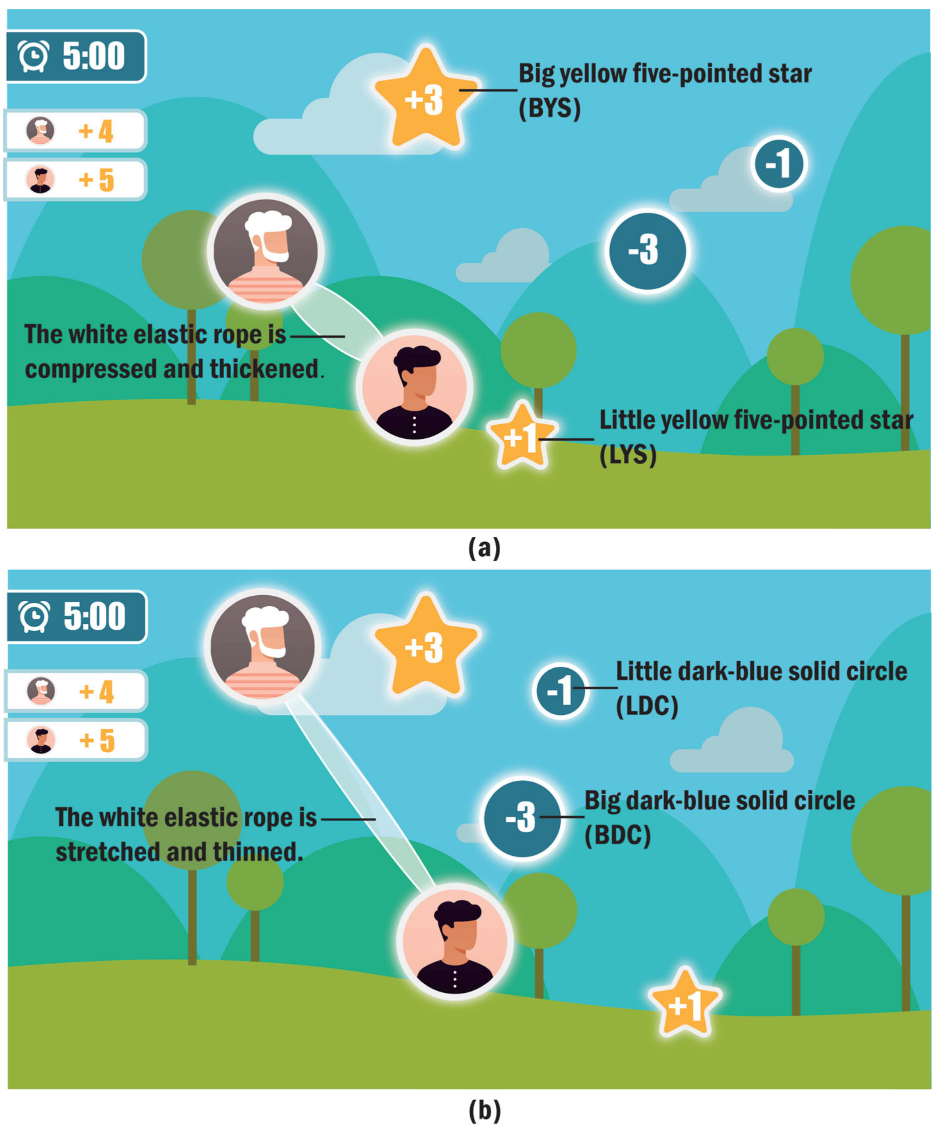

Figure 4. The user interface design of mediated play and co-located play. Animation effects: (a) If the distance of two avatars becomes closer, the white elastic rope is compressed and thickened; (b) Otherwise, the white elastic rope is stretched and thinned or even broken.

Figure 5. Game outcome.

3.2. Hypotheses

The study was designed to understand how the system impacted participants' social interaction. Based on four research questions in Section One, we proposed three hypotheses regarding exergame modes, participant roles, and gender differences. Additionally, we discussed the implications of designing exergaming technology to support intergenerational interaction.

We mainly formulated the hypotheses regarding how exergame modes (virtual *vs.* mediated *vs.* co-located play) would affect participants' social interaction. Specifically, according to RQ1, RQ2, and RQ3, we present three relevant hypotheses for the experiment. RQ4 is answered by qualitative data collected from post-experiment interviews.

H1: All participants perceive significantly different levels of social interactions under the three different modes of the Social Balance Ball exergame.

We expect participants to perceive higher levels of social interaction and positive feelings in both the mediated human player mode and the co-located human player mode (i.e., the human players interact) than in the virtual player mode (i.e., the human players do not interact). Since participants in the co-located setting can perceive a richer social interaction (Gajadhar et al., 2008), including both nonverbal and verbal cues, this mode is expected to have the best performance.

H2: Older and younger participants perceive significantly different social interactions in the Social Balance Ball exergame.

H3: Male and female participants perceive significantly different social interactions in the Social Balance Ball exergame.

3.3. Independent variables

Three independent variables are identified below:

The *first independent variable* is the mode of the exergames. This variable is treated as a within-subjects factor. According to the level of social presence of the co-player, it has three conditions:

(1) virtual play (i.e., two remote human players not playing together despite the presence of co-player's game avatar); (2) mediated play (i.e., two remote human players playing the exergame online together); (3) co-located play (i.e., two face-to-face human players playing the exergame together). In this experiment, mediated play and co-located play are considered due to the following reasons:

1. Because of the coronavirus disease impact, older adults are limited in social distance and must stay indoors. In such situations, online exergames provide them an opportunity to engage in physical activity and establish social connectedness with younger people at a remote distance.
2. We want to investigate whether playing the face-to-face exergame enhances social interaction between older adults living in the elderly home (or institutions) and younger people working or living around.

The *second independent variable* is the role of participants. This variable is treated as a between-subjects factor. It has two conditions: (1) older and (2) younger participants.

The *third independent variable* is gender. This variable is treated as a between-subjects factor. We want to know whether gender could influence social interaction. It has two conditions: (1) male and (2) female.

3.4. Statistical analysis

In quantitative data analysis, to test hypotheses, we present a $3 \times 2 \times 2$ mixed ANOVA, using the exergame mode [(1) virtual play, (2) mediated play, (3) co-located play] as the within-subjects factors, and participant roles [(1) older participants, (2) younger participants] as the between-subjects factors, as well as gender [(1) male, (2) female] as the between-subjects factor.

In qualitative data analysis, we used a thematic analysis to analyze post-experiment interview data. This method was chosen due to our purpose of establishing a set of structured, systematic categories (themes) (Braun & Clarke, 2006). We followed six phases of thematic analysis, which included (1) *becoming familiar with the data*, (2) *generating initial code*, (3) *searching for themes*, (4) *reviewing themes*, (5) *defining and naming themes*, and (6) *making the report* (Braun & Clarke, 2006). All the interviews were audio-recorded. They were transcribed verbatim through the online speech-to-text software (www.iflytek.com) and manually proofread by the first author. Quotes were selected from the interview transcript regarding how participants perceived this exergame and their suggestions for improvements to generate rich empirical knowledge for future design research. Two coders (i.e., the first and second authors) analyzed qualitative data. The coders explained and argued with each other about the initial coding results, and discrepancies were resolved by discussion between the two coders.

3.5. Participants

To estimate the sample size required for this study, we performed a prior statistical power analysis using the GPower software package (version 3.1.9.7) (Erdfelder et al., 1996). The effect size was set to 0.5, which is considered to be a medium value based on Cohen's criteria. With an alpha of 0.05 and a power of 0.80, the estimated sample size required for this effect size is approximately $N = 31$ for this within-between group interaction comparison. We also considered using a similar sample size from the study testing social interactions between blind and sighted people, consisting of 20 pairs of participants ($N = 40$) (Qiu et al., 2020a, 2020b). Finally, we recruited a total of 36 participants, consisting of 18 old ($M_{age} = 64.94$, $SD = 3.46$) and 18 young ($M_{age} = 22.06$, $SD = 3.21$). The selection of older participants is based on four criteria: (a) their age ranges from 55 to 70; (b) they should at least have a junior high school education and higher to ensure sufficient ability to answer the written questionnaires; (c) they can speak Mandarin Chinese with "no bad accent," to guarantee no oral communication barrier with participants and the experimenters; (d) they do not have any medically diagnosed cognitive, motor and visual impairments. We contacted Ying Chun Neighborhood Committee nearby Shanghai Jiao Tong University to recruit older participants. The neighborhood committee director helped us to post the recruitment information on the WeChat group of older volunteers. The researchers invited older volunteers interested in this study to attend a face-to-face appointment in the Neighborhood Committee Office to register their participation information. Younger participants are university students, including freshmen to doctoral students. Typically, their age range is between 17 and 35 years old, which belongs to the age group of young people. The whole experiment process is time-consuming, and university students are generally busy with classes, so participants should ensure that they have enough time to participate in the experiment. We posted the recruitment information on the university website (www.tongqu.me) to find qualified student participants at Shanghai Jiao Tong University.

Older and younger participants were strangers. In the mediated and co-located plays, they were grouped in pairs and not familiar with each other. Each team consisted of an older and a younger participant of the same gender to avoid any possible heterosexual effect influencing their emotional feelings during communication. Compensation for each participant was 100 CNY for one and a half hours.

Aside from participants' basic information, we also collected information regarding their situation of doing exercises and receiving social support in their daily lives from pre-test questionnaires (Table 1). The Lubben Social Network Scale (LSNS-6) (Lubben et al., 2006) was used to test whether there was a significant difference in social support between older and younger participants at baseline. An abbreviated version of LSNS-6 included six items with two subscales (*Family* and *Friendships*). *Family* refers to the family social network, including the people related by birth or marriage. *Friendships* refer to the friendship social network consisting of all participants' friends (e.g., people who live in the neighborhood). From the data analysis, we observed that older participants ($M = 7.94$, $SD = 3.21$) had a larger family social network than younger participants ($M = 7.22$, $SD = 2.78$). This difference was not significant $t(34) = 0.72$, $p = .48$. Meanwhile, older participants ($M = 9.28$, $SD = 2.40$) had a larger friendship social network than younger

Table 1. Participants' demographic information.

Participant role		Older	Younger
Age	Minimum	59	17
	Maximum	70	31
	Mean	64.94	22.06
	Std. deviation	3.46	3.21
Gender	Male	5	5
	Female	13	13
	Total	18	18
Education	Junior high school	7	0
	Senior high school	6	0
	Bachelor student	1	11
	Master student	0	6
	Ph.D. student	0	1
	Junior college	1	0
	Secondary teachers school	1	0
	Secondary vocational school	1	0
	Not mentioned	1	0
Frequency of doing exercises every week (%)	7	27.78%	0
	6	11.11%	0
	5	16.67%	11.11%
	4	11.11%	0
	3	0	5.56%
	2	0	5.56%
	1	0	11.11%
	0	0	27.78%
	Not mentioned	22.22%	27.78%
Social networks	Family (mean/std. deviation)	7.94 (3.21)	7.22 (2.78)
	Friendships (mean/std. deviation)	9.28 (2.40)	8.94 (2.62)

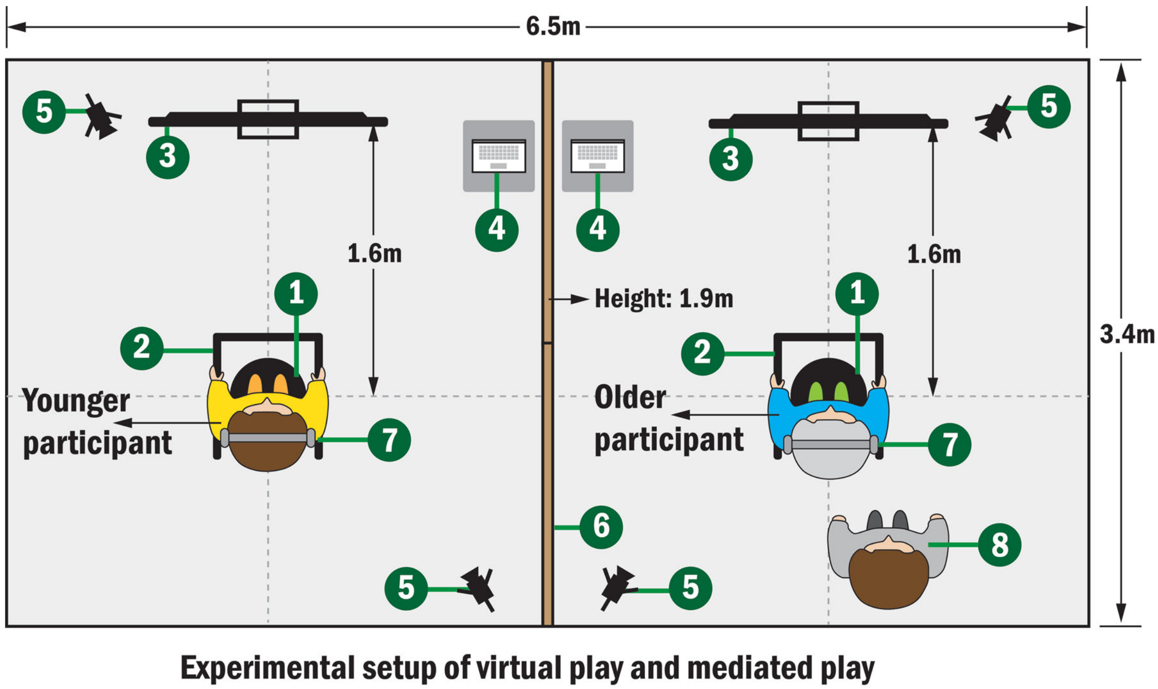

Figure 6. Experimental setup of virtual play and mediated play: (1) Social Balance Ball; (2) bracket with two armrests; (3) TV screen; (4) laptop; (5) camera; (6) wooden partition; (7) headphone; (8) an experimenter who stands next to the older participant to keep his/her safe.

participants ($M = 8.94$, $SD = 2.62$). This difference was also not significant $t(34) = 0.40$, $p = .69$. These statistical results are not significant, indicating that there were no significant differences between older and younger participants for their initial social network of family and friendships.

3.6. Setup

User experiments were conducted in a usability lab inside Neobay, located nearby Shanghai Jiao Tong University. Participants stood on the Social Balance Ball, around 1.6 m away from a 65-inch TV screen. One experimenter stood next to the older participant during exergaming to guarantee his/her safety. Compared with the previous version of the prototype (Kaisar et al., 2021), we replaced one large balance ball with four small balance balls to make the base more stable. Also, a bracket with two armrests was added to ensure the safety of participants. Pilot tests were conducted to carefully check the prototype system and all equipment to avoid any safety hazards.

In the virtual and mediated play, two participants were located separately in the same room by the wooden partition with a height of 1.9 m. In the virtual play, the same game software was installed on two laptops and connected to two TV screens via USB cables. When the game ran, its graphic interface was displayed on the TV screen, and the auditory feedback was delivered through the headphone. The headphones could guarantee two participants in the same room played the game independently without sound interference from each other. The mediated play attempted to simulate a scenario where two participants from a distance played an online game together by controlling their tangible balanced ball. In this mode, they were still separated by the wooden partition and wore the headset to avoid face-to-face social interaction. One laptop with the game software was connected to two TV screens via USB cables. Thus, participants could control avatars that appeared in the same game. In the co-located play, two participants without wearing headphones were in the same experimental area. They could talk and interact with each other during exergaming. The distance between participants was around 2.1 m, to follow the indoor social distancing during the COVID-19 pandemic. To enable co-located play, the wooden partition was moved 1.2 m from the center to the left. The auditory feedback of the game was provided by the speaker of the laptop. Figures 6 and 7 present the experimental setup of three exergame modes.

3.7. Procedure

Shanghai Jiao Tong University and Ying Chun Neighborhood Committee approved the study. It is conducted in accordance with the Declaration of Helsinki. The empirical study was conducted from May to July 2021. In each test, an older and a younger participant of the same gender were grouped in a pair. Participants were required to sign the written consent forms before taking part. Researchers provided them with an information sheet explaining the purpose of the study and the data being collected. All participants' names presented in this study are pseudonyms. After that, they completed the pre-experimental questionnaire, including demographic information and the Lubben Social Network Scale. Three modes of exergames (i.e., virtual play, mediated play, and co-located play) were performed in a counterbalanced order to avoid carry-over effects.

At the beginning of the game, the graphic user interface of the game guide was presented on the TV screen. The

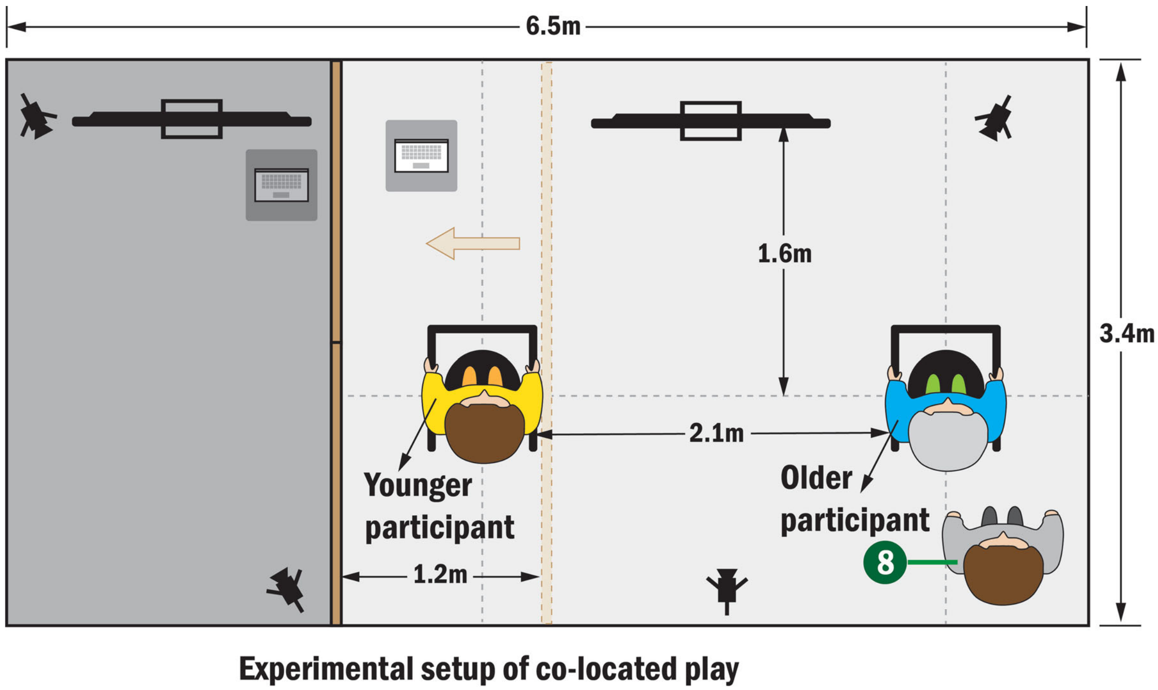

Figure 7. Experimental setup of co-located play.

researchers helped explain how to use the game and go through the game menu for participants. During exergaming, participants could ask for help from the researchers who stood nearby. Each exergame mode lasted 6 min, covering four scenario transitions of spring, summer, autumn, and winter. Each seasonal scenario lasted approximately one and a half minutes. Initially, we set every exergame mode for 8 min. One female and one male student volunteer were invited to attend the pre-test to check the feasibility of the experimental procedure. The female student reported feeling a little tired after completing three times of the 8-min exergame in one test. Additionally, considering the physical strength of older participants, the exergaming duration was shortened to 6 min for each mode. In the experiments, all participants can finish three modes of exergames without difficulty.

Before starting the first exergame mode, the game interface displayed the user guide. Researchers briefly explained game instructions to participants. After completing each exergaming session, participants took 10–20 min to finish the post-experimental questionnaires. Finally, researchers interviewed two participants separately, and all the interviews were audio-recorded. Figure 8 shows the overall experimental procedure.

3.8. Measurements

To evaluate Socially Assistive Systems, Qiu et al. (2021, 2022) summarized some relevant standardized questionnaires. They are previously validated, yielding consistent results from repeated samples and different researchers over time (Boynton & Greenhalgh, 2004). Among them, we selected a set of standardized questionnaires that have been used in past empirical studies (Davis et al., 2017; Qiu et al., 2020a, 2020b) to evaluate social interaction. Here, we measure participants' perceived social interaction from the dimensions of social presence, social connectedness, and emotional state. The detailed description of each questionnaire can be found in the Appendix.

- **Social presence** means a "sense of being with another" (Biocca et al., 2003). "Another" refers to either an artificial agent (e.g., a digital avatar) or a person (Biocca et al., 2003). We used the "Networked Minds Social Presence Inventor" (NMSPI) (Harms & Biocca, 2004) to measure the psychological and behavioral involvement of the participant with other social entities, including in-game characters, mediated (e.g., playing online), or co-located (IJsselsteijn et al., 2008).
- **Social connectedness** is "the experience of belonging and relatedness between people" (van Bel et al., 2009). We used the "Inclusion of Other in the Self" (IOS) Scale (Aron et al., 1992) to measure participants' social connectedness in exergames.
- **The emotional state** is evaluated by the "Positive and Negative Affect Schedule" (PANAS) (Watson et al., 1988). It is the most widely and frequently used scale to assess positive and negative feelings (Díaz-García et al., 2020). We used PANAS to measure participants' emotional state after each exergame mode.

  In addition to standardized questionnaires, we collected system logs and did a semi-structured interview to help assess participants' performance and experience during exergaming.
- **System logs** are JSON (JavaScript Object Notation) files generated by C# code in the unity game that record users' total scores after completing each exergame mode.

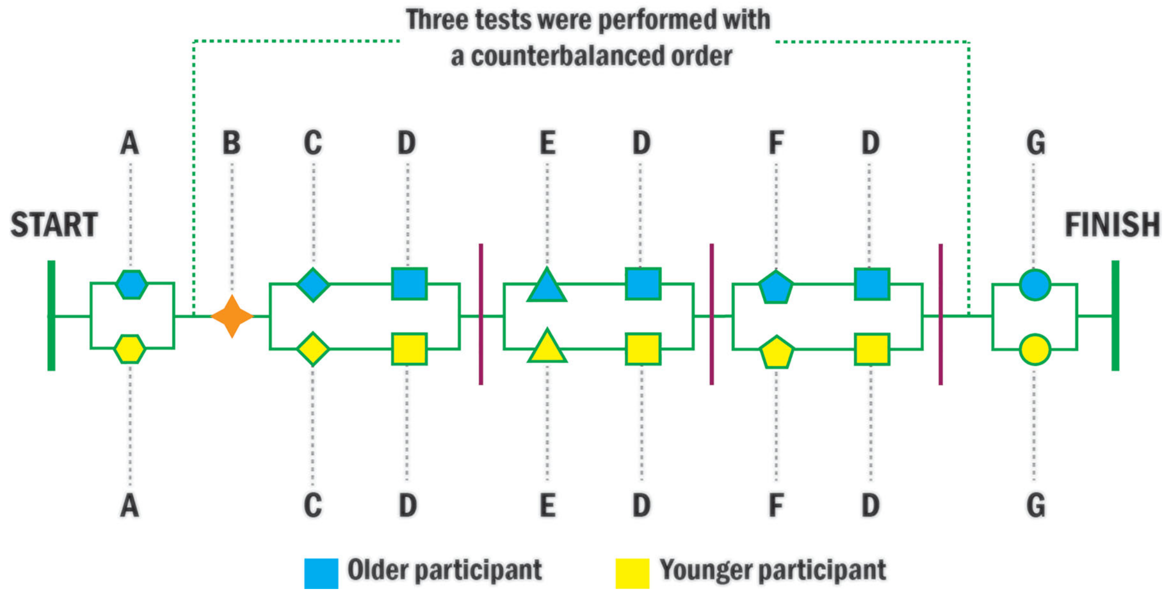

Figure 8. The procedure of the experiment: (A) complete consent forms and the pre-experimental questionnaires; (B) (experimenters) explain game instructions; (C) test for the virtual play; (D) complete the post-experimental questionnaire; (E) test for the mediated play; (F) test for the co-located play; (G) semi-structured interviews.

Table 2. Items of social presence, social connectedness, emotional state, and system logs in older and younger participants in the virtual play, mediated play, and co-located play.

	Experimental conditions mean (standard deviation)					
	Virtual play		Mediated play		Co-located play	
	Older	Younger	Older	Younger	Older	Younger
Social presence						
Co	4.54 (1.33)	3.64 (1.35)	5.29 (0.83)	5.89 (0.65)	5.45 (0.60)	5.99 (0.59)
At	4.13 (0.92)	3.41 (1.25)	4.41 (1.18)	4.60 (0.90)	4.74 (1.13)	4.74 (1.04)
PMU	4.35 (0.74)	3.73 (1.30)	4.73 (1.13)	4.58 (1.08)	4.87 (0.92)	4.94 (1.03)
PAU	4.04 (0.99)	3.23 (1.24)	4.70 (1.10)	4.21 (0.74)	4.74 (1.06)	4.56 (0.98)
PBI	1.49 (4.80)	1.33 (2.64)	0.64 (5.25)	0.85 (5.60)	0.84 (5.60)	0.91 (5.78)
PEI	4.13 (1.53)	3.51 (1.43)	4.26 (1.21)	4.42 (0.78)	3.71 (1.40)	4.93 (1.08)
Social connectedness	4.12 (2.47)	1.50 (1.25)	5.35 (1.58)	4.06 (1.89)	5.41 (1.70)	4.72 (1.67)
Emotional state						
Pos	3.52 (0.78)	2.78 (0.71)	3.52 (0.80)	2.79 (0.87)	3.59 (0.75)	2.92 (0.92)
Neg	1.28 (0.31)	1.19 (0.18)	1.28 (0.38)	1.26 (0.28)	1.34 (0.47)	1.29 (0.28)
System logs						
Tot	88.53 (28.61)	123.17 (28.75)	73.39 (25.99)	73.39 (25.99)	56.28 (22.59)	56.28 (22.59)

Co: co-presence; At: attentional allocation; PMU: perceived message understanding; PAU: perceived message understanding; PBI: perceived behavioral interdependence; PEI: perceived emotional interdependence; Pos: positive affect; Neg: negative affect; Tot: total score.

The logs enable statistical analysis for comparisons to be made between different modes.

- **Semi-structured interviews** are conducted to gain a deeper understanding of participants' gaming experience at the end of each test. The interview data helped interpret the quantitative data collected from standardized questionnaires and system logs. Two researchers independently interviewed older and younger participants (e.g., "Please share your experience and feel when you play each exergame mode" and "Do you have any suggestions for the system improvement"), allowing sufficient space for participants to freely provide feedback according to their experience. The interview data helped interpret the quantitative data collected from standardized questionnaires and system logs.

4. Results

4.1. Quantitative results

Results are presented in Tables 2–5.

4.1.1. Analysis of social presence

4.1.1.1. Co-presence. Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(2) = 17.47$, $p \leq .001$; therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .69$). The predicted main effect of the exergame modes was significant, $F(1.39, 43.01) = 37.51$, $p \leq .001$, $\eta_p{}^2 = .55$. The *post-hoc* contrast analysis revealed that participants felt significantly higher co-presence in co-located play ($M = 5.72$, $SE = .11$) and mediated play ($M = 5.63$, $SE = .16$) than in virtual play ($M = 4.02$, $SE = .24$).

Table 3. Items of social presence, social connectedness, emotional state, and system logs in male and female participants in the virtual play, mediated play, and co-located play.

	Experimental conditions mean (standard deviation)					
	Virtual play		Mediated play		Co-located play	
	Male	Female	Male	Female	Male	Female
Social presence						
Co	3.67 (1.72)	4.22 (1.27)	5.69 (0.63)	5.57 (0.85)	5.69 (0.37)	5.75 (0.72)
At	3.30 (1.01)	3.92 (1.17)	4.56 (0.93)	4.49 (1.08)	4.33 (0.87)	4.88 (1.11)
PMU	3.85 (1.19)	4.09 (1.08)	4.65 (1.07)	4.66 (1.12)	4.91 (0.87)	4.90 (1.01)
PAU	3.74 (1.48)	3.58 (1.10)	4.74 (0.81)	4.35 (0.99)	4.65 (0.89)	4.65 (1.06)
PBI	1.97 (3.80)	1.74 (3.65)	0.74 (5.26)	0.78 (5.49)	0.55 (5.67)	0.96 (5.70)
PEI	4.26 (1.72)	3.66 (1.41)	4.59 (1.10)	4.26 (0.97)	4.78 (1.15)	4.18 (1.43)
Social connectedness	2.78 (2.68)	2.77 (2.25)	4.89 (1.90)	4.62 (1.86)	5.22 (1.48)	5.00 (1.79)
Emotional state						
Pos	3.27 (0.52)	3.10 (0.91)	3.46 (0.60)	3.03 (0.97)	3.51 (0.70)	3.15 (0.95)
Neg	1.32 (0.36)	1.21 (0.21)	1.23 (0.15)	1.29 (0.37)	1.41 (0.41)	1.28 (0.37)
System logs						
Tot	116.67 (35.85)	102.77 (32.29)	80.22 (30.51)	70.15 (23.94)	55.00 (25.04)	56.85 (22.17)

Co: co-presence; At: attentional allocation; PMU: perceived message understanding; PAU: perceived message understanding; PBI: perceived behavioral interdependence; PEI: perceived emotional interdependence; Pos: positive affect; Neg: negative affect; Tot: total score.

Table 4. Results of main and interaction effects of levels of social presence, social connectedness, emotional state, and system logs for the exergame modes.

Source		df	SS	MS	F	p	η_p^2
Exergame Mode	Co	1.39	48.43	34.91	37.51	<0.01**	0.55
	At	1.80	15.46	8.59	15.34	<0.01**	0.33
	PMU	2.00	11.40	5.70	7.79	<0.01**	0.20
	PAU	2.00	14.55	7.28	11.59	<0.01**	0.27
	PBI	1.39	54.56	39.23	27.72	<0.01**	0.47
	PEI	1.74	3.56	2.04	2.58	0.09	0.08
	Soc	1.38	79.95	58.14	19.14	<0.01**	0.38
	Pos	2.00	0.34	0.17	1.29	0.28	0.04
	Neg	1.91	0.13	0.07	0.95	0.39	0.03
	Tot	2.00	37,403.97	18,701.99	45.20	<0.01**	0.59
Exergame Mode* Participant Role	Co	1.39	15.25	10.99	11.81	<0.01**	0.28
	At	1.80	3.12	1.73	3.09	0.06	0.09
	PMU	2.00	2.72	1.36	1.86	0.16	0.06
	PAU	2.00	2.31	1.15	1.84	0.17	0.06
	PBI	1.39	26.19	18.83	13.30	<0.01**	0.30
	PEI	1.74	12.14	6.96	8.82	<0.01**	0.22
	Soc	1.38	13.90	10.11	3.33	0.06	0.10
	Pos	2.00	0.02	0.01	0.09	0.91	0.00
	Neg	1.91	0.10	0.05	0.76	0.47	0.02
	Tot	2.00	6165.61	3082.81	7.45	<0.01**	0.19
Exergame Mode * Gender	Co	1.39	0.92	0.66	0.71	0.45	0.02
	At	1.80	1.75	0.97	1.73	0.19	0.05
	PMU	2.00	0.14	0.07	0.09	0.91	0.00
	PAU	2.00	0.55	0.27	0.43	0.65	0.01
	PBI	1.39	0.86	0.62	0.44	0.58	0.01
	PEI	1.74	0.39	0.22	0.28	0.73	0.01
	Soc	1.38	0.11	0.08	0.03	0.93	0.00
	Pos	2.00	0.26	0.13	0.98	0.38	0.03
	Neg	1.91	0.17	0.09	1.26	0.29	0.04
	Tot	2.00	688.51	344.25	0.83	0.44	0.03
Error(Exergame Mode)	Co	43.01	40.03	0.93			
	At	55.79	31.25	0.56			
	PMU	62.00	45.36	0.73			
	PAU	62.00	38.94	0.63			
	PBI	43.12	61.02	1.42			
	PEI	54.05	42.68	0.79			
	Soc	42.63	129.46	3.04			
	Pos	62.00	8.17	0.13			
	Neg	59.29	4.14	0.07			
	Tot	62.00	25,653.81	413.77			

Abbreviations: Co: co-presence; At: attentional allocation; PMU: perceived message understanding; PAU: perceived message understanding; PBI: perceived behavioral interdependence; PEI: perceived emotional interdependence; Soc: social connectedness; Pos: positive affect; Neg: negative affect; Tot: total score.
Significant group difference; $^{**}p < 0.01$.

A significant interaction effect was observed between the exergame modes and participants' roles, $F(1.39, 43.01) = 11.81$, $p < .001$, $\eta_p^2 = .28$. It indicated that participants' co-presence toward the exergame modes differed according to participant roles. In the virtual play, older participants felt significantly higher co-presence than

Table 5. Results of main effects of levels of social presence, social connectedness, emotional state, and system logs for participant role and gender.

Source		df	SS	MS	F	p	η_p^2
Participant role	Co	1.00	1.14	1.14	1.00	0.32	0.03
	At	1.00	0.83	0.83	0.33	0.57	0.01
	PMU	1.00	4.69	4.69	2.54	0.12	0.08
	PAU	1.00	10.26	10.26	5.31	0.03*	0.15
	PBI	1.00	11.85	11.85	8.45	0.01*	0.21
	PEI	1.00	0.41	0.41	0.13	0.72	0.00
	Soc	1.00	75.37	75.37	13.39	<0.01**	0.30
	Pos	1.00	8.56	8.56	4.99	0.03*	0.14
	Neg	1.00	0.21	0.21	1.11	0.30	0.03
	Tot	1.00	3471.35	3471.35	2.75	0.11	0.08
Gender	Co	1.00	0.26	0.26	0.23	0.64	0.01
	At	1.00	2.49	2.49	0.98	0.33	0.03
	PMU	1.00	0.01	0.01	0.01	0.93	0.00
	PAU	1.00	1.24	1.24	0.64	0.43	0.02
	PBI	1.00	0.02	0.02	0.01	0.91	0.00
	PEI	1.00	6.26	6.26	2.00	0.17	0.06
	Soc	1.00	2.06	2.06	0.37	0.55	0.01
	Pos	1.00	2.34	2.34	1.36	0.25	0.04
	Neg	1.00	0.12	0.12	0.61	0.44	0.02
	Tot	1.00	829.38	829.38	0.66	0.42	0.02
Error	Co	31.00	35.21	1.14			
	At	31.00	78.76	2.54			
	PMU	31.00	57.28	1.85			
	PAU	31.00	59.88	1.93			
	PBI	31.00	43.47	1.40			
	PEI	31.00	97.20	3.14			
	Soc	31.00	174.50	5.63			
	Pos	31.00	53.13	1.71			
	Neg	31.00	5.86	0.19			
	Tot	31.00	39151.47	1262.95			

Abbreviations: Co: co-presence; At: attentional allocation; PMU: perceived message understanding; PAU: perceived message understanding; PBI: perceived behavioral interdependence; PEI: perceived emotional interdependence; Soc: social connectedness; Pos: positive affect; Neg: negative affect; Tot: total score.
Significant group difference; $^*p < 0.05$, $^{**}p < 0.01$.

younger participants. However, younger participants felt significantly higher co-presence than older participants in mediated and co-located play.

4.1.1.2. Attentional allocation. Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(2) = 9.59$, $p = .008$, therefore degrees of freedom were corrected using the Huynh-Feldt correction ($\varepsilon = .90$). The predicted main effect of the exergame modes was significant, $F(1.80, 55.79) = 15.34$, $p \leq .001$, $\eta_p^2 = .33$. The *post-hoc* contrast analysis revealed that participants felt significantly higher attentional allocation in co-located play ($M = 4.61$, $SE = .21$) and mediated play ($M = 4.53$, $SE = .21$) than in virtual play ($M = 3.63$, $SE = .22$).

4.1.1.3. Perceived message understanding. The predicted main effect of the exergame modes was significant, $F(2, 62) = 7.79$, $p \leq .001$, $\eta_p^2 = .20$. The *post-hoc* contrast analysis revealed that participants felt significantly higher perceived message understanding in co-located play ($M = 4.92$, $SE = .19$) than in virtual play ($M = 4.02$, $SE = .20$).

4.1.1.4. Perceived affective understanding. The predicted main effect of the exergame modes was significant, $F(2, 62) = 11.59$, $p \leq .001$, $\eta_p^2 = .27$. The *post-hoc* contrast analysis revealed that participants felt significantly higher perceived affective understanding in co-located play ($M = 4.67$, $SE = .20$) and mediated play ($M = 4.57$, $SE = .18$) than in virtual play ($M = 3.72$, $SE = .22$). The predicted main effect of participants' roles was significant, $F(1, 31) = 5.31$, $p = .03$, $\eta_p^2 = .15$. The *post-hoc* contrast analysis revealed that older participants ($M = 4.68$, $SE = .23$) felt significantly more perceived affective understanding than younger participants ($M = 3.96$, $SE = .21$).

4.1.1.5. Perceived behavioral interdependence. Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(2) = 17.29$, $p \leq .001$; therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .70$). The predicted main effect of the exergame modes was significant, $F(1.39, 43.12) = 27.72$, $p \leq .001$, $\eta_p^2 = .47$. The *post-hoc* contrast analysis revealed that participants felt significantly higher perceived behavioral interdependence in co-located play ($M = 5.70$, $SE = .17$) and mediated play ($M = 5.39$, $SE = .14$) than in virtual play ($M = 3.80$, $SE = .28$). The predicted main effect of participants roles was also significant, $F(1, 31) = 8.45$, $p = .01$, $\eta_p^2 = .21$. The *post-hoc* contrast analysis revealed that older participants ($M = 5.35$, $SE = .20$) felt significantly higher perceived behavioral interdependence than younger participants ($M = 4.58$, $SE = .18$).

A significant interaction effect was observed between the exergame modes and participants' roles, $F(1.39, 43.12) = 13.30$, $p < .001$, $\eta_p^2 = .30$. It indicated that participants' perceived behavioral interdependence toward the exergame modes differed according to the participant roles. In the virtual play, older participants felt significantly higher perceived behavioral interdependence than younger participants. However, in both mediated play and co-located play, older participants generally felt the same perceived behavioral interdependence as younger participants.

4.1.1.6. Perceived emotional interdependence. The predicted interaction between the exergame modes and participants' roles was significant, $F(1.74, 54.05) = 8.82$, $p < .001$, $\eta_p^2 = .22$. It indicated that participants' perceived emotional interdependence toward the exergame modes differed according to the participant roles. In the virtual play, older participants felt higher perceived emotional interdependence than younger participants. In the mediated play, older participants generally felt the same perceived behavioral interdependence as younger participants. In the co-located play, younger participants felt significantly higher perceived emotional interdependence than older participants.

4.1.2. Analysis of social connectedness

Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(2) = 18.18$, $p \leq .001$; therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .69$). The predicted main effect of the exergame modes was significant, $F(1.38, 42.63) = 19.14$, $p \leq .001$, $\eta_p^2 = .38$. The *post-hoc* contrast analysis revealed that participants felt significantly higher social connectedness in co-located play ($M = 5.16$, $SE = .33$) and mediated play ($M = 4.82$, $SE = .34$) than in virtual play ($M = 2.89$,

$SE = .38$). The predicted main effect of participants roles was significant, $F(1,\ 31) = 13.39$, $p \leq .001$, $\eta_p^{\ 2} = .30$. The *post-hoc* contrast analysis revealed that older participants ($M = 5.26$, $SE = .39$) felt significantly higher social connectedness than younger participants ($M = 3.32$, $SE = .36$).

4.1.3. Analysis of positive and negative affect

4.1.3.1. Positive affect. The predicted main effect of participants' roles was significant, $F(1, 31) = 4.99$, $p = .03$, $\eta_p^{\ 2} = .14$. The *post-hoc* contrast analysis revealed that older participants ($M = 3.60$, $SE = .22$) felt significantly higher positive affect than younger participants ($M = 2.94$, $SE = .20$).

4.1.3.2. Negative affect. We did not find any statistically significant results for negative affect.

4.1.4. Analysis of system logs

4.1.4.1. Total score. The predicted main effect of the exergame modes was significant, $F(2,\ 62) = 45.20$, $p \leq .001$, $\eta_p^{\ 2} = .59$. The *post-hoc* contrast analysis revealed that participants obtained significantly higher total score in virtual play ($M = 108.43$, $SE = 5.60$) than in mediated play ($M = 75.09$, $SE = 5.14$) and in co-located play ($M = 55.94$, $SE = 4.59$). Participants also obtained significantly higher total scores in mediated play than in co-located play.

A significant interaction effect was observed between the exergame modes and participants' roles, $F(2,\ 62) = 7.45$, $p < .001$, $\eta_p^{\ 2} = .19$. Participants' total scores toward the exergame modes differed according to participant roles. In the virtual play, younger participants obtained significantly higher total scores than older participants. In mediated and co-located play, younger and older participants co-played the exergame and obtained the same total score.

4.1.5. Summary

The predicted main effect of the exergame modes was significant. From the subjective questionnaires, we found that participants felt significantly higher co-presence, attentional allocation, perceived message understanding, perceived affective understanding, perceived behavioral interdependence, and social connectedness in co-located play than in virtual play (Figure 9). Participants also felt significantly higher co-presence, attentional allocation, perceived affective understanding, perceived behavioral interdependence, and social connectedness in mediated play than in virtual play (Figure 9). Interestingly, from system logs, we observed that participants obtained significantly higher total scores in virtual play than in mediated play, and co-located play. Participants also obtained significantly higher total scores in mediated play than in co-located play (Figure 10). A significant main effect of the participant roles was observed. During three exergame modes, older participants felt significantly higher perceived affective understanding, perceived behavioral interdependence, social connectedness, and positive affect than younger participants (Figure 11). We did not find a main effect of gender.

A significant interaction effect was observed between the exergame modes and participant roles (Figures 12 and 13). It revealed that in virtual play, older participants perceived significantly higher co-presence and perceived behavioral interdependence than younger participants. However, older participants obtained significantly lower total scores than younger participants in virtual play. In the mediated play, younger participants felt significantly higher co-presence than older participants. Additionally, in co-located play, younger participants felt significantly higher co-presence and perceived emotional interdependence than older participants.

4.2. Qualitative results

In this study, we collected 189 quotes from 36 participants to identify the major categories and sub-categories regarding their attitudes and design suggestions. We address these qualitative findings below.

4.2.1. Attitudes toward the exergame modes

One hundred and twenty-two quotes mention participants' positive and negative attitudes toward three exergame modes (Table 6). Every participant was assigned a unique ID to indicate the source of the quotes. "O" and "Y" denote "older participants" and "younger participants," respectively.

4.2.1.1. Virtual play. Eighteen quotes show positive attitudes of older participants toward virtual play, while three quotes mention the opposite ideas. The example positive quotes are "*feel excited*" (O5, O9, O29, O35), "*relaxed and feel free*" (O7, O11, O17, O35), "*simple and easy to learn*" (O3, O15), as well as "*interesting and without any pressure*" (O25, O33). O7 explained: "*The exergame in virtual play can follow my heart, controlling (the avatar) moving up and down. It is a cool feeling. However, if two people are playing together, we need to communicate, cooperate and coordinate, a little bit difficult. We must play a few more times to establish such tacit understanding.*" The negative quotes from older participants (O9, O15, O17) are "*feel lonely*," "*nervous*," and "*feel less responsive than younger adults.*"

Eleven quotes mention younger participants liked the virtual play, while 11 quotes show the opposite ideas. The typical positive quotes are "*feel interesting and happy*" (Y6, Y12, Y22, Y36), "*control the game easily without being influenced by others*" (Y10, Y14, Y28, Y36), as well as "*relaxed and concentrated*" (Y18, Y34). On the other hand, younger participants also identify negative factors of playing the exergame in this mode, such as "*monotonous and nothing special*" (Y2, Y4, Y8, Y24), "*feel bored and no challenge*" (Y2, Y8, Y12), as well as "*unable to interact and feel lonely*" (Y10).

4.2.1.2. Mediated play. Thirteen quotes show positive attitudes of older participants toward this mode, while nine quotes show negative attitudes. The example positive quotes are "*consider others and have team spirit*" (O1, O7, O9, O13, O15), "*feel well*" (O5, O11, O17, O33), as well as "*enhance*

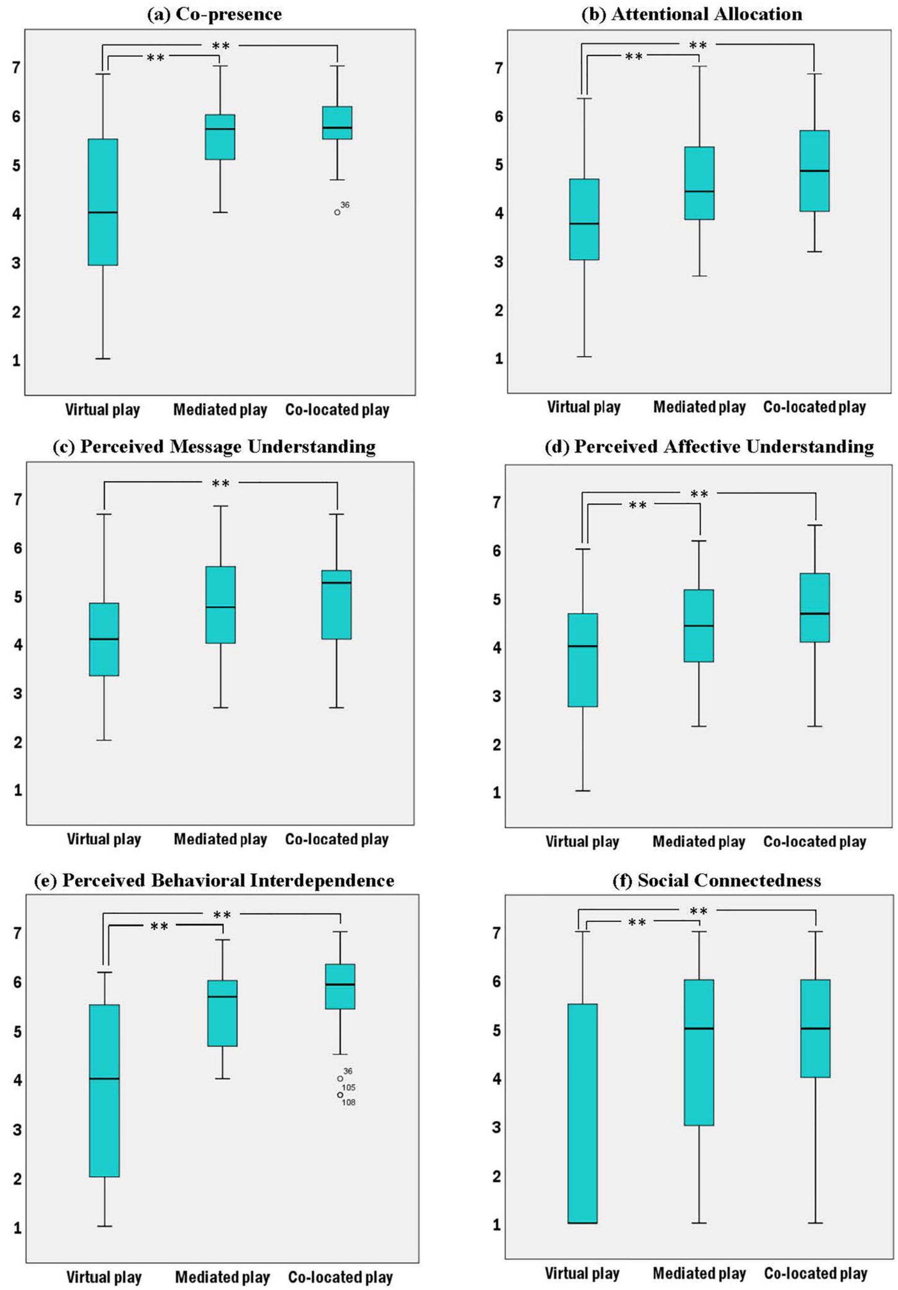

Figure 9. Boxplot of the main effect of the exergame modes on co-presence (a), attentional allocation (b), perceived message understanding (c), perceived affective understanding (d), perceived behavioral interdependence (e), and social connectedness (f). Significant group difference; $^{**}p < .01$.

feelings and tacit understanding during interaction" (O27). Example negative quotes are "*cannot feel the presence of the younger partner*" (O19, O29), "*not excited*" (O3, O21), and "*be a drag on the younger partner*" (O11).

Seven quotes mention younger participants liked this mode, while 12 quotes report their negative attitudes. The example positive quotes are "*interesting and happy experience*" (Y6, Y8, Y24), "*concentrated and positive thinking*" (Y18), as well as "*a high degree of tacit understanding and a strong sense of interaction*" (Y12). The example negative quotes are "*not able to well communicate and feel anxious*" (Y14, Y22, Y32, Y36), "*influenced by the partner and feel unhappy*" (Y10), "*sense of constraint*" (Y34).

4.2.1.3. Co-located play. Fifteen quotes mention older participants liked this mode. The example quotes are "*happy, excited and easy to communicate*" (O3, O15, O21, O25, O31), "*easy to know the intention of the partner*" (O1, O13), as well as "*relaxed and be more confident*" (O17). Also, two quotes reveal why older participants disliked this mode, i.e., "*more nervous after being blamed*" (O9) and "*not as fun as mediated play*" (O11).

Thirteen quotes indicate the positive attitudes of younger participants toward this mode. The example quotes are "*interesting, happy and excited*" (Y6, Y8, Y12, Y16, Y24, Y32), "*increase communication and interaction*" (Y4, Y10, Y12, Y18, Y28), as well as "*cooperate easily and reduce *mental stress*" (Y34). Y32: "*I feel like a game at this difficulty level might be easier for me to play than an older adult. I will be happy if she can get more points and be happy too.*" Eight quotes show negative attitudes of younger participants, such as "*limited and difficult communication*" (Y14, Y20, Y26, Y36), "*easily disturbed by the other*" (Y10), and "*the older partner looks embarrassed*" (Y22). Y22 found that her partner looked upset and embarrassed if she tried to guide her through the game. Finally, she gave up getting high scores and followed the older partner.

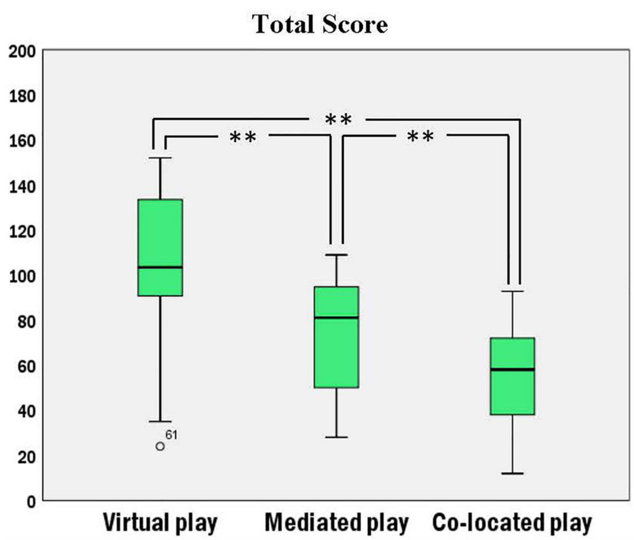

Figure 10. Boxplot of the main effect of the exergame modes on participants' total score. Significant group difference; $^{**}p < .01$.

4.2.2. Design suggestions

Sixty seven quotes report design suggestions of participants (Table 7).

4.2.2.1. Game mechanism. There are 31 quotes relevant to the game mechanism; *enhancing richness* (13 quotes) and *challenges* (10 quotes) are quoted relatively more than the other two categories: *scoring mechanism* (five quotes) and *motion mechanism* (five quotes). In *enhancing richness*, quotes are mainly about the richness of elements and various levels because the limited elements are boring.

Interestingly, in the category of *challenges*, O17, O29, and Y18 suggested the exergame should be more challenging, "*It would be more exciting for me if the exergame was harder*" (O17). This implies that older adults also welcome the challenges and excitement in the game and may not be as vulnerable to challenges. Six participants (O21, O23, O35, Y2, Y22, Y34) mentioned the importance of providing different game challenge options. On the other hand, Y34 said: "*I*

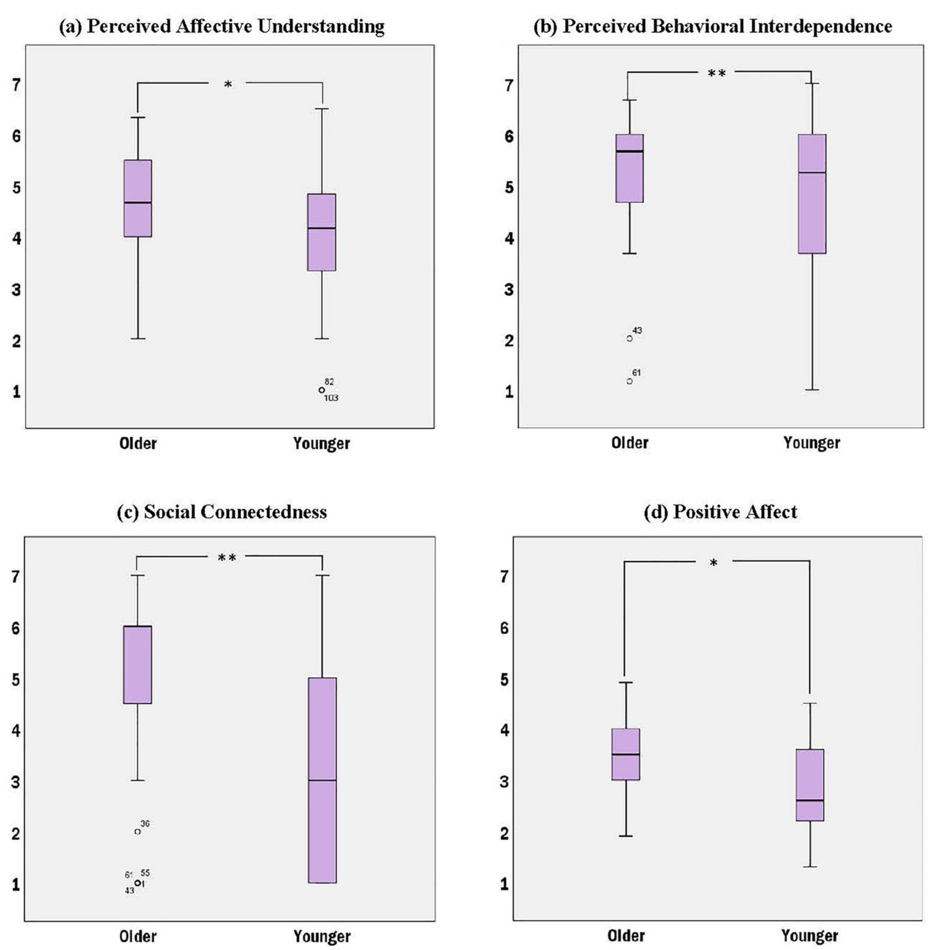

Figure 11. Boxplot of the main effect of participants' roles on perceived affective understanding (a), perceived behavioral interdependence (b), social connectedness (c), and positive affect (d). Significant group difference; $^{*}p < .05$, $^{**}p < .01$.

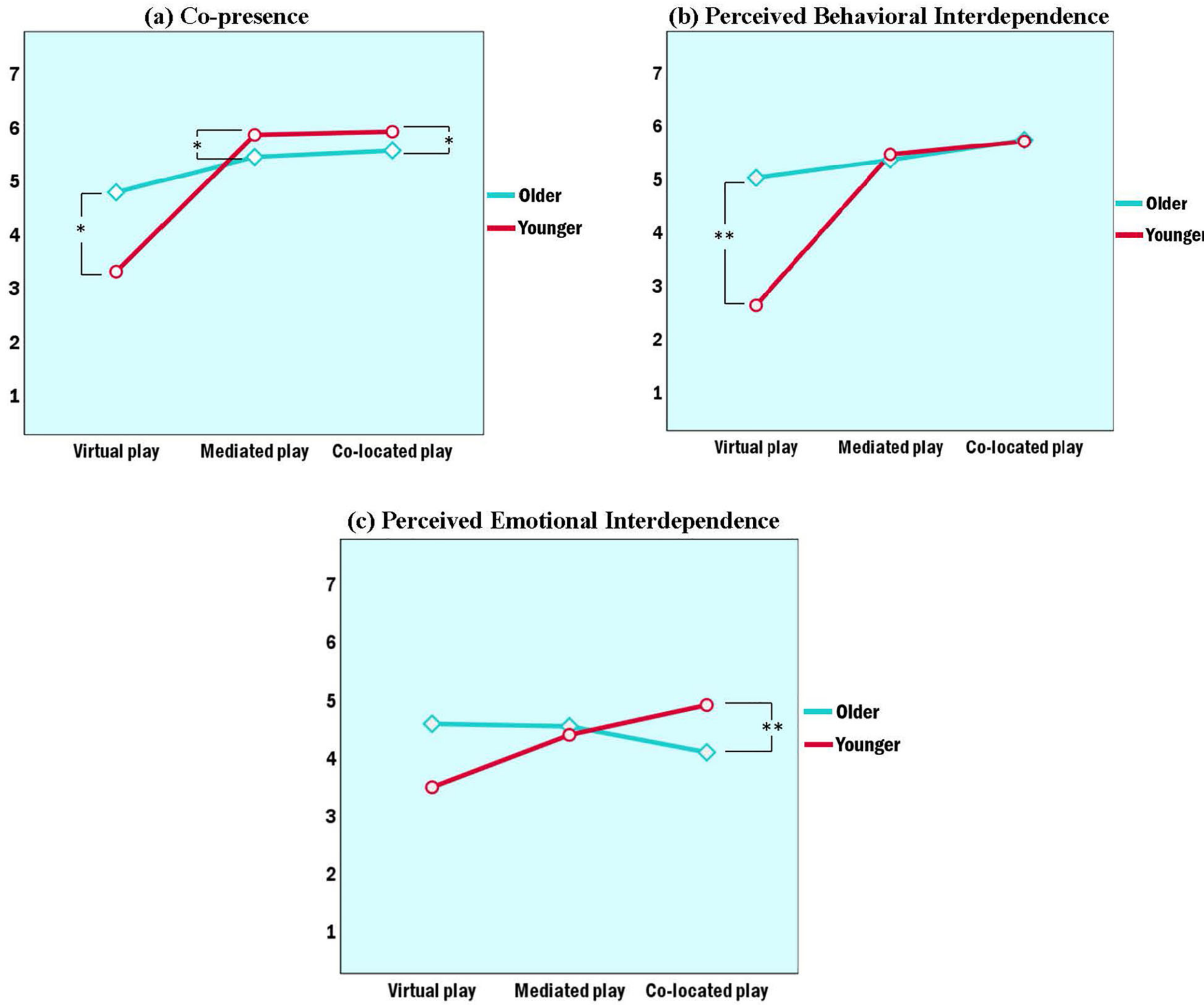

Figure 12. Interaction effects between the exergame modes and participant roles on co-presence (a), perceived behavioral interdependence (b), and perceived emotional interdependence (c). Significant group difference; $^{*}p < .05$, $^{**}p < .01$.

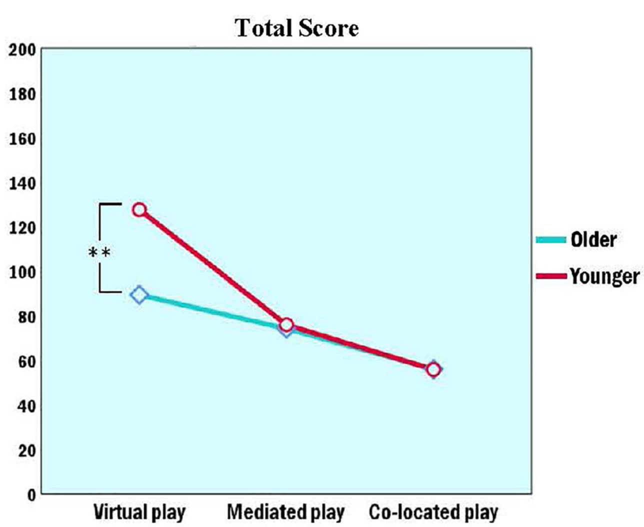

Figure 13. Interaction effects between the exergame modes and participant roles on participants' total score. The total score reflects the cooperation performance, and the algorithm is mentioned in Section 3.1.2. Significant group difference; $^{**}p < .01$.

want to choose the easy mode while I am not in the mood because I just want to have a good time." These quotes suggest that fewer challenges for older adults and more for young people are not always the case.

There are two prominent opinions on the *scoring mechanism;* one is a more detailed explanation of different scoring mechanisms between three exergame modes.

Table 6. Frequency of positive and negative quotes of older and younger participants regarding three exergame modes.

Modes	Participant roles	Frequency of positive quotes	Frequency of negative quotes
Virtual play	Older	18	3
	Younger	11	11
	Total	29	14
Mediated play	Older	13	9
	Younger	7	12
	Total	20	21
Co-located play	Older	15	2
	Younger	13	8
	Total	28	10
Total	Older	46	14
	Younger	31	41
	Total	77	55

Table 7. Design suggestions.

Theme	Category	Quotation example	Frequency
Game mechanism	Enhancing richness	*"There should be new scenes for each level, for example, this is the journey over the world and each level we are in a new country. We can also make changes to our avatars in different scenes. This will create a narrating of the game and may attract my partner and me more."* (Y8) *"Scenes and elements should change with time; otherwise, I will get bored by those repeating things."* (Y10)	13
	Challenges	*"The challenges of the exergame should increase as we play, and in this way, we can see our improvements and feel more confident, and then we can get fit in the long run."* (O21)	10
	Scoring mechanism	*"What can we do with those scores? Can we buy new equipment or clothes for the game? These things can make it more attractive?"* (Y26)	5
	Motion mechanism	*"Can you add hand motion interaction? Then my whole body gets involved in the exercise."* (O27)	5
Hardware	Space efficiency	*"The hardware takes too much space; I hope it can be smaller and folded like an umbrella while I do not use it."* (O1)	12
	Latency	*"Hardware latency should be reduced for better gaming experience."* (Y2)	2
Game interaction	Interface and sound design	*"Optimize the animation effect of scoring and losing points to enrich the game experience."* (Y24)	9
	Personalization	*"The image of the game avatar can be turned into a small cartoon character so the player can re-dress it."* (Y8)	3
Social interaction	User groups and scenarios	*"Playing the exergame together can stimulate more communication among family members. Now there is little communication at home. My son and daughter-in-law are very busy with work, and most importantly, they have to help their child do homework after work. We do not have much time to talk with each other, and there does not seem to be much to talk about."* (O15)	4
	Online voice communication	*"It does not seem feasible for two people to play an online exergame without any verbal communication."* (Y16)	3
	Cooperative mechanism	*"Maybe you can let the younger player run the game and then directly invite the older player to join, reducing the difficulty of operation for the older player."* (Y30)	3

All participants mentioned the hand motion interaction mechanism in the category of *motion mechanism*. Y8 reported, "*More cooperation and interaction may be achieved with adding hand motion; for example, I can use my hand motion to stretch the line between two game characters.*"

4.2.2.2. Hardware improvement. Fourteen quotes provide suggestions for hardware improvement, while 12 are concerned with space efficiency, and only two are recommendations for reducing the latency of the hardware. Participants preferred the hardware to be compact, so it does not take up much space and can help players to set up easily before playing.

4.2.2.3. Game interaction design. In total, 12 quotes describe participants' suggestions regarding game interaction design, including *interface and sound design* (nine quotes) and *personalization* (three quotes). The example suggestions regarding *interface and sound design* are summarized below:

- Provide more visible feedback on how much time is left in the game (Y12).
- Improve the interaction of the elastic rope between two game avatars (Y20, Y28).
- Make game music more athletic rather than relaxing (Y26).
- Minimize the error sound feedback because all players wish to gain a sense of achievement rather than depression (Y30).

Three quotes mentioned the *personalization* of game interaction design. Also, Y34 suggested that players can set different game modes according to their emotional state in mediated play and co-located play.

4.2.2.4. Social interaction. Ten quotes mention the aspect of social interaction, including *user groups and scenarios* (four quotes), *online voice communication* (three quotes), and *cooperative mechanisms* (three quotes). Four participants suggested playing the exergame at home (O15, O21, Y14) or involving more than three players (Y16). O15 and O21 chose to play this exergame with their family members because the exergame promoted intergenerational communication in families. Y12, Y16, and Y28 suggested adding voice communication to the mediated play.

Three participants proposed cooperative mechanisms for the exergame. Y18 recommended differentiating task difficulty for older and younger players as their cognitive and physical abilities differ. Younger players needed more effort to achieve the same result as older players, for example, using a gust of wind in the game to increase operational resistance for younger players.

5. Discussion and conclusion

In this section, we answer four research questions and acknowledge limitations and future work.

5.1. RQ1: "How does the social balance ball impact the social interaction of all players in three conditions?"

H1 is supported by both quantitative and qualitative data. The quantitative results demonstrated that participants felt significantly perceived social interaction in mediated play and co-located play than in virtual play. According to the experimental results from Gajadhar et al. (2008), participants who played digital games in the co-located setting perceived higher positive affect than in the mediated setting (i.e., online). Similar results have been reported by Mandryk and Inkpen (2004) regarding collaborative play. Different from their findings, in our study, we did not observe a significant difference in participants' perceived social interaction between mediated play and co-located play. There are two possible reasons. First, their studies used friends or familiar participants in pairs to play collaborative games, while our study involved strangers. The initial familiarity of participants can influence their perceived social interaction and engagement in games (Ravaja et al., 2006). Second, the duration of this exergame might not last long enough to identify the significant difference in perceived social interaction between these two exergame modes. As stated by Rice et al. (2013), generally, the longer the gameplay progressed, the better young-old pairs improved social interaction. The differences in social interaction between the two modes can become more pronounced as playtime increases. It is worth noting that this finding can provide helpful insights into the context of the COVID-19 pandemic. Due to the impact of the coronavirus disease, people have reduced their in-person social activities and stayed indoors. In our case, the mediated play of the Social Balance Ball can provide indoor people with an approximate social experience as the co-located play.

Interestingly, according to the analysis of the system logs, the total scores of participants in virtual play were significantly higher than those in mediated play and co-located play. The qualitative findings could explain this. Participants mentioned that virtual play was more straightforward. As stated by O7, mediated play, and co-located play required people to communicate, cooperate, and coordinate, a little bit more difficult to get scores than virtual play.

5.2. RQ2: "Do older and younger players perceive social interaction differently in this exergame?"

H2 is supported by both quantitative and qualitative data. The quantitative results demonstrated that older participants perceived significantly higher social interaction than younger participants. In more detail, older participants felt a significant difference in PAU, PBI, social connectedness, and positive affect during the three modes than younger participants. The qualitative analysis also supported these findings. Regarding participants' attitudes across all three modes, older participants reported more positive quotes (Older: 46 quotes *vs.* Younger: 31 quotes) and fewer negative quotes (Older: 14 quotes *vs.* Younger: 41 quotes) than younger participants. We speculate the following possible reasons:

1. Older adults are more likely to be satisfied with social technologies. After retirement, they are usually busy with housework and have fewer opportunities to come into contact with interesting technologies. When scoring questionnaires, they tend to have high scores. Consistent with the findings of Kruse et al. (2022), in VR exergames, older adults rated the games more positively in terms of higher enjoyment and desire to play again compared to younger adults;
2. Young people like games and are often exposed to various games, which are not easy to arouse interest. Compared with older adults, they showed lower satisfaction and more suggestions for improvements;
3. We follow the rules of inclusive design. When designing the game, we put the cognitive needs of older adults first. Therefore, in the eyes of young people, the game design may be relatively simple and lack sufficient challenge, which leads to a decline in their satisfaction. Difficulty adjustments for older and younger players should be considered in game design (Cantwell et al., 2012; Kruse et al., 2022).
4. Unlike general stereotypes, such findings demonstrated that games are very attractive to older adults and are an effective way to promote socialization.

Relevant interaction effects also showed that older participants perceived significantly higher co-presence and PBI than younger participants in the virtual play. In comparison, they felt significantly lower co-presence and PEI than younger participants in the co-located play. The likely reason is that compared with the virtual play, older participants perceived pressure from younger players in the co-located play. People become slower (e.g., the processing speed decreases) as they grow older (Loos & Kaufman, 2018; Salthouse, 1996, 2004). Due to the physical and cognitive decline, it is difficult for older participants to keep up with younger participants while exergaming, such as speed, reaction time, memory, attention, hand-eye coordination, and problem-solving (Loos & Kaufman, 2018). Compared with the simplicity of virtual play, co-located play needed a joined effort from both sides. For example, O9 made some mistakes during exergaming and was afraid of being blamed by the younger player. Y22 also mentioned the older participant looked embarrassed if she tried to guide her in the game. Instead of aiming for a high score in the game, she took on a more supportive role in helping the older participant. In line with the quantitative results, most quotes (13/21) from younger participants expressed their positive attitudes toward the co-located play. One typical reason is younger people can feel happy to help older adults (Y32).

5.3. RQ3: "Does gender affect the perceived social interaction of players in this exergame?"

Our findings do not support H3. Xu et al. (2016) reported that there were few significant interaction effects between exergames and gender among older participants. Consistent with their findings, we did not find a significant difference in perceived social interaction between male and female participants across three modes.

5.4. RQ4: "How do the findings from this study inform us about designing exergames in a social context?"

- **Differentiating the Difficulty of Game Tasks.** Because older and younger people have different physical and cognitive abilities, careful consideration must be given to determine their task difficulty to make more individual contributions to games. Similarly, the concept of "adaptive difficulty" (Cantwell et al., 2012) was pointed out to deal with the same problem. The prototype with "adaptive difficulty," enables each player to decide their own difficulty level while playing together.
- **Considering "Family-based" Intergenerational Settings.** This study focused on investigating the exergame in unfamiliar young-old pairs. However, we found that older adults (e.g., O15, O21) preferred playing the exergame with their family members. Playing the Social Balance Ball can provide them a good opportunity to stimulate interaction and have fun together.
- **Narrative Contents.** Narrative contents are storylines that players get involved in by controlling their avatars, and lack of narrative content has been seen as a reason for players rating the exergame as boring (Baranowski et al., 2008). It also provides a way to enrich the exergame, as the Y8 and Y10 mentioned in the user experiments, with new scenes and elements that can be linked together along the storyline.
- **Various Tasks.** Tasks of different challenges enable players to choose the task according to their skills, ages, and even their moods to help produce a flow state (Csikszentmihalyi & Rathunde, 1992; Rauterberg, 2021), in which players can have a highly intrinsically motivating experience. In this way, two players do not need to have some skills and abilities to cooperate, which is very important in intergenerational gameplay due to the possibilities of gaps between two generations.
- **More Motion Interaction Mechanism.** As for the hardware, although many participants in our experiment mention the hand motion, the whole body should be considered because it would enable players to exercise any parts of their body they want (Santos et al., 2015).

We acknowledge the limitations of this study and the opportunities for future work.

First, the older participants' ages range from 59 to 70, and this group is limited in representing other age groups of older adults. According to the classification by Xu et al. (2016), in general, older adults below 75 could be categorized as young-old adults, while those over 75 are regarded as old-old adults. Due to the consideration of participants' physical and mental abilities, we involved young-old adults in this study. In our future work, we can try to recruit old-old adults to participate in our research, although it is more challenging.

Second, we did not use physiological data to measure participants' social interaction in the game. As mentioned by Qiu et al. (2022), it is not very common to use physiological data for measuring Socially Assistive Systems since social interaction is a complicated procedure that often involves two or more people exchanging ideas and sharing emotions. Sometimes physiological data cannot reflect participants' mental processes and behaviors. In our study, we cannot simply use physiological data, such as electromyography (EMG) signals, heart rate (HR), and galvanic skin response (GSR) to measure the perceived social interaction of participants during exergames. Because it is difficult to identify whether the fluctuations in physiological data are caused by social interaction and the emotional state of participants or their physical activities. Instead of directly measuring their social interaction, in our future work, we can use gaze data to measure participants' engagement in the game.

Third, in sociology, a dyad (namely two people) is regarded as the smallest social group (Charon, 1996). It is ideal for studying social behaviors because observing and developing a social connection between participants is more accessible. Thus, the dyad has been used in this study. Our future work can be extended to explore testing social exergames in a multiplayer scenario.

Finally, a pair of participants took only 6 min for each mode in the controlled lab-based experiments. Each session's short duration may influence participants' perceived social interaction. A long-term intervention in field settings is still needed. For example, we can conduct a long-term field study to observe the gaming behaviors of participants in an elderly home.

Overall, this study has three significant contributions:

1. Empirical evidence is provided that participants perceive higher levels of social interaction and positive feelings in the mediated human player mode and the co-located human player mode (i.e., the human players interact) compared to the virtual player mode (i.e., the human players do not interact);
2. Contrary to the general stereotype, the findings showed that older participants perceived social interaction significantly higher than younger participants in the Social Balance Ball exergame, suggesting that social exergame is highly attractive to older adults, and is an effective way to promote social interaction.
3. We also provide design suggestions, insights, and opportunities for game designers and researchers regarding the design and development of social exergames.

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Author contributions

S.Q. and E.K.: conceptualization. S.Q.: experimental design. E.K.: software. E.K., R.D., and S.Q.: experiment implementation. S.Q., and E.K.: formal analysis and writing—original draft preparation. S.Q., E.K., and

M.R.: writing—review and editing. T.H., S.Q., M.R., and J.H.: supervision. All authors have read and agreed to the submitted version of the manuscript.

Disclosure statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, "Social Balance Ball: Designing and Evaluating an Exergame that Promotes Social Interaction between Older and Younger Players."

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Appendix

Video link

https://youtu.be/cQCyMeuONT8

We provide a video demonstration to illustrate the effect of an elastic band between two players and its relationship to the overall score.

Details descriptions of questionnaires

NMSPI consists of 36 items with a seven-point Likert scale ranging from one (strongly disagree) to seven (strongly agree). Six subscales of NMSPI are illustrated below:

a. *Co-presence* refers to the degree of peripheral or focal awareness of the other (e.g., "(My partner) noticed me").
b. *Attentional allocation* addresses the amount of attention the person provides to and receives from the partner (e.g., "I did not receive (my partner's) full attention").
c. *Perceived message understanding* is the ability of the person to understand the partner's message and the level of message understanding (e.g., "It was easy to understand (my partner)").
d. *Perceived affective understanding* is the ability of the person and the partner to understand their mutual emotional and attitudinal states (e.g., "(My partner's) emotions were not clear to me").
e. *Perceived emotional interdependence* is the extent to which the person's emotional state influences and is influenced by the partner's emotional states (e.g., "My feelings influenced the mood of our interaction").
f. *Perceived behavioral interdependence* is the extent to which the person's behavior influences and is influenced by the partner's

behavior (e.g., “My behavior was closely tied to (my partner’s) behavior”).

IOS is a seven-point pictural scale using two overlapping circles to indicate the level of closeness between people and their partners; more overlapping circles stand for higher levels of perceived closeness.

PANAS consists of two 10-item scales (i.e., the Positive Affect (PA) subscale and the Negative Affect (NA) subscale). A total of 20 items are rated on a scale ranging from one (very slightly or not at all) to five (extremely). The PA subscale reflects a person’s positive feelings (e.g., attentive, active, excited, enthusiastic, and inspired). In contrast, the NA subscale reflects a person’s negative feelings (e.g., stressed, upset, guilty, scared, hostile, and irritable).

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