Focus on Cooperation: A Face-to-Face VR Serious Game for Relationship Enhancement

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Abstract—Exploring effective approaches to enhance face-to-face interactions and interpersonal relationships is an important topic in the applications of affective computing. According to the co-actualization model, we propose a face-to-face co-participation serious game for relationship enhancement, with a focus on battling COVID-19. Moreover, a prototype system is developed using an immersive virtual environment and a low-cost brain-computer interface. Through this system, a dynamic flow experience enhancement tool is utilized to involve partners in the cooperative task. To evaluate the system performance, two studies are conducted with schoolmates as participants. Study 1 compares the cooperative and competitive modes, and demonstrates that the former elicited higher level of decision-making challenge and affections, which are beneficial for forming relationships. Study 2 further examines the effect of the dynamic flow enhancement tool in the cooperative task and the results show its effectiveness in promoting flow experience, perceived closeness, and intimacy in relationships. Given this short-term participation, participants felt a greater sense of closeness and intimacy than they had before the test. In conclusion, our proposed system is effective in enhancing schoolmate relationships.

Index Terms—relationship enhancement, virtual reality, positive face-to-face interaction, flow experience assessment.

1 Introduction

Healthy and supportive relationships (between families, friends, lovers, etc.) are protective factors associated with higher life satisfaction and well-being [1] [2]. To develop well-functioning relationships between family members or a range of constructive relationships among a group of colleagues or friends, a positive face-to-face interaction is very important [1] [3]. According to existing studies, factors such as time and space constraints (e.g., work-family conflict, long-distance) hinder the development of relationships in the physical world [4] [5]. Therefore, increasing the amount of time spent in face-to-face communication helps to strengthen the links between people. However, a special but important counter example occurred during the "lockdown" period of the global COVID-19 pandemic: as lockdown duration increased, conflicts occurred between family members, which resulted in negative feelings and thoughts about the relationships [6]. These feelings and thoughts may in turn negatively impact the way we communicate with each other [7] [8]. A possible reason is the lack of effective ways to create a positive mental atmosphere for face-to-face interactions. Therefore, the way to effectively enhance relationships is becoming an important topic in today's life [9].

According to the model of co-actualization, the reciprocal influence among a forming relationship[1], co-participation, self-organization, and environment is an important aspect for forming well-functioning relationships [10]. Emerging information technology (IT) has great potential to enhance these aspects. Moreover, the overuse of IT techniques (e.g., online social media) may lead to negative outcomes (e.g., social isolation) [11] [12]. Thus, only an appropriate use of these tools can achieve positive effects in enhancing relationships [12]. The introduction of serious game and Virtual Reality (VR) techniques has been proved to be effective in enhancing participation motivation, behavioral intention, collaboration, connections with partners, and social integration [13] [14] [15] [16]. In particular, a study in the US showed that 81.8% of the participants enjoyed the closeness and connection of playing video games with their families [17]. Therefore, this paper aims to use the model of co-actualization as the design principle and propose a novel type of VR serious game to enhance interpersonal relationship.

Flow experience is an essential factor that keeps people actively and sustainedly engaged in an activity [18]. Flow experience is referred as the holistic sensation that people feel when they act with total involvement [19], which is a concept commonly used for characterizing people's feelings of deep involvement and engagement. During co-participation activities, flow experiences at higher levels or for longer durations result in getting the desired outcomes, such as a stronger participation motivation, better positive emotions, and better interactive performance [20] [21], which can further help with enhancing relationships between peers. However, flow experience is rarely used in the design of real-time interactive systems, due to the lack of assessment and enhancement methods for dynamic flow

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1. It is defined as an associative process entity denoting the unfolding relationship with its own emergent properties [10].

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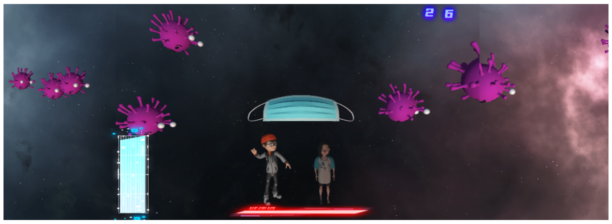
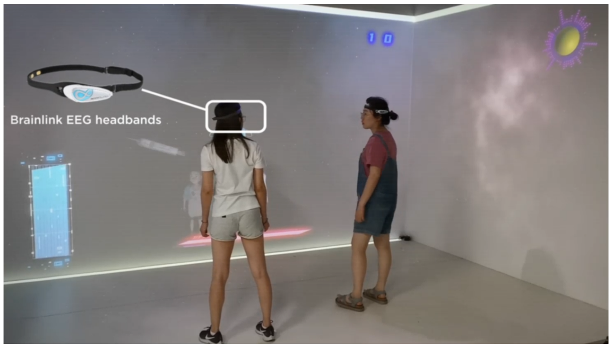


(a) The game's mission is fighting COVID-19



(b) Two schoolmates take part in the game

Fig. 1. Snapshots of the proposed face-to-face co-participation serious game and its prototype system. More details can be found in the accompanying demo video.

experiences. Therefore, proposing a method for dynamic flow experience assessment and applying it to dynamically optimize flow experience may contribute to positive outcomes of the serious game, which is also a focus of this paper.

In summary, the overall research objective is to explore an effective, novel method to enhance face-to-face (FtF) interactions and interpersonal relationships. In this paper, we propose a co-participation serious game (Fig. 1) with dynamic flow experience assessment, and we performed experiments to examine its effectiveness. The main contributions can be summarized as follows:

- A co-particpation serious game for relationship enhancement is proposed according to the co-actualization model, and a prototype system is implemented in an Immersive Virtual Environment (IVE).
- A dynamic flow experience assessment tool is provided using a low-cost BCI to optimize the flow experience.
- Two studies are conducted, and the results demonstrate the effectiveness of the prototype system. The findings show that the cooperative co-participation model and the dynamic flow experience enhancement contribute to enhancing relationships.

2 Related Work

2.1 Model of co-actualization

The co-actualization model provides a theoretical perspective for understanding the development of well-functioning relationships. The model of co-actualization is characterized by an open system interacting with its environment, where the actualization takes place dynamically and the process of co-actualization promotes new and ongoing relationships [22]. According to this model, each productive relationship has a self-developing quality that also enhances the relationship among partners.

Co-actualization refers to the reciprocal actualization (*i.e.* the reciprocal influence between a forming relationship and both/all actualizing relationship partners) of two or more partners in a person-centered relationship while forming their relationship [10]. It develops from the interdependent self-actualization processes of each partner (*e.g.* couples) in conjunction with the growth-promoting of the relationship—which result in mutual understanding, influence, benefit, and expectations that create the possibility for enhanced self-discovery, self-efficacy, and perspective taking. For example, co-actualization is potentially realized in a couple relationship, contingent upon the absence of competitive attitudes in the relationship and the presence of reciprocity, mutual influence, and trust. It is conducive to both couples to experience themselves as being 'better off' and being better people as a result of the relationship [23].

Important real-world relationships, such as personal friendships, well-functioning families, teams, and other intimate groups, can be potentially characterized and enhanced by the co-actualization process. Therefore, the model has great practical value to provide effective methods and environments (like those proposed in this paper) to activate the actualization processes for developing more positive relationships in the real-world. However, the model is rarely used as a design framework to develop applications for building relationships.

2.2 Challenges in relationship enhancement

Close social relationships positively contribute to individual well-being [24]. Moreover, a positive perception of social relationships plays an important role in protecting the physical and mental health [25] [9]. There are several factors that are important for developing and maintaining good interpersonal relationships, such as personal characteristics (*e.g.* shyness, poor social and communication skills) [26] [16] and environmental conditions (*e.g.,* stressful work environments, natural disasters, etc.) [8]. In addition to these traditional factors, a new social factor has rapidly emerged in recent years: a huge amount of data is generated and shared as a result of the rapid development of information and communication infrastructures in modern society. Getting information from this data makes people spend less time communicating with their families, which psychologically accelerates mental separation within families. [12].

When focusing on relationships with family members or friends, information techniques were used to ameliorate factors related to isolation and loneliness, but mixed results were reported [27] [28]. As aforementioned, a study in the U.S showed that most of the participants enjoyed the closeness and connection of playing video games with their families [29]. However, a latter study did not find that games enhance relationships with family members or friends [11]. The difference between both studies may be that older adults lack the experience of playing games with family or friends [30].

We also note that IVE was shown to be effective in improving relationships between partners [31] [32], because a shared IVE can successfully promote interdependent interactions. [33] [34]. Therefore, we aim to develop a serious game in an IVE environment to enhance face-to-face interactions and improve relationships between schoolmates who have similar gaming experiences.

2.3 Evaluation of flow experience

The flow experience is a highly enjoyable mental state in which the individual is fully immersed and engaged in the activities [35], [36]. In order to completely engage people in VR activities (including VR games), an optimal design principle is to achieve good flow experience [37]. In the HCI field, flow experience is often described as a natural and fluid state of being productively engaged with a task without being aware of the technology that is driving it [38]. To make a game entertaining and fulfilling when diverse players participate in, it is essential to have the ability to adjust the settings for these players (in particular to keep them in good flow experience).

Some studies investigated the brain mechanism of flow experience and mapped specific Electroencephalogram (EEG) indicators to flow experience [37], [39], [40]. For instance, Berta et al. exploited a 4-electrode EEG tool to perform a spectral characterization of the video-gaming experience [39]. Few works already successfully identified the flow experiences of players by capturing their physiological responses [18], [41], [42], [43]. These studies found that the most informative frequency bands in EEG for discriminating different gaming conditions vary around low beta values. By using a Support Vector Machine (SVM) classifier, three user states levels were classified with good accuracy [39]. However, most of the existing methods can only assess flow experience in the post hoc phase, *i.e.,* after a task was executed. A tool based on real-time EEG signals for dynamic flow experience assessment is still absent.

To achieve the research purpose based on the above review, we propose a novel co-participation serious game by combining flow experience with low-cost brain-computer interfaces in an immersive environment. The effective co-participation mode as well as the function of dynamic flow assessment and enhancement are two key points to support the effectiveness of the game. Therefore, this paper includes three research questions as follows. The logical relationship among them is shown in Fig. 2.

- Question 1: How to design a novel approach and implement a prototype system for relationship enhancement?
- Question 2: Does effective co-participation mode contribute to relationship enhancement (Hypothesis 1)?
- Question 3: Does dynamic flow assessment and enhancement contribute to relationship enhancement (Hypothesis 2)?

To explore question 1, we introduce the design and implementation of the co-participation serious game in section 3. To explore the question 2 and question 3, we introduce study 1 in section 4, and introduce study 2 in section 5. The results obtained from the two studies can prove the effectiveness of our proposed co-participation mode design

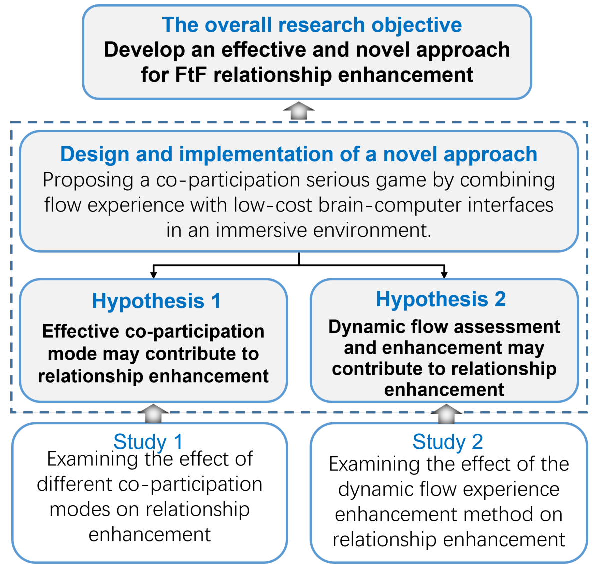


Fig. 2. The main research questions (within the dashed box) and the logical connection between them.

(Hypothesis 1) and dynamic flow experience assessment and enhancement method (Hypothesis 2), as well as the overall effectiveness of the proposed approach on relationship enhancement.

3 Design Elements and Prototype System

Based on the idea of fighting COVID-19, a serious game was designed for relationship enhancement and a prototype system was developed in an immersive CAVE that supports two players/partners to play together face to face. The design principles are proposed in Section 3.1 and the construction of the prototype system is presented in Section 3.2. Two studies are shown in Sections 4 and 5, demonstrating the advantage of the proposed system.

3.1 Design framework and elements

Based on the model of co-actualization [10], we use a design framework as shown in Fig. 3 to guide the design of a serious game for relationship enhancement. In this framework, three entities are defined to characterize the co-actualization in a system: the actualization processes of two persons A and B who are reciprocally interconnected, and a forming relationship between them (refer to footnote 1 in page 1 for the definition of a forming relationship). Two carriers are also included in this framework to enhance the actualization process: the first is a co-participation task that can be designed and manipulated to stimulate face-to-face interaction, and the second is an interactive environment powered by IT technologies (*e.g.,* VR equipment), which can be used to strengthen the mental atmosphere for co-participation. From a system point of view, the actualization takes place in the process of co-actualization with a dynamic relationship (*i.e.,* a forming and ongoing relationship) [10]. The hollow arrows in Fig. 3 indicate the influence of the interactive environment and the co-participation task on the actualization processes.

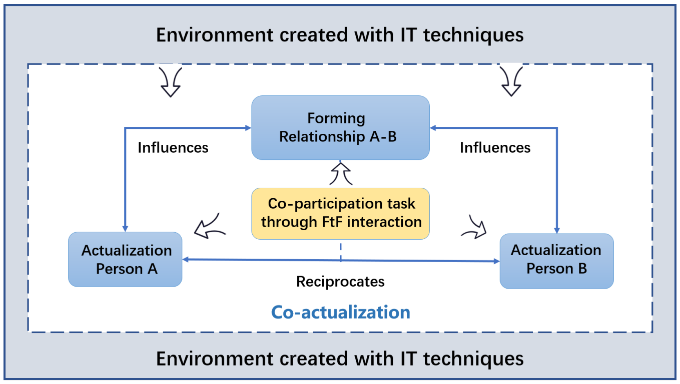


Fig. 3. The design framework based on co-actualization modeL [10].

According to the proposed framework, it is necessary to strengthen the reciprocal interconnection between the partners by designing an appropriate co-participation task and by using an interactive environment for face-to-face interaction. For this purpose, we outline three guidelines in designing a serious game for the relationship enhancement:

- Providing a co-participation task to achieve reciprocal interconnection between partners.
- Providing an interactive and immersive environment.
- Providing tools to make partners highly involved in the task.

According to these guidelines, the following four elements are considered in our system.

3.1.1 Element 1: A theme or storyline with significance

Previous studies demonstrated that the use of themes and storylines can enhance user's involvement and his intentional engagement [44] [45]. Therefore, the relationship enhancement-oriented theme and the storyline should be integrated in our system.

3.1.2 Element 2: Self-avatar for self-presence

Self-avatars provide self-representation in the virtual space and contribute to self-presence, *i.e.*, a state in which users experience their avatar as their real selves [46] [47]. Moreover, self-avatars have shown to be an effective way to improve performance on collaborative task and increase interpersonal trust in shared IVEs [34], [48], [49]. Accordingly, the proposed system allows players to choose their favorite avatar to participate in the game. The control of the self-avatar to complete tasks allows the players to improve their feelings of involvement and self-presence.

3.1.3 Element 3: Collaborative task with appropriate challenges

Working with others to overcome mental and physical challenges can give participants a sense of collaborative satisfaction, especially when this collaboration requires close coordination [34]. Research on social psychology themes has shown that working with others can make players/participants feel connected, similar, and close to each other. By considering these positive results, serious games should include collaborative tasks with common goals and appropriate challenges [50]. Moreover, the ability to change strategy according to a player's skills, provide an optimal level of challenge, and keep players in good flow experience is crucial in making the game enjoyable and satisfying.

3.1.4 Element 4: Feedback and sharing

Sharing ideas and feelings is an important factor in relationship development [51]. To help players effectively perceive their feeling and performance during the game task, the system should be able to give players quantitative and visual feedback on how they are doing. This can help players identify their deficiencies in performing the required tasks; players can discuss strategies together, share their feelings, and improve their performance iteratively.

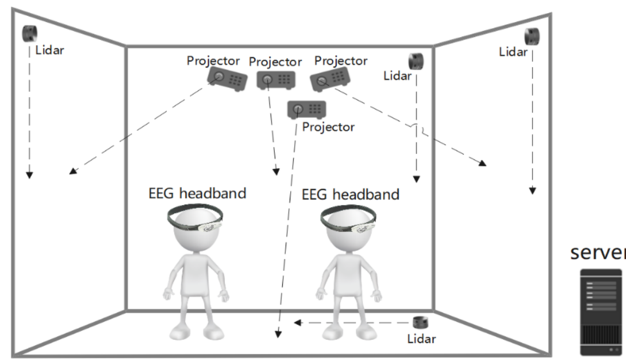


Fig. 4. Hardware layout of the immersive virtual environment.

(a) (b)

Fig. 5. Some hardware in the prototype system. (a) An immersive CAVE with 4 projectors and 4 Lidars. (b) A low-cost portable EEG headband.

3.2 Construction of the prototype system

We developed a prototype system according to the design framework and the four elements presented in Section 3.1; as for its hardware and software parts, they will be presented in this section in detail.

3.2.1 Hardware

We illustrate the hardware layout of our prototype system in Fig. 4. It consists of the following:

Display devices. We used a cave automatic virtual environment (will be referred to CAVE in the remaining part of the paper) in the system, in which virtual contents were displayed through the projection on four surfaces (three walls and ground) of a room-sized cube. The reason why we adopted the CAVE was that the immersive environment possesses a number of features superior to traditional video

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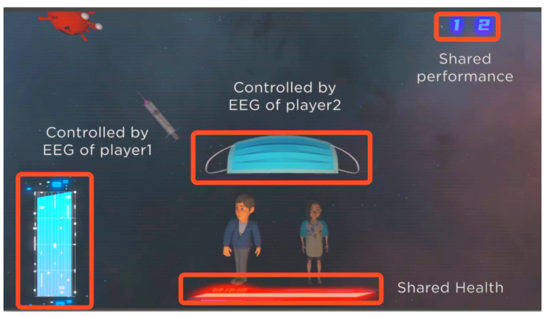
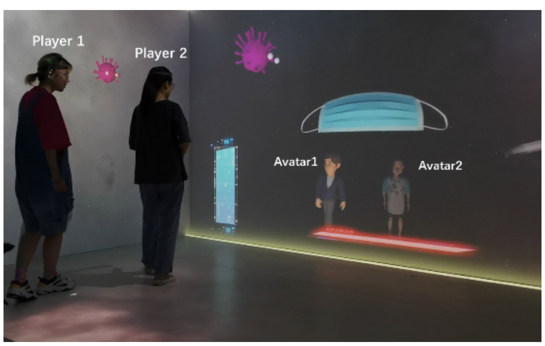
games in collaborative tasks. We compare the features between CAVEs and 2D monitors (i.e. traditional video games) in Appendix A. The dimensions of the room-sized cube are 3 m (in width) × 4 m (in length) × 4 m (in height). Four projectors (Panasonic PT-SMZ67C) were also used to display a high-resolution virtual scene and a PC (Lenovo ren 7000) was utilized to run the operating system. Fig. 5(a) shows a snapshot of the CAVE.

Interactive devices. The system included a portable EEG device to interact with the user [52] and dynamically evaluate the user experience [39]. More specifically, a low-cost EEG headband (Brainlink lite 2) with NeuroSky's single-channel EEG sensor was integrated in the system to collect EEG signals (as shown in Fig. 5 (b)). We chose the NeuroSky sensor because it was widely used in practical man-machine interactive systems [53] [54]. The headband contains a single dry electrode that needs to be attached to the player's forehead at the *Fp1* location according to the international 10–20 system. The EEG signals are sampled at a frequency up to 512 Hz and transmitted wirelessly via a Bluetooth connection [55].



(a) Screenshot of a task interface in stage 3



(b) A snapshot of two players experiencing the task

Fig. 6. Some screenshots/snapshots of the software interface in the prototype system with the theme of fighting COVID-19. More details can be found in the accompanying demo video.

Each projected surface in the CAVE was equipped with a 360^o laser rangefinder (YDLIDAR G2 With 5-12 Hz scan frequency and 0.1-12 m range distance), which supports multi-touch interaction on each of the four projected surfaces.

3.2.2 Software

In the prototype system, the software of a VR serious game was developed using a widely used game engine *Unity 3D*, based on the four design elements introduced in Section 3.1. Fig. 6) shows some snapshots of the software. We present the complete details below:

(1) Implementation of Element 1

The game storyline uses the theme of fighting COVID-19 to inspire people's willingness to cooperate and protect their partners. In particular, two players will cooperate to eliminate the virus and survive together. Using the audio-driven talking face generation technique [56], we built an avatar with the image of a famous doctor in history (or any other character the player suggests). This avatar serves as a virtual narrator to introduce the storyline.

(2) Implementation of Element 2

To take full advantage of self-avatars for self-presence, players can choose their favorite virtual character to serve as self-avatars in the game. Fig.7 shows some avatar examples. These avatars do not follow the participants'motions, and their actions are driven by the participant's attention level evaluated through the EEG headband. In more detail, the eSense patented algorithm provided by the EEG headband (Brain-link lite 2) is used to evaluate the player's attention level. The eSense algorithm outputs attention values at a 1 Hz frequency and these values (varying between 0 and 100) indicate the intensity of concentration on selective information (whether they are subjective or objective) [57] [58]. Moreover, these attention values show strong positive correlations with the self-assessment and other physiological-based measures of attention [59] [60]. Note that the attention values of each player were recorded throughout the task.

Fig. 7. Some examples of self-avatars used in the prototype system.

Fig. 8. The players driving their self-avatars to collect the target boxes to strengthen the sense of self-presence.

As for the process, the players were required to control their self-avatars by completing a collection of tasks to further strengthen the sense of self-presence. Throughout the collection process, medical kits randomly appeared on the ground in the virtual scene. Players were required to move and stand together on the target boxes to collect them (as displayed in Fig. 8) by driving their self-avatars using the

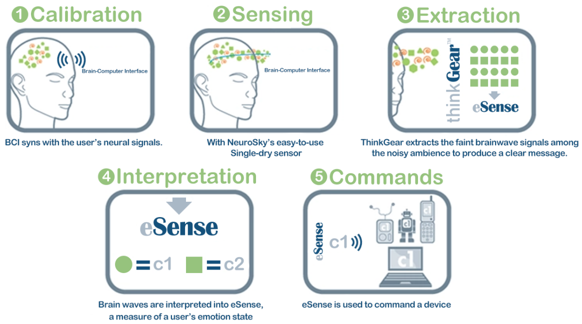


Fig. 9. The eSense algorithm for processing EEG signals.

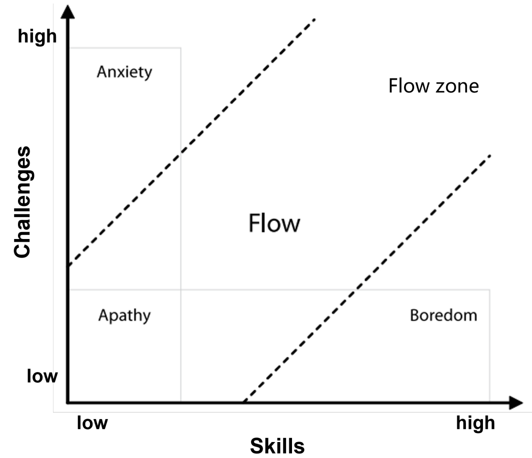


Fig. 10. The two-dimensional four-channel model of flow experience where the four states are defined as follows: flow (high challenge/high skill), boredom (low challenge/high skill), apathy (low challenge/low skill), and anxiety (high challenge/low skill) [19], [61], [62].

attention evaluated by the EEG headband. The processing of EEG signals (using the eSense algorithm) is shown in Fig. 9.

(3) Implementation of Element 3

The proposed system adopts a cooperative task with the goal of "protect each other." Two players work together to eliminate the COVID-19 virus and its variants to stay healthy. The following designs were applied to establish the co-participation principle. Each of the two players has distinct responsibilities throughout the game: one is responsible for killing viruses whereas the other is responsible for activating the mask shield against virus attacks. Both players share health scores to strengthen their bond as shown in Fig. 6 (b). During the game, medical supplies are generated at random positions on the walls of the immersive virtual environment. Both players can touch a supply at the same time to restore their health scores to some extent. This operation also helps to reduce interpersonal distance.

Dynamic flow experience assessment and enhancement. As summarized in Section 2.3, the flow experience and its related terms were commonly evaluated after the completion of the task in previous studies. To maintian a good flow experience by adjusting the game difficulty, we propose an adaptive model to modulate the flow and develop a tool for real-time flow experience assessment based on the proposed model. The adaptive model is proposed based on the two-dimensional four-channel model of flow experience (as shown in Fig. 10), which is widely used to describe gameplay experiences [19], [61], [62]. According to the model, the operational definitions of the four states were defined in previous studies: flow (high challenge/high skill), boredom (low challenge/high skill), apathy (low challenge/low skill), and anxiety (high challenge/low skill) [63] [19]. Moreover, Chen coined the term "flow zone" and defined it as a state between boredom and anxiety that grows or falls depending on the level of challenges and the game skill (the diagonal zone represented in Figs. 10 and 11 (a)) [64]. However, the challenge level could not be directly measured in previous work.

To make the flow experience computable, we develop the operational definition for the flow experience [65]. Based on the above review, the flow experience can be characterized by optimizing the physiological activation (moderate or medium level) to have full concentration on coping with environmental or task demands [37]. Accordingly, flow experience is defined as a state with high performance level and moderate arousal from the task challenge. Previous study showed that meditation refers to a reduction in the active mental processes of the brain and is negatively related to arousal [66]. The arousal level can be measured with the meditation meter that indicates the level of relaxed/stressed (it has been widely used in previous studies [53], [57]). Moreover, this level is calculated using the eSense algorithm based on the acquired EEG signals.

As a short summary, we define the four states of the four-channel model in a more operatable and computable way as follows (refer to Fig.11(a)):

- Apathy: a state of low performance and high meditation. In this state, the player has little motivation to participate [63];
- Boredom: a state of high performance and high meditation, which is consistent with the condition that the challenge level is lower than the player's skill level. In this state, the player is not challenged enough [63];
- Anxiety: a state of low performance and low meditation, which is consistent with the condition that the challenge level is excessively higher than the player's skill level. In this state, the player feels too challenged to complete the task [63];
- Flow: a state of high performance and moderate mediation, which is consistent with the condition that the challenge levels match the skill levels of the player. In this state, the player feels moderately challenged and can still complete the task [63].

The measurement method of the different performance levels and meditation is presented in Fig.11(b). The values of performance and meditation are refreshed with the frequency of 1 Hz, so the experience states in the model can also be calculated with the same frequency. Only when the player is calculated to be in a same state continuously for three seconds (*i.e.,* three consecutive times) will he/she be determined to be in this state. When at least one player is evaluated as bored, the system automatically increases the virus generation rate (each time by 2%). Conversely, when at least one player is evaluated as anxious, the system automatically decreases the rate of virus generation (each

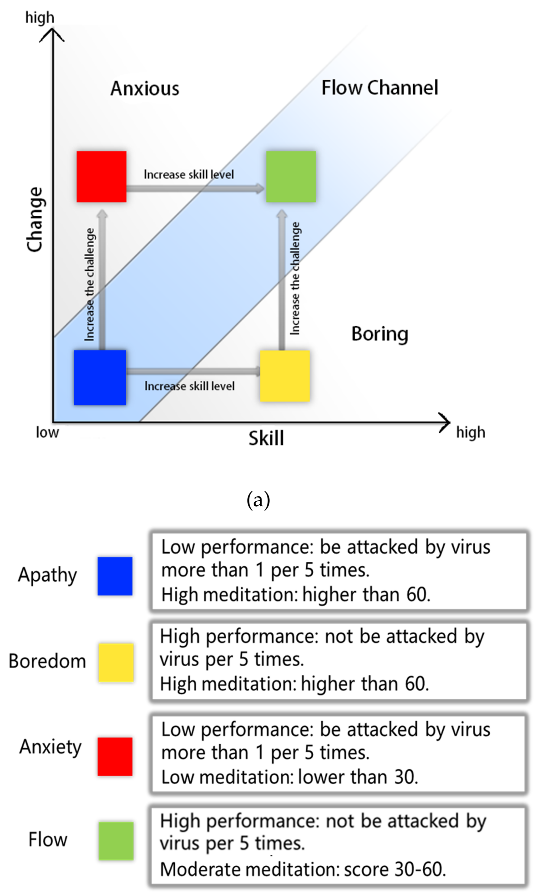


Fig. 11. A model for dynamically flow experience assessment and enhancement (b) based on the two-dimensional four-channel model of flow experience (a).

time by 5%). Moreover, when players are evaluated as being in flow experience, the system maintains the current virus generation rate. The values 2% and 5% were determined by a pilot experiment, which is summarized in Appendix B. In summary, we adopted a stricter criterion of adjustment for a negative experience. This strategy did not cause the mismatch of the task challenge with the player's skill to impact the flow experience. On the contrary, this strategy can help avoid negative experience as much as possible when considering the overall process, thus it helps the pair of participants to match the task challenge with their skills and achieve a common flow state together.

(4) Implementation of Element 4

After completing the task, the system will show the players' game data, including their task score, health value, and the time spent in flow experience during the game. Furthermore, the players can follow the prompts from the system to share their feelings or discuss strategies.

To evaluate the performance of the proposed prototype system, we present below two studies to investigate the key factors in the relationship enhancement, i.e. the effect of co-participation mode (presented in Section 4) and the effect of dynamic flow enhancement (shown in Section 5) regarding the perceived relationship.

4 Study 1: Effect of Co-participation Mode on Perceived Relationship

4.1 Purpose and hypothesis

Study 1 aims to examine the effect of different co-participation modes on the relationship related to feelings after a short-term co-play, which follows hypothesis 1:

Hypothesis #1: Effective co-participation mode may contribute to relationship enhancement. Specifically, the cooperative mode has more advantages than the competitive mode in inducing relationship enhancement related feelings.

4.2 Participants

A total of 18 pairs of undergraduate volunteers (18 males and 18 females) were recruited to participate in this study. The age of the participants ranged between 18 and 25 years (M= 20.08, SD=1.71). All participants were recruited from a local university, but most of them were not friends. All the participants had heterosexual orientations. To control the potential interference of gender factors, the participants were randomly matched in pairs while adopting three categories: male pair, female pair, and mixed pair. Finally, six pairs of participants were included in each pair type. No one dropped out of the study because of VR sickness or other discomforts. They did not know the purpose of the experiment.

4.3 Design

To avoid the extra effect of pre-existing relationship among different participants, we conducted a comparative experiment using within-subject designs. The independent variable was the co-participation mode, which included two types: cooperative mode and competitive mode. Except for the modes, the pairs of participants in each condition were totally the same. Participants' individual characteristics, pre-existing relationship, and other factors remained unchanged for both types, so they will not cause extra effects on the outcome. The dependent variables were the game experience (including the decision-making challenge and affection) and the perceived relationship (including the perceived closeness and the intimacy in relationship) during the game. Before the beginning of the study, the perceived closeness and intimacy in relationship were pre-tested. The order of experiencing the two types was counterbalanced. Specifically, the participants were randomly grouped to two halves (on the premise of equal sex ratio). One half of them first experienced the cooperative mode then the competitive mode, and the other half experienced the two modes in the opposite order. To avoid any interference that VR sickess might have on the participants' experience and the psychological data, we would stop the game and delete the data if the participants suffered from serious VR sickness or other discomforts during the game.

4.4 Environment

Based on the proposed prototype system, two different co-participation modes were defined:

- Cooperative mode (mode 1). In this mode (Fig. 12(a)), the system was basically the same as the one introduced in Section 3.

- Competitive mode (mode 2). In this mode, two players competed for the game scores and the main task was competing to eliminate more viruses and get higher scores for themselves (Fig. 12(b)).

In both modes, the pair of participants were alone in the CAVE, and the experimenters were not located in the CAVE. The virus generation method was static with a generation rate of one new virus each 2.3 seconds. Attacking a virus 2 or 3 times could eliminate it. The rate was chosen according to the results of a pilot experiment.

(a) Cooperative mode

(b) Competitive mode

Fig. 12. Two different co-participation modes in Study 1.

4.5 Measures

4.5.1 Decision-making challenge

The decision-making challenge (abbreviated as DM challenge) arises from having to make choices that were difficult or could lead to regrettable outcomes [67]. It was measured using the sub-scale "DM challenge" from the Challenge Originating from Recent Gameplay Interaction Scale (CORGIS) [67]. As for the CORGIS, it is a systematic, extensive, and reliable instrument to assess the level of players' perceived challenge in digital games. Four sub-scales (30 items in total) measuring four types of perceived challenge in video games were defined: the cognitive challenge, the performative challenge, the emotional challenge, and the DM challenge. The items were assessed on a 7-point Likert scale from 1 (strongly disagree) to 7 (strongly agree). The scale shows good structural validity and can be used to quantify a player's challenge experience. Moreover, the sub-scale of the DM challenge showed a good reliability in this study ($\alpha = 0.895$).

4.5.2 Sense of closeness and intimacy in relationship

A sense of closeness and intimacy resulting from social interaction is crucial to establishing and maintaining a long-term relationships [68] [69]. We summarized the existing tools to measure the sense of closeness and intimacy, but most of them were designed to measure daily relationships, such as the Emotional Closeness Questionnaire (ECQ), China Family Panel Studies (CFPS) and the Flores's 5-items questionnaire [70] [9]. Therefore, they are not suitable for measuring the current situational experience. Thus, we referred to the emotional closeness measure in CFPS that uses a single item on a 5-point scale and extanded it to a 11-point scale from 0 (not close at all) to 10 (very close). Similarly, the perceived intimacy was also measured using a single item in a 11-point scale.

4.5.3 Affection

In the present study, the Positive and Negative Affect Scale [71] was used to assess the participants' affections during the game. This scale consists of 20 items (e.g., strong, guilty, active, ashamed, etc.), which are rated on a 5-point Likert scale from 1 (very slightly or not at all) to 5 (extremely affected).

4.5.4 Perceived difficulty

To avoid the extra effect of perceived difficulty in the VR setting on the aforementioned measures of participants, we measured their perceptions on the 5-point Likert scale, ranging from 1 (very low) to 5 (very high).

4.6 Procedure

First, the participants finished a pre-test questionnaire before playing the games. Then, the researcher explained to them the game conditions. After that, each pair of participants wore the EEG headbands and practiced in the interaction method through a practice scene. Then, they played each version of the game in a certain order. When each game was over, the participants immediately completed a post-test questionnaire. It took about 30 minutes to experience each version of the game.

4.7 Results

Kolmogorov–Smirnov tests (K-S tests) were first performed, and the results supported the normality assumption ($ps > 0.05$). Before analyzing the results on the dependent variables, we examined the difference on perceived difficulty between the two co-participation modes. Using the paired-sample T test, the sample size was calculated to be 34 using G*Power (four predictors with a 2-sided testing, 0.80 power at the 0.05 alpha level and an estimated medium effect size Cohen's d=0.5 were considered [72]). Therefore, a sample size of 36 met the requirement. The results of the paired-sample T test showed no significant difference; thus, the difficulty would not disturb the following analysis. Next, a series of paired-sample T tests were performed to examine the differences between the two co-participation modes.

4.7.1 Difference on DM challenge

Results on the DM challenge indicated a significant difference between the two play modes $t_{(1,35)} = 2.541$, $p = 0.015 < 0.05$ (Fig. 13). Specifically, participants perceived higher levels of DM challenge in mode 1 (18.11 ± 7.58) than in mode 2 (14.58 ± 7.24). In other words, the cooperative mode led to significantly higher level of DM challenge than the competitive mode.

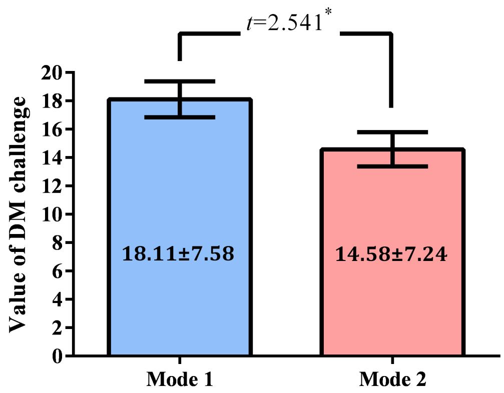


Fig. 13. Difference on DM challenge between the two game modes (*p <0.05, two-tailed; Bars represent 95% CI).

4.7.2 Difference on affections

The results showed a significant difference in one negative affection, which was guilty. Specifically, participants perceived significantly higher level of guilty in mode 1 than in mode 2, $t_{(1,35)} = 2.092$, $p = 0.044 < 0.05$ (refer to Fig. 14). Besides, results showed a significant difference in one positive affection, which was inspired. Specifically, participants perceived a higher level of inspired $[t_{(1,35)} = 2.249,\ p = 0.031]$ in mode 1 (refer to Fig. 14). These results might help with understanding the results in Section 4.7.3.

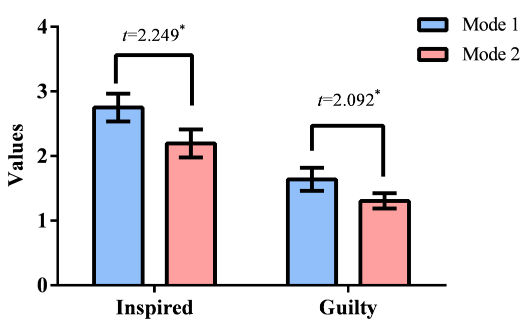


Fig. 14. Difference on affections between the two game modes (*p <0.05, two-tailed; Bars represent 95% CI)

4.7.3 Difference on perceived closeness and intimacy in relationship

Although the main purpose is to compare the difference on perceived closeness and intimacy in relationship between the two different co-participation modes, a prerequisite is to ensure that there is an improvement (or no decrease) on these feelings of relationship compared to the pre-test data. For example, if the results in the two modes were worse than the pre-test (which meansthe effect of the modes is negative and useless), understanding the difference between the two modes would be meaningless. Therefore, we should include the pre-test data in the analysis, in addition to comparing the values between the two modes. For repeated measures ANOVA, the sample size was calculated to be 29 using G*Power (5 predictors with a 0.80 power at the 0.05 alpha level, an estimated medium effect size Cohen's f=0.25, one group number, and three measurement members were considered). Therefore, a sample size of 36 met the requirement.

Then, two repeated measures ANOVAs were performed with perceived closeness and intimacy as dependent variables. Furthermore, Mauchly's test of sphericity revealed a violation to the homogeneity of the variance–covariance matrices ($ps < 0.05$), thus the degrees of freedom were adjusted and Huynh-Feldt values were reported.

Regarding the results on perceived closeness, there were significant differences among the three conditions $[F_{(1.594,55.805)} = 5.409,\ p = 0.011,\ \eta_p^2 = 0.134]$. The results of the pairwise comparisons showed that the perceived closeness in mode 1 was significantly higher than the values in the pre-test (*Mean Difference*=0.861, p=0.043, Bonferroni corrected). As for the perceived closeness in mode 2, it was marginally significantly higher than the values in pre-test (*Mean Difference*=0.750, p=0.059, Bonferroni corrected). However, the results did not reveal a significant difference between modes 1 and 2 (*Mean Difference*=0.111, p=1.000). These results are shown in Fig. 15(a).

As for the perceived intimacy, it was observed from the descriptive statistical results that the values between both modes were similar, but they recorded a higher value than the pre-test (refer to Fig. 15(b)). However, the results did not reveal a significant difference among the three conditions $[F_{(1.488,52.065)} = 1.168,\ p = 0.306,\ \eta_p^2 = 0.032]$.

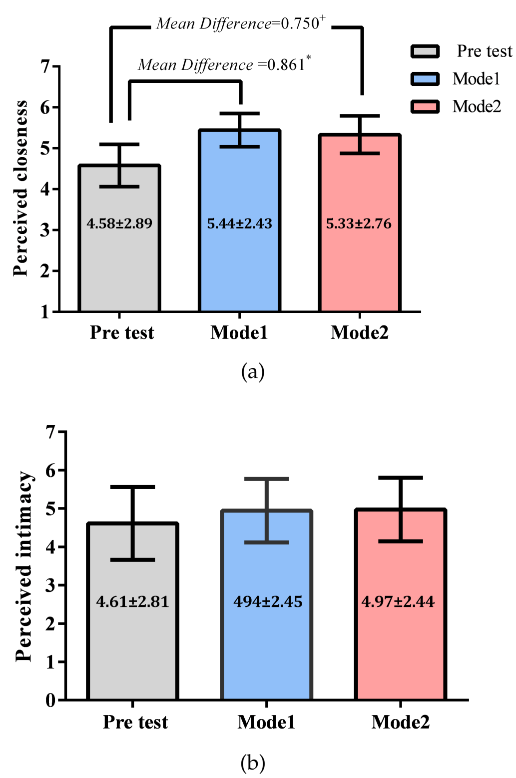


Fig. 15. Difference on perceived closeness (a) and intimacy (b) between the two modes of game with pretest scores (Bars represent SEM).

4.8 Brief discussion of Study 1

In this study, we compared the participants' DM challenge and affection experience as well as their perceived relationships between different co-participation modes after a short-term co-play.

It is worth noting that our results showed that participants in the cooperative mode felt more guilty than in the competitive mode. Although guilty is a negative self-conscious affection, it is a special one which could be a positive signal for building relationship. Previous evidence suggested that guilt can serve as a positive societal function [73]. Guilt proneness is associated with an increased empathic response to people's suffering and increased perspective taking [74]. Guilty feelings are also associated with a desire to improve subsequent performance, to apologize, and to correct a misdeed [75]. The beneficial features of guilt proneness may help in understanding why the participants felt more DM challenge in the cooperative mode. In this mode, participants are more likely to feel that their poor performance caused the injury to their partners, and are therefore more likely to feel guilty. As a result, there was a higher-level DM challenge for them. Therefore, the feeling of guilt and high DM challenge can be seen as positive signals to develop a relationship. In addition, communicating with each other to cope with this challenge is helpful to enhance their relationship. Moreover, our results show that participants felt more inspired in the cooperative mode than in the competitive mode, which is consistent with our expectation. This positive affection is beneficial to building better relationships, which is in line with the goals of designing a serious game to enhance the relationship. However, no significant differences concerning the perceived closeness and the intimacy were found between the two modes in this experiment. A possible reason is that the partners only experienced a very short-term face-to-face interaction in this study, which is not enough to turn the beneficial game experience into a sense of enhanced relationship. Therefore, hypothesis 1 was partly supported.

Moreover, both co-participation modes of the serious game showed significant higher levels of closeness than the pre-test. Previous studies show some proof that cooperative mode has positive effects on the relationship [68] [70], and there is also proof showing that non-hostile competition could improve closeness [76]. Therefore, both modes could be beneficial to enhancing closeness, which are supported by the results of this study.

In addition, both modes showed a significant higher level of closeness than the one found in the pre-test but did not show a significant effect on intimacy. A more significant effect on the perceived intimacy in relationships can be expected with increasing interaction time in the serious game. Another possible reason is that other tools are needed to improve the effect of cooperative games. Study 2 in the next section focuses on this point.

5 Study 2: Effect of Flow Experience Enhancement on Perceived Relationship

5.1 Purpose and hypothesis

Study 2 aims to explore the effect of dynamic flow experience enhancement on the perceived relationship and the experience after a short-term co-participation, which follows hypothesis 2:

Hypothesis #2: Using the design of dynamic flow experience enhancement can significantly enhance the perceived relationship.

5.2 Participants

A total of 21 pairs of undergraduate volunteers (21 males and 21 females) from a local university were recruited to participate in the study. The participants in this study are different from those present in Study 1. The age of the participants ranged between 18 and 25 years (M= 20.00, SD=1.87). As in study 1, all the participants have heterosexual orientations, and most of them were not familiar with each other. They were randomly matched in three types of pairs: male pair, female pair, and mixed pair. Finally, seven pairs of participants were included in each type of pair. No one dropped out of the study due to VR sickness or other discomforts. As in the first case, they did not know the purpose of the experiment.

5.3 Design

We conducted a comparative experiment using a within-subject design. The independent variable consisted of two conditions: with/without dynamic flow experience enhancement. Other factors remained unchanged in both conditions. The dependent variables were the perceived closeness and intimacy with the partners as well as the flow experience. Moreover, participants' closeness and intimacy in the relationship with their partners were pre-tested before the experiment. Same as study 1, the order of experiencing the two conditions was counterbalanced. In order to avoid any interference that VR sickness might have on the participants' experience and psychological data, we would stop the game and delete the data if the participants suffered from serious VR sickness or other discomforts during the game.

5.4 Environment

According to both conditions defined by the independent variable, the experimental setting consisted of two different VR game versions in this study. Considering that the cooperative mode showed more superiority than the competitive mode in Study 1, the two versions of the system were based on the cooperative mode.

- Condition 1: The dynamic flow experience assessment and enhancement proposed in Section 3.2.2 was used in this system version, where the virus generation rate was dynamically adjusted according to the real-time flow experience of the participants.
- Condition 2: The virus generation rate was fixed in this system version (without dynamic flow experience assessment and enhancement). Similar to study 1, the virus generation rate was fixed for the second condition with a frequency of 1 new virus every 2.3 seconds.

5.5 Measures

The measures of the perceived closeness and intimacy in relationships were similar to those obtained in Study 1.

5.5.1 Subjective flow experience

The level of subjective flow experience was measured with a Flow Short-Scale [65]. The scale includes 10 items (e.g., "My thoughts/activities run fluidly and smoothly"), which were assessed on a 7-point Likert scale from "1" (strongly disagree) to "7" (strongly agree). The scale was designed to assess flow experience in general activities, and it was shown to be a reliable measurement tool for flow experience in virtual environment; it was widely used in previous studies [77], [78], [79]. The scale reliability is good in this study ($\alpha = 0.898$).

In addition, we measured the participants' perceptions with a single item using a 5-point Likert scale from 1 (very low) to 5 (very high) to avoid the extra effect of perceived difficulty (same as that in Section 4.5.4).

5.6 Procedure

The experimental procedure was similar to Study 1.

5.7 Results

Similar to study 1, a minimum sample size of 29 was required for study 2. Therefore, a sample size of 42 participants met the requirement. Kolmogorov–Smirnov tests (K-S tests) were first performed, and the results support the normality assumption ($ps > 0.05$). The results of the paired samples T test showed that there was no significant difference concerning the perceived difficulty of task. Therefore, this element was not a disturbance variable of this experiment.

5.7.1 Results on flow experience

To explore the effects of our proposed dynamic flow experience assessment and enhancement, another paired-samples T test was performed. The results showed a significant difference between the two conditions [$t_{(1,41)} = 2.119,\ p = 0.040$], and the flow experience in condition 1 (53.79 ± 9.10) was significantly higher than the one obtained under condition 2 (50.50 ± 9.7) (refer to Fig. 16).

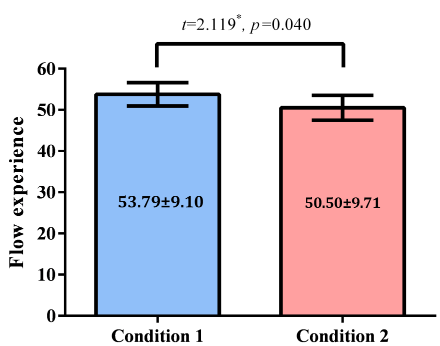


Fig. 16. Results on the flow experience between two conditions. (*p <0.05; Bars represent 95% CI)

5.7.2 Results on perceived closeness and intimacy in relationship

We examined the values of felt closeness and intimacy between conditions 1 and 2 as well as the pre-test values in order to examine the impacts of our suggested tool in the relationship enhancement. Two repeated measures ANOVAs with pairwise comparisons were respectively performed while considering the perceived closeness and the intimacy as dependent variables.

Results on perceived closeness: Mauchly's test of sphericity was not violated ($p > 0.05$), thus the degrees of freedom were not adjusted and the sphericity assumed values were reported. The results reveal significant differences among the three conditions [$F_{(2,82)} = 9.368,\ p < 0.001,\ \eta_p^2 = 0.186$]. Moreover, the results of the pairwise comparisons showed that the perceived closeness in condition 1 was significantly higher than the values in the pre-test (*Mean Difference*=1.405, p=0.001, Bonferroni corrected) and marginally significantly higher than the values in condition 2 (*Mean Difference*=0.643, p=0.075, Bonferroni corrected). The difference on the perceived closeness between condition 2 and the pre-test was not significant (*Mean Difference*=0.762, p=0.104) (refer to Fig. 17(a)).

Results on perceived intimacy: As the Mauchly's test of sphericity was not violated ($p > 0.05$), the sphericity assumed values were reported. The results were similar to those found on perceived closeness. However, there was a significant difference on perceived intimacy among the three conditions [$F_{(2,82)} = 7.934,\ p = 0.001,\ \eta_p^2 = 0.162$]. The results of the pairwise comparisons showed that the perceived closeness in condition 1 was significantly higher than the value in condition 2 (*Mean Difference*=1.048, p =0.003) and the pre-test (*Mean Difference*=1.333, p=0.001). The difference between the pre-test and condition 2 was not significant (*Mean Difference*=0.286, p=0.405) (refer to Fig. 17(b)).

To sum up, the results showed that using our proposed dynamic flow experience assessment and enhancement can significantly enhance the participants' perceived closeness and intimacy with their partners, while co-participation game without this design cannot enhance perceived closeness.

5.8 Brief discussion of Study 2

By comparing both conditions, we showed that our proposed dynamic flow experience assessment and enhancement is effective. This design enabled the system to dynamically adjust the task parameters based on players' real-time flow experience. Compared to the counterpart without this design, using this design can significantly/marginally significantly improve the perceived closeness, intimacy, and flow experience of the participants.

When focusing on the comparison of participants' perceived relationship with the pre-test levels, the system without the dynamic flow experience assessment and enhancement cannot significantly improve the perceived closeness and intimacy of participants. With this design enabling the system to dynamically adjust the task parameters, participants' sense of closeness and intimacy to partners are significantly higher than the pretest levels. In conclusion, dynamic flow experience and enhancement are required in order for the system to improve partner relationships. The design can provide them with better challenges through self-adapting their flow experiences. In this way, the participants' degree of engagement and cooperation will be promoted, which may further enhance the perceived closeness and intimacy to partners even after a short-term face-to-face interaction. Finally, it facilitates building their relationships. In summary, hypothesis 2 is verified.

In addition to schoolmate relationships, we also consider the effectiveness of the system in relationship enhancement

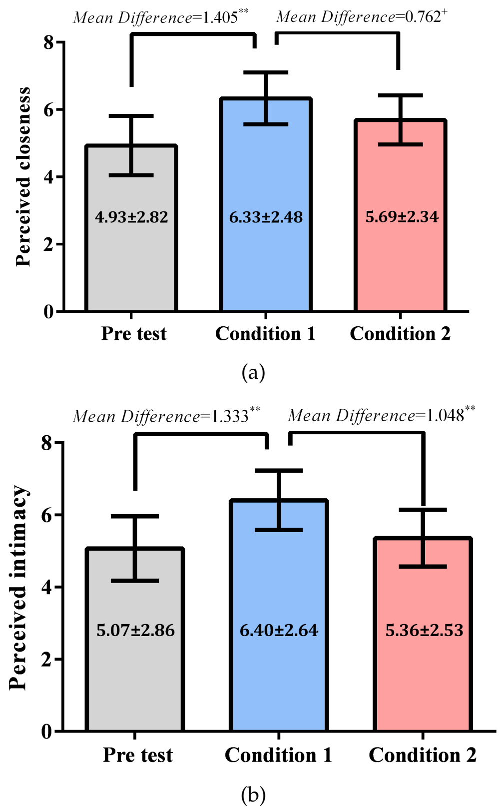


Fig. 17. Results on the perceived closeness (a) and intimacy (b) in relationship ($^{*}p$ <0.05, $^{***}p$ <0.001; Bars represent 95% CI)

with other types, such as family relationships, romantic relationships, etc. Therefore, we added an extended study in Appendix C.

6 DISCUSSIONS

Exploring the effective face-to-face interactions to enhance interpersonal relationships is important in many applications of affective computing. In this paper, we propose a face-to-face co-participation system, which is designed as a serious game for two players to enhance the reciprocity in their relationships. The effectiveness of the relationship enhancement is systematically examined and some important results are discussed below.

6.1 System design for relationship enhancement

The co-actualization model is rarely used as a design framework to develop applications for building relationships. The prototype system proposed in this paper is innovatively designed based on the model. According to this model, some important design elements related to the relationship enhancement are considered in the system, which have the potential to:

- Realize co-participation and reciprocal interconnection between multiple partners.
- Simulate and control the environment.
- Enable highly focused and engaged players in the collaborative task.

The IVE and EEG headband, along with the four basic elements, are all used to achieve the function of the system from the above aspects. Although there are previous studies that combined brain-computer interface with immersive environment for gaming [80] [81], this paper proposes a novel design framework of co-participation serious game for face-to-face relationship enhancement and is the first to design a collaborative brain-computer interface to achieve the specific goal. The specific application mode, design framework, and the combination of specific measures employed are original.

Two studies were carried out and the results showed that our prototype system can effectively improve reciprocal relationships between partners. Moreover, the cooperative mode and the dynamic flow experience assessment and enhancement are necessary to enhance relationships.

6.2 The effect of cooperative mode

Although prior literature on the psychology of gaming has compared cooperative and competitive games, the results are mixed [82] [83] [76]. This paper provides further evidence to support the effectiveness of cooperative co-participation mode on relationship enhancement and finds some new results in this specific application context.

In this paper, we compared the difference of perceived relationship and feelings between cooperative and competitive modes after a short-term co-play. An interesting result was that in the cooperative mode, participants reported higher levels of guilt, inspiration, and decision-making challenge. These feelings are beneficial to relationship building, as discussed in detail in Section 4.8. According to previous studies, these feelings can be taken as positive signals for building and enhancing relationships [68] [70]. Moreover, these feelings may help induce more empathy, face-to-face interaction, and communication between the partners, as well as aid in understanding the benefits of using cooperative mode in our prototype system. However, no significant difference on the perceived closeness and intimacy was found between both modes in this study. Increasing the time of face-to-face interaction may help turn the beneficial game experience into a sense of enhanced relationship, which is worth further explorations in future work.

As we expected, the significant positive effect of cooperative mode on closeness was proved. Moreover, the significant positive effect of the competitive mode on the closeness was also revealed. The possible reason is that the competition was non-hostile. The non-hostile competition provides a positive attribute and it was proven effective in improving closeness [76]. The next step study will also focus on the sub-types of cooperation and competition, and it will further explore their potential differences in influencing relationships.

6.3 Effect of dynamic flow experience assessment and enhancement

Although there are previous studies that evaluate flow using EEG [40] [84], as far as we know, they cannot achieve dynamic flow experience assessment and enhancement. This study innovatively makes use of an operational definition [65] and proposes a computable model for flow experience based on the traditional two-dimensional model. The proposed model can detect flow experience based on the user's real-time performance and meditation level, making the two-dimensional model more controllable and better support real-time flow detection and enhancement.

Based on this model, our system adopts a method for the dynamical assessment and enhancement of flow experience. The results of Study 2 showed that the dynamic adjustment of the task parameters according to the players' flow state can effectively improve the players' flow experience during game play. However, the effect size seems small. There are two potential reasons: First, when investigating the dynamic adjustment method of task parameters, this study only considered one parameter, *i.e.*, the generation speed of "virus". But in practical application, there will be more flow-relevant adjustable parameters. Therefore, a larger effect size could be expected if more parameters were included in the dynamic adjustment method. Second, the participants in our study only experienced a brief testing task of the system and only had a short gaming experience. Even so, the significant effect on flow experience was found. In practical applications, scenarios and tasks of the serious game will be more diverse, and the participants' experience time will be longer. Therefore, the effect of the dynamic adjustment method may be greater at that case. Moreover, this study provides first evidence to support its effectiveness in enhancing relationships.

Furthermore, we found that the dynamic flow experience assessment and enhancement effectively improved the perceived closeness and intimacy; therefore, they revealed the important role that flow exerpience has in relationship enhancement. These results can be interpreted as follows:

- Flow experience is essential in maintaining the participant's lasting involvement in a certain activity [18].
- Keeping flow experience at higher levels or for longer periods of time will help to achieve positive outcomes, such as stronger motivation to participate, more positive emotions, better interactive performance [20] [21], etc.
- These positive effects can also occur in co-participation activities [85], leading to more communications, interdependence, and complementary participation during the tasks [86].

Moreover, important aspects of relationship quality, perceived closeness, and intimacy benefit from these positive effects. In this way, the perceived quality of the relationship between partners will improve. Therefore, dynamic flow experience assessment and enhancement can be beneficial, even in the short term.

6.4 Limitations and future work

There are still some limitations in this paper, which needs to be solved in future work.

First, we focused on short-term relationships in this paper and only did the experiments in a single time point. More significant results on relationship-related measures could be expected if we performed several repetitions of experiments over a period of time. However, these expected results are still to be verified. Moreover, we leave exploring the long-term effects on relationships for future work.

Second, using a single channel EEG to measure arousal is quite challenging, especially in a set-up with so many high movement artefacts. In this study, we needed to achieve real-time interaction and evaluation of human state during the game with body movements, so we had to consider the ease-of-use of the device at the same time. Therefore, we chose to use the eSense algorithm to measure meditation based on a single channel EEG signal, which is widely used and showed acceptable results according to previous studies [53], [57]. In the future work, we will find a better method to measure arousal directly and more precisely.

7 Conclusions

Interpersonal relationships are built and developed in the process of interpersonal interactions. In this process, people's subjective feelings play a very important role in the maintenance of interactions. Moreover, effective computing techniques can help people to intuitively understand themselves and other people's emotional state, which leads to better inter-personal empathy and interaction. In this paper, we present a design of a co-participation serious game and implement a prototype system for relationship enhancement. Our system takes advantages of immersive VR and incorporates a method of dynamic flow experience assessment and enhancement. Two detailed studies are presented, showing that both the cooperative mode and dynamic flow experience assessment can contribute to better relationship enhancement.

Declaration The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Human Research Ethics Committee of Jining No.1 People's Hospital. When this study involved human participants, informed consent was received from each individual.

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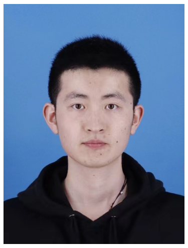

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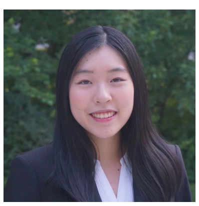

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