CoplayingVR: Understanding User Experience in Shared Control in Virtual Reality

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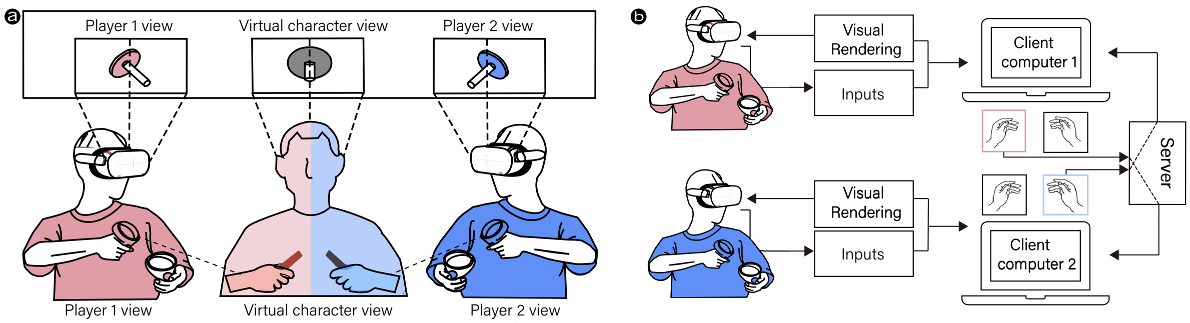

Fig. 1. Shared control concept and implementation. (a) Two users are able to independently control different limbs of the same avatar (b) by sharing the local input/output control through a networked server.

Shared control of avatars in virtual reality is emerging as a promising method to enhance collaborative interactions. While the literature investigates shared control as an input modality to understand the design of functional experiences, the user experience associated with shared control remains underexplored. In this paper, we investigate the user experience of shared control using a networked VR environment, "CoplayingVR". Through a user study comprised of three gaming tasks in VR with 48 participants, we collect both quantitative and qualitative data on the user experience and performance of shared control. Our findings reveal that the shared control mode significantly improved user experience factors and brought novelty to the play. Furthermore, shared control significantly enhanced the task efficiency for novice users. Finally, we discuss how our findings inform the implications for research and practice of shared control for the growing body of research in VR.

CCS Concepts: • **Human-centered computing** → **Virtual reality**.

Additional Key Words and Phrases: Shared control, Virtual Reality, Embodied Interaction, User Experience, Gaming Experience

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1 INTRODUCTION

Virtual Reality (VR) has altered the way we interact with digital environments, bringing a new era of immersive experiences in education [15], work [38], skill acquisition [13], gaming [36], and well being [4, 59, 60, 67, 92]. An emerging interaction paradigm in VR is *shared control* – the concept where several individuals or entities share a common virtual avatar or form [20, 26, 39]. The approach draws inspiration from work done in non-VR contexts, for instance using shared control for collaboratively controlled robots [21] and networked tele-operation systems [22] and also more recent work in physical shared control using technologies such as electrical muscle stimulation (EMS) and pneumatics [44, 56, 68]. In VR, shared control allows users to simultaneously experience and control a single avatar from a first-person perspective, facilitating the sharing of skills and knowledge for enhanced collaboration [20].

Previous literature examines shared control as an input modality to design functional experiences [20], and to investigate performance [18] and user immersion [73] in VR. Moreover, the majority of previous research adopted systems where user interactions were restricted and evaluated in a highly controlled manner. For instance, users were only allowed to make specific movements, such as raising their hands [39]. As a result, the user experience (UX) associated with these control mechanisms in a realistic VR setting remains underexplored. Therefore, there is a need to deepen the understanding of the impact of shared control interactions on user engagement, performance, agency, and body ownership in a typical VR scenario.

To address this gap, we designed a system, *CoplayingVR*, focusing on unrestrained shared hand control in VR games. Hands are the primary medium for interactions in VR and the previous works show they can be selected as an implementation for investigating user experience of shared control [78]. *CoplayingVR* lets two users play VR games together. At the beginning, each user chooses one hand (left or right), which they will have control over in a shared avatar. Once selected, the user's hand movements with respect to the avatar are not constrained within the game. We believe that *CoplayingVR* can bring insights from a scenario closer to a real-world application. Compared to the controlled cases investigated in literature [18, 39], we hypothesise that *CoplayingVR* approach can positively enhance user performance and experience for both experienced and novice users in a typical VR scenario. Through a user study using a series of VR games implemented on the *CoplayingVR* system, this paper investigates the user experience of shared control over virtual avatars. Particularly, we aim to answer three research questions: RQ1: *How does the shared control of hands influence user experience in VR games?* RQ2: *How does the shared experience of player expertise influence user performance in VR games?* and RQ3: *What are the effects of shared control on the sense of agency and body ownership for VR users?*

The paper presents results from a user study comprised of both *shared control* and *single-player* modes in VR with 48 participants. In the study, participants performed three gaming tasks from accuracy incentive to time incentive using the two control modes. We collect both quantitative and qualitative data on the user experience and performance of shared control. Our findings reveal that the shared control mode significantly improved user experience factors such as the challenging nature of gameplay, immersion within the game, negative affect, positive affect and brought novelty to the gaming experience [30]. Furthermore, shared control significantly enhanced the performance of novice users, and we did not observe a statistically significant performance decrease for experienced users. Additionally, there was a comparatively significant increase in the sense of agency and body ownership as the study progressed under the shared control mode. We further discuss how our findings inform the implications for research and practice of shared control for the growing body of research in VR, and we anticipate these will inform the design of future shared control systems.

The key contributions of the paper are:

- We present *CoplayingVR*, a system that allows sharing control of hands between two players in a typical VR game-play setting.
- We show empirical results on the impact of shared control on 1) user experience in VR games, 2) user performance, and 3) agency and body ownership.
- We discuss our findings and provide implications for both research and design. In particular, we provide design guidelines to benefit future research and the development of systems aimed at integrating shared control within VR gaming environments.

2 RELATED WORK

Collaborative multiplayer games such as Little Big Planet [84] and Donkey Kong [5] have been popular since the early days of gaming, allowing more than one player to collaborate and work towards a common goal. In comparison, shared control is employed as a collaborative input mechanism, where multiple players simultaneously control the same game element or characters [43]. Particularly, in collaboration, users take cooperative efforts with overlapping roles [9] while shared control focuses on mutual reliance with divided control [78]. In this paper, we aim to analyse the user experience of shared control in a VR setting. To this end, in this section, we discuss the literature on multiplayer and collaborative games, shared control approaches and methods used to evaluate user experience in VR and gaming settings.

2.1 Collaborative and Multiplayer Games

Collaboration is defined as the action of individuals or groups working together to achieve a common goal (i.e. a shared objective), for instance, seminal works by Johnson et al. have laid a robust foundation for understanding computer-supported collaboration through environments with predefined tasks [33]. While there are numerous works that focus on computer supported collaboration [8, 12, 28, 31, 72], since our tasks are primarily in games, we focus on literature in collaborative games. There are several aspects of collaborative games studied in previous research which facilitate complex social interactions and collective problem-solving. For instance, El-Nasr et al. present a set of collaborative design patterns and a Cooperative Performance Metrics (CPMs) for analysing and evaluating collaborative games [71]. Mitchell et al. focused on investigating social collaboration through digital bodily play using the HandyFeet platform, which combines physical activity with collaborative gaming, underscoring the potential to boost social interactions and teamwork [50]. Some research focuses on design patterns and game mechanics, such as studies by Rocha et al. [64] and Zagal et al. [90]. These studies offer valuable insights of user experience collaborative gaming environments. Such in-depth evaluations of user experience of shared control in VR is lacking in literature and are essential to examine the unique challenges of the concept. Our study design was inspired by the existing collaborative game design strategies and critically examines the applicability of those within shared control in VR. Particularly, we paid close attention to game mechanics in the multiplayer games and how measures such as CPMs reflect on the complementarity, shared goals, shared puzzles and shared objects between players [71].

2.2 Shared Control in Video Games

There are several works that explore shared control in video or 2D games. For instance, El-Nasr et al. devised and executed various conventional input mediators and visual overlays to implement shared control within video games [19]. These approaches include allocating control segments, assignment of specific control actions, and time-based control allocation. Lessel et al. introduced HedgewarsSGC, a test environment to investigate shared game control in situations where multiple players compete against one another while sharing control of various game components [42]. These studies have made significant contributions on 2D and traditional video game platforms, which inspire current research in shared control, however they are done in context very different to VR. Specifically, these approaches often focus on the distribution of decision-making without addressing the heightened sensory and spatial interactions, and the psychological engagement that immersive VR environments necessitate [43]. In contrast, our research extends these concepts into VR, focusing on immersive shared control and its impact on user experience. By transitioning from the straightforward shared decision-making in 2D games to complex shared control of hands in VR, we explore how physical embodiment and psychological factors intertwine to affect collaboration.

2.3 Shared Body Experiences

Different aspects of sharing control of virtual bodies have been studied to explore the perceptual aspects of embodiment and performance. Goldberg et al. proposed the idea of a multi-operator single robot (MOSR) system, where multiple players control a single robot [21]. Later, an advanced MOSR was introduced where the player controls a remote actor who responds to input in real time [22]. Such studies primarily focused on the performance of remote operations, and less on experiences. More recent studies expanded these to explore the effects of virtual body autonomy resulting from shared control by mirroring first-person perspective and multisensory information [61], and presented insights into the psychological aspects of shared control in a joint avatar, highlighting influences of a partner's intentions and goals [26]. Furthermore, phenomena such as "enfacement", where simultaneous multisensory stimulation of blended faces, leading participants to perceive morphed images as themselves, creates interesting experiential opportunities [51]. These findings underscore the potential of VR to manipulate and enhance user experiences through shared control.

Sharing control is also used in application towards learning and work. Kodama et al. [39] investigated VR approaches to enhance motor skill learning, comparing it with both solitary learning and sharing the teacher's perspective. Kasahara et al. [37] investigated the efficiency effects of sharing first-person perspectives at work. Similarly, Lasecki et al. [40] introduced Legion, a system that allows a population of remote anonymous workers to control an existing player interface by forwarding the worker's mouse and keyboard input to an input mediator. These studies have a highly controlled experimental conditions, and the main focus of the study is utility and performance. Our aim is to fill this gap by investigating the user experience of shared control in a unrestrained controlled setting using VR games.

2.4 Measuring Experience

Since our study aims to measure player experience in shared control, selecting the appropriate method and metrics is critical. Particularly, we used game-like tasks, so we decided to focus primarily on gaming experience metrics. There are tools developed to measure different aspects of user experience such as gamefulness [27] and players' feelings in games [52]. IJsselsteijn et al. [30] developed the Game Experience Questionnaire (GEQ) as an inclusive and comprehensive tool, which has been widely used to measure player experiences in various settings, including recent applications in virtual reality exergames [87]. The GEQ is composed of several modules, including the Core Questionnaire, Social Presence Module, and Post-Game Module, allowing for a multifaceted evaluation. Some recent criticism of its factor structure issues limits its suitability for all gaming contexts [41]. In this study, we focus on understanding specific aspects of shared control in VR, so the broad dimensions covered by the GEQ such as psychological and emotional aspects of gaming are still relevant and valuable. We specifically applied GEQ to assess dimensions like Challenge, Competence, Flow, Negative Affect, Positive Affect, Sensory and Imaginative Immersion (SII), and Tension, which are crucial for evaluating shared control in VR. We conducted additional evaluation of results to verify the consistency of finding of the GEQ to address the concerns.

Additionally in shared control, participants may feel as if their own body has been replaced by the self-avatar or the other players [23]. Embodiment is complex, as it involves not only ownership of the avatar's body but also agency, co-presence, and external appearance [23]. In terms of agency, a lack of body agency and autonomy in embodiment may have negative effects on social, perceptual, and behavioral performance [6]. In the shared control context in VR, players might perceive the avatar not only as an extension of themselves but also as an intertwined identity with other players, thereby influencing cooperative behaviors and gaming strategies. Thus, we employed an additional questionnaire to provide measurement of agency and ownership [24, 29]. Finally, as performance metrics, we collected completion times, and error rates where applicable.

3 DESIGN AND IMPLEMENTATION OF 'CoplayingVR'

Shared control is a concept where a system or a process is controlled by multiple individuals or entities, as opposed to a single entity having complete control. In computer games, shared control is implemented by distributing the control over the game character or elements among multiple players [78]. The implementation of shared control varies depending on the type of game and the mechanics involved. In this section we discuss design considerations and the implementation details of our 'CoplayingVR' system.

Sykownik et al. [78] presented an approach for the classification of the concept of shared control for a game character based on the concept of Locus of Manipulation (LoM). A LoM is defined as the "in-game position of the player's ability to assert control over the game-world" [7]. It denotes a clear in-game event that serves as evidence of a player's intentional manipulation of the virtual gaming environment. In the context of a VR game, we chose to implement the concept of "sharing control of distinct LoM that establish a coherent entity" [78] using hands since they serve as the primary means of interacting with the virtual world. This concept implies that every player has control over a separate LoM, but these LoMs come together to form one entity. Precisely, the control of one of the virtual hands of the virtual gaming character is given to one player so that the two players control the two hands independently (see Figure 1 for more details). However, as the two hands form a single gaming character, this prevents players from operating totally independently and involves a high level of player inter-dependency. However, it is important to note that it is not possible to isolate shared control from collaboration completely in games [78].

3.1 Input Control Mechanism

For the control mechanism, we mapped a virtual character's two hands to the controllers of two different participants, each of whom is wearing their own VR headset. The participants decided which of their hands (left or right) they would like to be mapped to control the virtual character's corresponding hand. Our study does not use combination of inputs by addition, average, and other methods as in previous work [85], but employs a control alternation between users. However, we prevented movements such as walking since this may lead to sharing control over the whole body, a condition that is out of the scope of the paper.

3.2 Rendering Visual Output

As the two participants are sharing the control of two virtual hands of a virtual character, the question of how virtual vision will be shared in a collaborative setting is an important consideration in the design of the shared control system. Collectively, the system creates a first-person experience of shared hand control by tethering virtual hands and head to a single body, creating the visual illusions as if they belong to the player. Although both hands are visually present, each player's control is limited to their selected hand, the other virtual hand reflects the other player. Furthermore, a virtual view that does not correlate to the participant's own head movement could create motion sickness. We mitigated this by letting players control the head rotation creating an independent perspective from the fixed body avatar location. Every gameplay action, triggered by either of the participant, is distributed to both headsets through the network, so they can see the changes happening in the virtual environment in real-time.

3.3 Implementation Approach

We used Unity platform to implement our 'CoplayingVR' concept. The system enabled two players to share a single virtual environment and synchronously reflect their real-time interactions on the same avatar. Our setup was based on two Oculus Quest 2 head-mounted displays and controllers. The application ran at a constant frame rate of 90 Hz on Unity 2021. Each pair of devices was connected to a separate computer using a USB cable and both computers were physically connected to the same network to minimize latency.

In the virtual environment, the two users were simultaneously tethered to a single anthropomorphic virtual character. The two players were physically co-located a few meters apart to accommodate user movements. The system allowed two playing modes, 'single-player mode' and 'shared control mode'. In the single-player mode, player's movement relied entirely on their own actions. In the shared control mode involving two players, we combined the hand movement inputs from both players.

We chose the "Photon Unity Networking" (Photon PUN) framework for implementing the shared control mode. We selected Photon since it provides Photon Cloud – a software as a service (SaaS) solution which enabled us to implement our multiplayer version of the game. Furthermore, we used an on-premises server application (Photon Server) that can be installed locally and a multiplayer game can be hosted on-site. This allowed us to reduce the delay between the participants actions to 5ms.

4 STUDY DESIGN

In this paper, we aim to evaluate the user experience and performance of shared control of virtual characters in VR. For our study, we designed three VR game tasks based on shared control. We based our tasks on the three types of VR games: casual games – *Control Task*, puzzle games – *Balancing Task*, and action games – *Shooting Task* and collected data on both user experience and performance. Our participants performed the game tasks in two playing modes: single-player mode (individually) and shared control mode. Participants were allowed to communicate with each other during the tasks.

4.1 VR Game Tasks

4.1.1 Control Task. The first task in our study, is a traditional peg-in-hole task (Figure 2-a) [79], which is a control task commonly used in manipulation studies [81]. This task required participants to build basic coordination, spatial awareness, and cooperative strategies through manipulating an object in space. Additionally, it needs precise coordination of movements from each hand (controlled by different players). Such skills are imperative as they form the foundation for the subsequent tasks. It was specifically chosen as the first task due to its simplicity to understand, focus on the manipulation, and lack of other gameplay elements. The task required participants to properly align a virtual peg in the game environment and insert it into a hole. To ensure both participants contributed to the control in the shared control mode, the positional control is done by one player and the rotation is done by the other. Both players need to grab the peg simultaneously to control the two aspects to minimize turn taking. Whoever initiated the control aspect (rotation or movement) had complete control of that aspect regardless of the second player's input. The other player could control the other aspect simultaneously.

In total, the task required to complete 3 peg-in-hole activities. Participants were required to successfully position each peg into its designated hole, with each peg appearing only after the previous peg had been successfully positioned. For this task, the user controlled the location, the depth, the combination of axes required for rotation. Tasks were marked complete once the peg was correctly inserted into the hole reaching a specific depth. We recorded the task completion time, positions and rotations of hands and heads of the players.

4.1.2 Balancing Task. The second task is a balancing board game with puzzle elements, which was inspired by the work of Seif El-Nasr et al. [71] (Figure 2-b). This task requires participants to work together to balance a maze board, thereby enhancing coordination and introducing control over two axes, which emphasizes the necessity

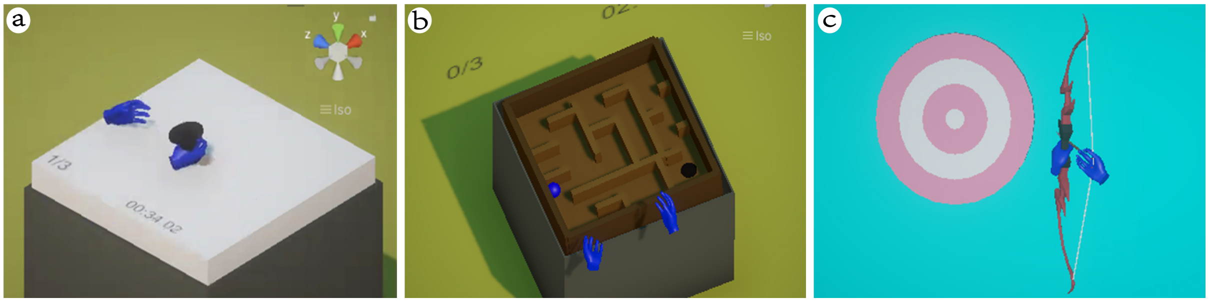

Fig. 2. The three gaming tasks used in the user study. Each hand is controlled by a separate player. (a) Control task: Two hands are used to move a peg into a hole. (b) Balancing task: Two hands are used to tilt the maze to drive the ball to the correct path. (c) Shooting task: One player controls the bow to aim, the other shoots the arrow. The hand models used in this study were downloaded from the Oculus Developer website. The bow and arrow models were sourced from Quaternius.

for synchronized movements and reactions to navigate the maze successfully. The activity involved participants guiding a ball into a hole in a maze by tilting the board in two axes. They used virtual hands to control how the board is tilted. The task involved completing three levels, each comprising three mazes that became progressively more complex. Aim of the progression was to develop the participants' skills. In the shared control mode, to successfully guide the ball into the hole the participants needed to be able to work together to balance the tilt angle. We recorded the task completion time for each level along with positions and rotations of the hands and heads, the ball, and the table.

4.1.3 Shooting Task. The third task was a fast-paced archery game that involved shooting a target, inspired by the work of Loparev et al. [43] (Figure 2-c). This task builds on the coordination developed in previous activities. It applies and extends these skills through precise hand-eye coordination, timing and teamwork. It brings a challenging scenario and thus placed third in the order of tasks.

The players are offered two primary control options: "Aiming" and "Shooting". One virtual hand could be employed to grasp the bow and aim at the target, while the other hand could be used to pull the string for shooting arrows. Upon stretching the string of the bow, an arrow is spawned and ready to be released. Within the virtual environment, targets periodically appeared and advances towards the virtual player at a consistent velocity. Over the course of the game, a total of 50 targets were available, with each accurately hit target resulting in the score of one point. Participants were encouraged to maximize their shooting prowess to achieve a higher overall score.

We recorded data pertaining to archery shots, specifically recording the elapsed time between stretching the bowstring and releasing the arrow for each shot, the count of accurate shots made, and the total number of shots taken by participants along with the hand and head positions and rotations.

4.2 Experimental Setup

We conducted the experiment in a 2.5 x 3.5 meter laboratory room. User activities were recorded using GoPro cameras for later analysis. Both users wore VR headsets and could communicate with each other.

4.3 Experimental Data

4.3.1 Player Experience. In our study, we employed the Game Experience Questionnaire (GEQ)[30] to evaluate the gaming experience of participants since it has been used in similar studies [3, 87, 88]. We tested the GEQ's factor stability and verified that the reliability is in acceptable to good range using Cronbach's alpha analysis [41].

Table 1. Questionnaire used in the sense of body ownership and agency test

Variable	Question
Body Ownership	Q1: "I felt as if the two virtual hands were my hands" Q2: "It felt as if the virtual hands I saw was someone else" Q3: "It seemed as if I might have more than one hand"
Agency	Q1: "It felt like I could control the virtual two hands as if they were my own hands" Q2: "The movements of the virtual hands were caused by my movements" Q3: "I felt as if the movements of the virtual hands were influencing my own movements" Q7: "I felt as if the virtual hand was moving by itself"

The specific questions rated the Challenge, Competence, Flow, Negative Affect, Positive Affect, Sensory and Imaginative Immersion (SII) and Tension of game experience. Challenge measured person's perception of how difficult the game was [35]. Competence included a sense of achievement, excitement and pride during the game [62]. Flow measured the gamer's perception of the "total absorption in the game and the non-self-conscious enjoyment of it" [17]. Negative Affect summarized feelings related to a bad mood and boredom that came from the gaming experience [62]. Positive Affect included feelings of happiness and enjoyment that came from the gaming experience [62]. Sensory and Imaginative Immersion (SII) described mental involvement of the user in the game [3]. Tension refers to feelings of annoyance, frustration, and pressure perceived during the game [62].

4.3.2 Performance. We measured the performance of participants using three variables: the task completion time, the error rate and the behavioral measurements (how participants engaged their hands in the game). Specifically, the task completion time for the *Control Task* is calculated from when the peg appeared until it is successfully inserted into the hole. Similarly, in the *Balancing Task*, completion time is measured from the moment the ball appears in the game until it is successfully inserted into the hole. For the *Shooting Task*, since it has a fixed play time, we quantified the error rate as the performance metric by tallying the number of accurately hit targets out of a total of 50 presented during the game. We did not let participants see the performance outcomes during the experiment to avoid comparisons and competition.

4.3.3 Agency and body ownership. As a measure of the degree of experience with the shared virtual body, we assessed agency and body ownership by using Avatar Embodiment Questionnaire (AEQ) [23]. We selected the earlier version compared to a more recent questionnaire [57] because of its strong focus on sense of agency. We removed some questions that were not directly related to our experiment. Our aim was to make it more focused and effective for our specific research needs. We administered the questionnaire (Table 1) before and after the experiment. Specifically, since the training session initially introduced participants to the virtual environment and avatar, mirroring the first exposure phase in [23], we decided to have participants complete the questionnaire after the training session and then again after the third task. They completed it in different tablets individually.

4.4 Experimental Conditions and Procedure

4.4.1 Participants. We recruited 48 participants (28 female, 20 male) for the study from a university student population representing different backgrounds. They were recruited individually, and not as pairs. Background information such as gender identity, VR gaming experience were collected and used to create participant pairs. We also did not consider handedness as a factor since we used both hands in the experiment, and let the participants choose which hand they like to use in the game. However, a majority of participants let us randomly assign them to each hand. The participants' age ranged from 21 to 34 years old (M=24, SD=3.05).

4.4.2 Experimental Conditions. We employed a within-subjects experimental design. All participants completed the experiment in both conditions – shared control and a single-player mode. To minimize any potential fatigue or learning effects, we counterbalanced the order of conditions presented to the participants with a break between each task and conditions. This ensured that any fatigue did not disproportionately affect one condition over the other, thereby maintaining the integrity of our results.

4.4.3 Procedure. First, we briefed participants on the experiment's purpose and procedure. Then, the participants gave the written consent. During this stage, we collected participants' background information (e.g., age, gender, previous VR gaming experience (novice or experienced players), gaming preferences).

Next, we assisted the participants to wear VR headsets and handed them the controllers. Prior to starting the experiment, our participants went through a training session to familiarize themselves with the equipment and tasks. The training session lasted approximately 5 minutes. After the training was completed, participants began the experiment. The participants always followed the same task sequence: Control Task → Balancing Task → Shooting Task. In our study's setup, participants were physically located a few meters apart from each other and could communicate with each other verbally. Participants in the same group completed the experiment in the same order to avoid the potential impact on the experience gap.

When allocating the participants into pairs, we accounted for their previous gaming experience. In total we had 3 groups of participants:

(1) The first group was comprised of participants (N=16) who had prior experience in playing VR games, i.e., both of the participants within one gaming session had previous experience of playing VR games.
(2) The second group was comprised of participants (N=16) both with and without previous gaming experience in VR, i.e., within one gaming session we had one participant who had prior experience playing VR games, whereas the second participant did not have prior VR experience.
(3) Finally, the third group had participants (N=16) with no prior experience of playing games in VR, i.e., both participants within one gaming session have not played VR games before.

After completing each task, participants took off their VR headsets, and completed the questionnaire. We ensured they did not discuss the answers to the questionnaire during this stage.

At the end of the experiment, we conducted brief semi-structured interviews first individually and then in pairs. Individual interviews allowed each participant to express their personal experiences and views. This was followed by a joint interview in pairs to explore their collective experience and management of shared control in the VR environment. Questions focused on their perceptions of performance under different conditions, the effects of shared control on their experience, and any challenges faced during the game.

The experiment lasted for approximately 40 minutes including the briefing, training, data collection, and final interviews. We did not provide any compensation for our participants for their participation. The study received ethics clearance from the Human Research Ethics Committee (HREC) of the University of Sydney (2019/553).

5 RESULTS

5.1 Effects of Playing Mode on Game Experience

In this section, we analyse and present the results from the game experience questionnaire. Our aim is to understand how the game experience is affected by shared control and single-player modes.

During this study, 288 game experience questionnaires were administered, and our participants answered a total of 4032 questions for the game experience test in both single-player and shared control modes. In both modes, we calculated the average Likert ratings for seven different aspects of the game experience for each of the games and for the overall gaming experience. These aspects are Challenge, Competence, Flow, Negative Affect,

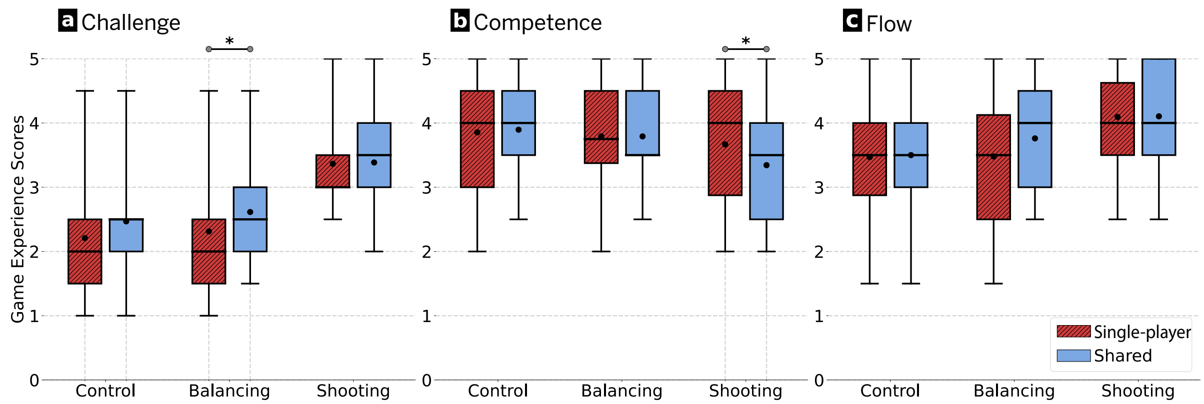

Fig. 3. The averages of Likert ratings in shared control and single-player modes on the first three game experience measures. The three conditions in each graph are Control Task, Balancing Task and Shooting Task. * denotes p < .05.

Positive Affect, Sensory and Imaginative Immersion (SII) and Tension [30]. The data was not normally distributed, therefore, we conducted the Wilcoxon Signed-Rank Test to investigate the differences.

In light of concerns regarding the GEQ's factor stability, we conducted a Cronbach's alpha analysis to verify the internal consistency of its scales within our study. The Cronbach's alpha and 95% confidence interval respectively for each factor are: Challenge - 0.849 (0.731, 0.916), Competence - 0.741 (0.538, 0.855), SII - 0.805 (0.652, 0.891), Flow - 0.748 (0.550, 0.859), Tension - 0.740 (0.536, 0.854), Negative Affect - 0.777 (0.602, 0.875), and Positive Affect - 0.711 (0.484, 0.838). Findings suggest that our results are within acceptable to good range in terms of consistency.

5.1.1 Control Task (Figures 4 and 3): First, we analysed the gaming experience in the *Control Task*. For the overall game experience, we found statistically significant differences for measures of "Negative Affect", "Positive Affect", and "Sensory and Imaginative Immersion (SII)". Precisely, "Negative Affect" in the shared control mode ($M = 1.20,\ SD = 0.41$) was significantly lower ($Z = -4.1084,\ p < 0.01$) compared with the single-player mode ($M = 1.79,\ SD = 0.78$). Furthermore, "Positive Affect" in the shared control mode ($M = 3.90,\ SD = 0.63$) was significantly higher ($Z = -3.6935,\ p < 0.05$) than in the single-player mode ($M = 3.37,\ SD = 0.74$). Finally, "Sensory and Imaginative Immersion (SII)" in the shared control mode ($M = 3.85,\ SD = 0.80$) was significantly higher ($Z = -4.6456,\ p < 0.01$) than in the single-player mode ($M = 3.00,\ SD = 0.85$).

For measures of "Challenge" ($Z = -1.704,\ p = 0.089$), "Competence" ($Z = -0.2656,\ p = 0.787$), "Flow" ($Z = -0.0089,\ p = 0.992$), and "Tension" ($Z = -1.7623,\ p = 0.078$), we did not find statistically significant differences in averages between the two modes.

5.1.2 Balancing Task (Figures 4 and 3): For the *Balancing Task*, we found statistically significant differences in measures of "Challenge", "Negative Affect", "Positive Affect", and "Sensory and Imaginative Immersion". In particular, "Challenge" in the shared control mode ($M = 2.61,\ SD = 0.83$) was significantly higher ($Z = -2.3251,\ p < 0.05$) than the single-player mode ($M = 2.31,\ SD = 0.85$). "Negative Affect" in the shared control mode ($M = 1.23,\ SD = 0.47$) was significantly lower ($Z = -3.3306,\ p < 0.01$) compared to that in the single-player mode ($M = 1.73,\ SD = 0.61$). Furthermore, "Positive Affect" in the shared control mode ($M = 4.14,\ SD = 0.69$) was significantly higher ($Z = -2.6472,\ p < 0.05$) compared to that in the single-player mode ($M = 3.73,\ SD = 0.74$). "Sensory and Imaginative Immersion" in the shared control mode ($M = 3.85,\ SD = 0.75$) was significantly higher ($Z = -3.8375,\ p < 0.01$) than that in the single-player mode ($M = 3.26,\ SD = 0.86$). However, for measures of "Competence" ($Z = -0.2057,\ p = 0.833$), "Flow" ($Z = -1.82,\ p = 0.068$), and "Tension" ($Z = -0.1429,\ p = 0.888$),

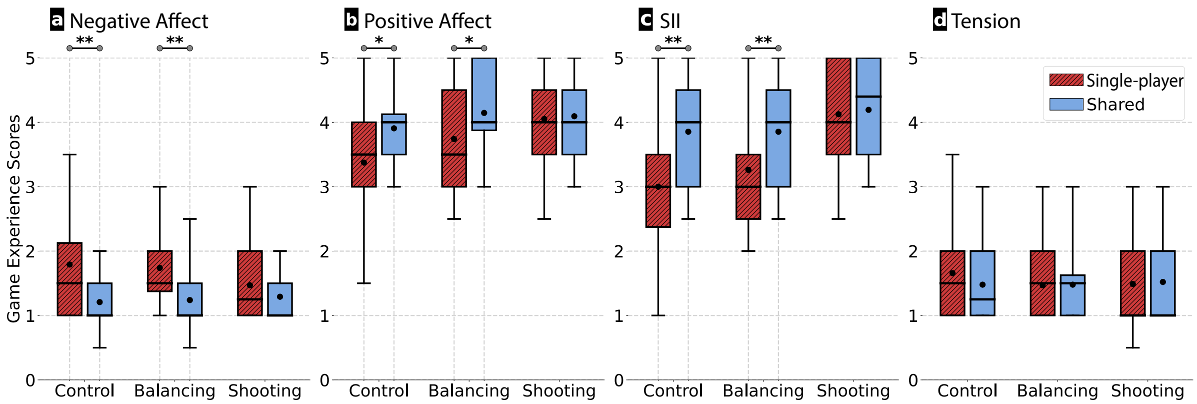

Fig. 4. The averages for Likert scale ratings for game experience measures in shared control and single-player modes on the three conditions Control Task, Balancing Task, and Shooting Task. * indicates p < .05 and ** indicates p < .01.

we did not find their averages in the shared control mode and their averages and in the single-player mode are statistically significant different.

5.1.3 Shooting Task (Figures 4 and 3): For this task, we only found statistically significant differences for measures of "Competence". Particularly, "Competence" in the shared control mode ($M = 3.20,\ SD = 0.89$) was significantly lower ($Z = -2.4515,\ p < 0.05$) compared to the single-player mode ($M = 3.66,\ SD = 0.91$). However, we did not find statistically significant differences between averages for "Challenge" ($Z = -0.1282,\ p = 0.896$), "Flow" ($Z = -0.0841,\ p = 0.936$), "Negative Affect" ($Z = -1.6337,\ p = 0.103$), "Positive Affect" ($Z = -0.1666,\ p = 0.865$), "Sensory and Imaginative Immersion" ($Z = -0.6273,\ p = 0.528$), and "Tension" ($Z = -0.1429,\ p = 0.888$).

5.1.4 Overall Gaming Experience. For the overall game experience, we found statistically significant differences for measures of "Challenge", "Negative Affect", "Positive Affect", and "Sensory and Imaginative Immersion". For instance, "Challenge" in the shared control mode ($M = 2.82,\ SD = 0.82$) was significantly higher ($Z = -2.4277,\ p < 0.05$) than that of the single-player mode ($M = 2.62,\ SD = 0.94$). "Negative Affect" in the shared control mode ($M = 1.24,\ SD = 0.41$) was significantly lower ($Z = -5.4028,\ p < 0.01$) compared to the single-player mode ($M = 1.66,\ SD = 0.67$). In alignment with this, "Positive Affect" in the shared control mode ($M = 4.04,\ SD = 0.65$) was significantly higher ($Z = -4.0242,\ p < 0.01$) than in the single-player mode ($M = 3.72,\ SD = 0.77$). Furthermore, "Sensory and Imaginative Immersion" in the shared control mode ($M = 3.96,\ SD = 0.76$) was significantly higher ($Z = -5.6477,\ p < 0.01$) compared to the single-player mode ($M = 3.46,\ SD = 0.93$). For measures of "Competence" ($Z = -0.7437,\ p = 0.459$), "Flow" ($Z = -1.2781,\ p = 0.200$), and "Tension" ($Z = -0.9241,\ p = 0.357$), we did not find statistically significant differences between averages for the two modes.

To summarise, our findings in section 5.1 answer RQ1: *"How does the shared control of hands influence user experience in VR games?"*. Precisely, our results demonstrate a significant effect of the shared control mode on user experience in the *Control Task* in terms of "Negative Affect", "Positive Affect", and "Sensory and Imaginative Immersion". We further found that the shared control mode in the *Balancing Task* had a significant effect on "Challenge", "Negative Affect", "Positive Affect", and "Sensory and Imaginative Immersion". We have also found that the shared control mode had a significant effect on "Competence" in the *Shooting Task*. For the overall user experience in VR games, our findings show that the shared control mode had a statistically significant effect on "Challenge", "Negative Affect", "Positive Affect", and "Sensory and Imaginative Immersion".

5.2 User Performance – Prior Experience and Task Completion Time

In this section, we aim to answer RQ2: *How does the shared experience of player expertise influence user performance in VR games?* By analyzing task completion time, error rate, and behavioral observations using the recorded video, we aim to uncover how sharing VR gaming experience influences participants' performance in the shared control and the single-player modes.

We compared the task completion time between different modes in the *Control Task* and the *Balancing Task*. Task completion time in the *Shooting Task* was the same for all participants since the mechanics of the game relied on the number of accurately shot targets within a specified time. Nevertheless, for the *Shooting Task*, we measured the error rates in two playing modes.

To analyse the data we grouped the pairs of our participants into three groups. The groups were as follows: one comprised of participants (N=16) both with and without prior VR gaming experience, referred to as the *mixed pair* group; the second group (N=16) had participants who had prior VR gaming experience, referred to as *experienced players*; and the final group (N=16) was comprised of participants without any prior VR gaming experience, referred to as *novice players*. Sample sizes of the groups align with the standards used in HCI research identified by Caine et al. [14].

For the *mixed pair* group, we had 8 *novice players* and 8 *experienced players* to complete the tasks in the single-player mode; however, for the shared control mode, these participants were grouped together to complete the tasks. To analyse the performance of the *mixed pair* group we looked at the differences in performance between the *experienced players* in the single-player mode, *novice players* in the single-player mode, and mixed-experience in the shared control mode. For the *experienced players* and *novice players* groups, we looked at the differences in performance between the shared control mode and the single-player mode for each of the groups. In our study, we used Aligned Rank Transformation (ART) to analyse the effects of two different modes on participant performance in three tasks. The ART test allows us to effectively handle non-parametric data and complex interactions, suitable for our study's groups and varying distributions. The test revealed statistically significant differences in performance data between the three groups.

5.2.1 Control Task – Task completion time for mixed pair group: For the *Control Task* (Figure 5(e)), the ART analysis revealed that the task completion time in the shared control mode ($M = 0.77,\ SD = 0.03$) for *mixed pairs* group was significantly shorter ($F(1, 15) = 5.62,\ p < 0.05$) than the task completion time for *novice players* in the single-player mode ($M = 1.69,\ SD = 0.36$). Furthermore, the task completion time in the *Control Task* for the *experienced players* (Figure 5(e)) in the single-player mode ($M = 0.74,\ SD = 0.15$) was significantly shorter ($F(1, 15) = 6.45,\ p < 0.05$) than the task completion time for the *novice players* in the single-player mode ($M = 1.69,\ SD = 0.36$).

However, our analysis did not reveal any statistically significant difference ($F(1, 15) = 0.85,\ p = 0.400$) when comparing the task completion time of the *Control Task* for *experienced players* in the the single-player mode ($M = 0.74,\ SD = 0.15$) versus *mixed pairs* group in the shared control mode ($M = 0.77,\ SD = 0.03$). The ART analysis did not reveal a statistically significant interaction effect ($F(1, 15) = 2.07,\ p = 0.17$).

5.2.2 Control Task – Task completion time for experienced players and novice players groups: Additionally, the ART analysis revealed that the *novice players* (Figure 5(c)) in the shared control mode exhibited significantly shorter task completion times ($M = 1.50,\ SD = 0.25,\ F(1, 15) = 4.32,\ p < 0.05$) than in the single-player mode ($M = 1.72,\ SD = 0.38$). For the *experienced players*, our analysis revealed no significant difference between the *experienced players*' performance in the shared control mode ($M = 0.72,\ SD = 0.18$) versus their single-player mode ($M = 0.74,\ SD = 0.15$).

5.2.3 Balancing Task – Task completion time for mixed pair group: In the *Balancing Task*, our analysis showed that there is a statistically significant difference ($F(1, 15) = 11.38,\ p < 0.05$) in task completion time between *experienced players* ($M = 0.73,\ SD = 0.10$) and *novice players* ($M = 1.99,\ SD = 0.87$) in the single-player mode. Similarly, no significant difference ($F(1, 15) = 0.70,\ p = 0.660$) was found when comparing the task completion times for *experienced players* in the single-player mode ($M = 0.73,\ SD = 0.10$) with *mixed pair* group in the shared control mode ($M = 0.77,\ SD = 0.05$).

5.2.4 Balancing Task – Task completion time for experienced players and novice players groups: For the *novice players* (Figure 5(c)) in the *Balancing Task*, ART analysis showed significantly shorter completion times in the shared control mode ($M = 1.50,\ SD = 0.30,\ F(1, 15) = 6.57,\ p < 0.05$) compared to their single-player mode ($M = 1.99,\ SD = 0.87$). Furthermore, our analysis revealed no significant differences ($F(1, 15) = 0.42,\ p = 0.68$) in completion times for *experienced players*' performance between shared control mode ($M = 0.77,\ SD = 0.05$) and single-player mode ($M = 0.73,\ SD = 0.10$). The ART analysis showed a significant interaction effect ($F(1, 15) = 4.22,\ p < 0.05$) between player experience and game mode on task completion times in the Balancing Task.

5.2.5 Shooting Task – Error Rate for mixed pair group: We then analysed the performance data of players in the *Shooting Task*. ART analysis revealed that the error rate for *mixed pairs* (Figure 5(f)) group in the shared control mode ($M = 27.25,\ SD = 2.65$) was significantly higher ($F(1, 15) = 5.65,\ p < 0.05$) than the error rate for *novice players* in the single-player mode ($M = 15.75,\ SD = 1.66$). Furthermore, there was a significant difference ($F(1, 15) = 6.78,\ p < 0.05$) in error rates when comparing the performance of *experienced players* in the single-player mode ($M = 12.25,\ SD = 1.38$) to *mixed pairs* group in the shared control mode ($M = 27.25,\ SD = 2.65$). Additionally, our analysis indicated that the error rate for the *experienced players* in the single-player mode ($M = 12.25,\ SD = 1.38$) was significantly lower ($F(1, 15) = 5.42,\ p < 0.05$) than for the *novice players* ($M = 15.75,\ SD = 1.66$) in the *Shooting Task* for the *mixed pairs* group.

5.2.6 Shooting Task – Error Rate for experienced players and novice players groups: The ART analysis shows that the *novice players* (Figure 5(d)) had a significantly lower error rate in the shared control mode ($M = 15.00,\ SD = 1.50,\ F(1, 15) = 8.67,\ p < 0.01$) compared to their performance in the single-player mode ($M = 15.75,\ SD = 1.66$). However, no significant difference was found ($F(1, 15) = 0.58,\ p = 0.457$) when comparing the error rate of the *experienced players* in the shared control mode ($M = 12.50,\ SD = 1.40$) with their single-player mode ($M = 12.25,\ SD = 1.38$). The analysis indicated a significant interaction effect ($F(1, 15) = 4.95,\ p < 0.05$) between the player experience and game mode.

To summarise, our findings in section 5.2 answer RQ2: *"How does the shared experience of player expertise influence user performance in VR games?"*. Particularly, our results demonstrate that *mixed pairs* group, where novice users are put together with the experienced users, performed better in terms of task completion time compared to their performance in the single-player mode for the *Control Task*. Furthermore, our results show that when *novice players* work together in the shared control mode, their performance is significantly better compared to when they complete the tasks in the single-player mode. This statement holds true for task completion time for the *Control* and the *Balancing Tasks* and error rate in the *Shooting Task*.

5.2.7 Behavioral Observations: In our behavioural observations, we looked at the movements of the participants' real hands that were not engaged in performing the tasks in the shared control mode. We found that during the *Control Task*, the participants actively used their hands unintentionally, even though they were not using them in VR. This observation indicates that the participants perhaps tried to cooperate with their non-engaged hand subconsciously during the shared control mode. However, surprisingly, this behaviour of our participants changed in the *Shooting Task*, which was the last task. It appears with experience, the participants exhibited minimal movement with their non-engaged hands, engaging more with the shared control mode.

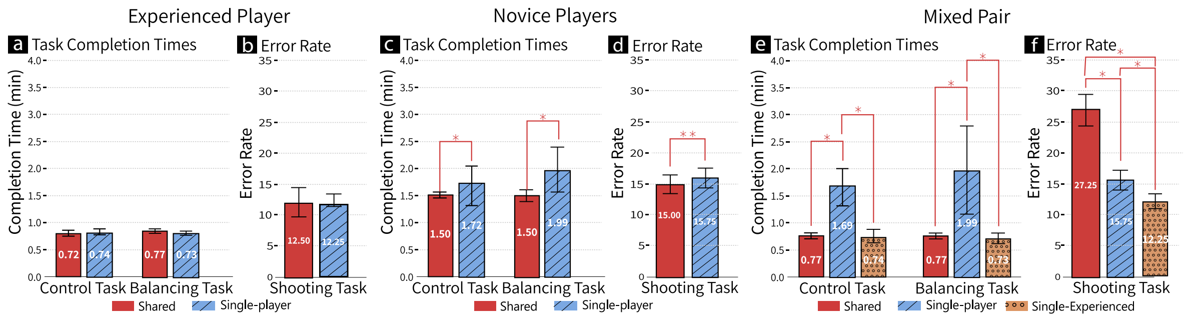

Fig. 5. The figure shows the averages for: (a) the task completion time and (b) the averages for the error rates in the experienced players group; (c) the task completion time and (d) the error rate in the novice players group; and, (e) the task completion time and (f) the error rate in the mixed pair group. * indicates p < .05 and ** is p < .01.

5.3 Agency and Body Ownership

We analysed how the sense of agency and body ownership changed throughout the experiment. To measure the sense of "agency" and "body ownership" we used the embodiment standardized questionnaire identified by Gonzalez-Franco and Peck [23]. For this, we followed the approach described in [20], and performed two measurements of agency and body ownership throughout the study:

- *First Phase* – before the gaming experience (i.e., before the Control Task)
- *Last Phase* – after the gaming experience (i.e., after the Shooting Task)

The data met the test assumptions since it was normally distributed. Therefore, we used two-way repeated measures ANOVA to analyse the effect of the phases on the sense of "agency" and "body ownership".

In the "sense of agency", two-way repeated measures ANOVA showed that the phases of the task had a statistically significant effect ($F(1, 47) = 4,\ p < 0.01$). The post hoc comparisons using Tukey's HSD indicated that the sense of agency in the shared control mode ($M = 10.50,\ SD = 3.88$) was significantly lower ($F(1, 47) = 33.18,\ p < 0.01$) than in the single-player ($M = 15.21,\ SD = 2.13$) in the *first phase*.

After the *last phase* of the study, we observed a significant interaction effect between task phases and game modes concerning "agency". The "agency" of the shared control mode after the *last phase* ($M = 12.49,\ SD = 3.31$) showed a statistically significant increase compared to the same before the *first phase* ($F(1, 47) = 16.52,\ p < 0.05$). This increase indicates a substantial improvement in the sense of agency for participants in the shared control mode as they progress through the experiment. No statistically significant difference ($p > 0.05$) was observed between the first and last phases for "agency" in the single-player mode. Similarly, there was no significant difference between the sense of "agency" after the *last phase* in the shared control mode compared with the single-player. This trend highlights the potential of shared control environments to foster a sense of agency in participants, approaching the levels for a sense of "agency" in the single-player modes.

Similarly, we employed a two-way repeated measures ANOVA to see if the sense of "body ownership" changed throughout the experiment. Our findings indicate that "body ownership" increased towards the end of the experiment ($F(1, 47) = 4.06,\ p < 0.05$). Tukey's HSD post hoc test revealed that the "body ownership" was significantly lower ($F(1, 47) = 58.81,\ p < 0.01$) in the shared control mode ($M = 2.13,\ SD = 1.20$) compared to the single-player mode ($M = 4.56,\ SD = 1.42$) before the *first phase*. After the *last phase*, the "body ownership" in the shared control mode ($M = 2.92,\ SD = 1.62$) significantly increased ($F(1, 47) = 4.27,\ p < 0.05$) compared to before the *first phase* ($M = 2.13,\ SD = 1.20$). When comparing the "body ownership" within different modes, our results reported that after the *last phase*, in the shared control mode ($M = 2.92,\ SD = 1.62$), the sense of "body ownership" was significantly lower ($F(1, 47) = 33.04,\ p < 0.01$) than in the single-player mode ($M = 4.77,\ SD = 1.51$). Furthermore, there was no statistically significant effect of the phase ($p > 0.05$) in the single-player mode on "body ownership". We additionally evaluated the interaction effect between task phases and the game modes in our analysis. The data indicated no statistically significant difference ($p > 0.05$) between task phases and game modes concerning "body ownership".

To summarise, our results in section 5.3 answer RQ3: *What are the effects of shared control on the sense of agency and body ownership for VR users?* Precisely, our findings demonstrate that the sense of agency and body ownership increases throughout the gaming experience in the shared control mode.

5.4 Qualitative Results

We used thematic analysis to analyse the qualitative data collected from our participants during the semi-structured interviews. First, we read through each of the responses. Then the two authors of the paper independently completed the initial coding of the data. Next, the two authors compared their initial codes and finalised the codes based on their similarity. To validate the consistency of the thematic analysis, the data was independently coded by two researchers. The inter-rater reliability, measured using Cohen's Kappa, was found to be κ=0.63, signifying the reliability and precision of the coding process employed in our study. We then independently coded participants' responses according to the finalised codes. Lastly, we identified the themes by reviewing our coding and described below.

Theme 1 – Innovation and Novelty in Gameplay through Shared Control.

Many participants (N=13) stated that the shared control brings new features to the game. For example, one participant mentioned that the shared control mode brings innovation to the game experience. "I like both [modes], but the shared control mode is more fresh for me" (P15). Another participant highlighted, "Shared control changes how we play the game together — it's like we're teaming up in a whole new way" (P22). Furthermore, several participants (N=3) mentioned that shared control mode brought more fun to the gaming experience "Shared control one is more fun" (P28). Additionally, another participant emphasized the distinct nature of the game experience within the shared control mode, particularly in contrast to traditional multiplayer games. "I [used to] avoid multiplayer games for their lack of real teamwork. But in [this] VR games, like moving the ball together. It's new and fun, making us work together in a way I've never experienced before" (P23). "It's like you're seeing a whole new side to an old game", said another participant (P19). Also, one participant added, "With shared control, playing feels more like a dance, where every move is smoothly linked to the next" (P34).

This highlights the unique challenges and experiences of shared control instead of general collaboration interaction. Finally, one participant mentioned that playing games in the shared control mode was very interesting. "I found it interesting that two people fused into one body and shared each other's experiences" (P08). All the new features were derived from feedback provided by the participants.

Theme 2 – Collaborative Complexity – Discovering Challenges of Shared Control.

The majority of our participants (N=22) found the shared control game mode to be more challenging in the playing process because it was hard to communicate with each other during the game. "Hard to chat with others, but I like multiplayer games" (P18). "I think the hardest part is we [could not] to talk with each other" (P24). Another participant highlighted the impact of this communication barrier, "The need for quick decisions made it difficult to coordinate with my partner, adding an extra layer of challenge to the game" (P35). Moreover, some participants (N=7) also reported that the challenge of the shared control mode depended on the pace of the game: "I failed too many times in the last game. I found it hard to keep up with the pace" (P13). "When the game picks up speed, it's not only about how fast you react but also about how quickly you can get on the same page with your teammate" (P26). Several participants (N=10) mentioned that the type of the task (game) also affected the difficulty of the shared mode: "For the shared control in third one [game], I should always find the position to control my arrow, because another player should shoot for it" (P23). Furthermore, according to some participants (N=8), fast-paced games were the hardest to play in the shared control mode: "The shared mode is difficult when it's fast-paced, but I feel I have more of a challenge to do it." In addition, one participant mentioned that they found it challenging to manipulate their hands in the shared control mode: "I think it's hard for controlling hand movement" (P03). Furthermore, several of our participants (N=3) mentioned that they were subconsciously willing to engage their non-rendered hand in the study. For example, P14 mentioned: "In the first two tasks, I felt the urge to use my left [non-rendered] hand, like an instinctive reaction, but not in the last task, he [another participant] and I have become better at working together". We also found the shared control mode highlighted the challenge related to the immersive nature of VR (N=3); for example participants said, "Each level is a fresh adventure where we need to sync up our moves and even our thoughts" (P12). "It's like you're merging minds with your teammates to tackle the game" (P21). Moreover, P29 noted, "The times we had to communicate and synchronize our actions were the most intense and satisfying moments". Furthermore, from our observations, we notice that in the first two tasks (*Control Task*, *Balancing Task*), participants use their non-engaged hand more in the experiment as compared to the last task (*Shooting Task*). We argue this is because their sense of body ownership has increased with time, as our quantitative results demonstrate.

Theme 3 – Empowering Choice – Personal Preference for Shared Control.

We also found that the fondness of a certain mode depended on participants' personal preferences. Many participants (N=15) said that they preferred the shared control mode because they did not have experienced it before: "I liked the shared control mode because I did not have much experience [in using it]" (P11). This sentiment was echoed by another, who highlighted the immersive quality of shared control, saying, "The shared control felt more engaging; it was like being part of the game rather than just playing it" (P24). Some participants (N=10) also reported that the mode preference depended on the type of the game. "I thought the second game had a good shared control mode, but the third game was faster for me to play on my own than in pairs" (P8). This perspective was further supported by another participant "For quick-paced games, I prefer going solo because it lets me react faster without needing to sync with someone else" (P17). Whereas few participants (N=4) mentioned that their preference also depended on the pace of the game: "I liked the single-player version of the third game. Because the two-player mode was so fast-paced that it made it difficult for us to communicate in time" (P8). "In the third game the [*Shooting Task*], I found that the single-player mode would be easier. For the second game the [*Balancing Task*], the shared mode is more interesting because the second game the ([*Balancing Task*]) has a clear job for each person" (P7). Also, one participant reported that the shared control mode would enhance the game experience: "I think this could add more to the gaming experience" (P02). Furthermore, many participants noted a deeper emotional engagement with the game even though the preferences varied widely initially (N=2). P26 talked about getting used to it: "It was tough to adapt at first, but once we clicked, it quickly became my favourite mode to play". Also, one participant reflected on the learning curve, "Mastering this mode feels really rewarding. It's like going on a shared adventure" (P39).

5.5 Summary of Results

To summarise, our results demonstrated a statistically significant effect of the shared control mode on user experience during certain game tasks. Furthermore, our results demonstrate that in the shared control mode, the performance of novice players improves. Moreover, our results also showed that the sense of agency and ownership of the shared hands increases throughout the gaming experience. Finally, our qualitative data revealed that the shared control mode introduced new game features and new challenges to the gaming experience. Many people reported that the shared control mode brought innovation to the game, whereas other participants found the shared control mode to be more difficult. In addition, our results showed that the participants enjoyed or preferred the shared control mode because of their personal preference.

6 DISCUSSION

In this section, we expand on our results and offer additional insights on the interplay between collaboration method and the sense of agency and body ownership.

6.1 Understanding The Game Experience in The Control Task

In the context of the *Control Task*, our results highlighted that the shared control mode can improve task efficiency, particularly for novice players. Notably, performance results indicated that the skillfulness of experienced players potentially augmented the task efficacy of their novice counterparts, as has been shown in previous research [91]. Our qualitative findings reveal that participants under the shared control mode expressed considerable enthusiasm for exploring novel features of the shared control mode, potentially denoting their receptivity to these new elements [43]. Lastly, our findings also revealed that participants had a favourable attitude towards the shared control mode, resulting in a significant decrease in "Negative Affect" and a simultaneous increase in "Positive Affect" while engaging in the *Control Task*. Those insights aligned with prior research [34], highlighting that integration of advanced features into games enhances participant enjoyment.

6.2 Understanding The Game Experience in The Balancing Task

In our study, as mentioned by some participants, the *Balancing Task* emerged to be the most suitable for the shared control mode among the three tasks due to its optimal pacing in gameplay. Therefore, one could speculate that the *Balancing Task* was the most favoured to be played in the shared control mode.

Similar to the *Control Task*, the participants' sense of "Challenge" is increased during the shared control mode in the *Balancing Task*. This result aligns with findings from Sykownik et al. [78]. Furthermore, the shared control mode in the *Balancing Task* enhanced "Positive Affect" and reduced "Negative Affect", suggesting potential mood enhancement. The significant reduction in "Negative Affect" in the shared control mode could potentially be due to the slow-paced nature of the games, which might lead participants to experience enjoyment, thereby improving their overall mood [34]. Furthermore, our research showed that the shared control mode enhanced participants' levels of "Sensory and Imaginative Immersion". The increased "Sensory and Imaginative Immersion" in the shared control mode might be attributed to the heightened sense of partnership between the participants, fostering a deeper engagement with the game world and the narrative [82]. Furthermore, it demonstrates that in the case of VR, it significantly enhances sensory and emotional engagement through virtual embodiment. Our findings are in line with prior research demonstrating that collaborative discussions of strategies can lead to more dynamic gameplay and result in players' increased engagement and immersion in the game environment [43].

6.3 Understanding The Game Experience in The Shooting Task

In the *Shooting Task*, the most fast-paced task, participants reported lower "Competence" in the shared control mode compared to the single-player mode. This finding suggested that the participants' perception of achievement, excitement and pride was lower when they played in shared control mode for fast-paced games. This might have been because users experienced a lack of personal control [77] or disagreements [49]. Furthermore, our qualitative data indicated that the *Shooting Task* was the least preferred among the three tasks when played in the shared control mode. According to our participants, this was caused by feeling a lack of capability to perform well in the game due to the shared control as well as experiencing misalignment and asynchronicity of actions with the other player in the shared control mode.

Performance data also revealed that within the *Shooting Task*, the error rate for participant pairs in the shared control mode was significantly higher than that for novice players in a single-player mode. This observation can be explained by the fact that experienced players encountered difficulties in aligning and synchronizing their strategies with other users due to miscommunication or mismatched expectations [46]. Additionally, the error rate for novice players in a single-player mode is significantly higher than that of experienced players in the single-player mode, which is consistent with prior research demonstrating that the lack of familiarity of the novice players can lead to more mistakes [1].

In the *Shooting Task*, the dynamics of the shared control in VR brought specific challenges, particularly in managing fast-paced interactions, which contrast with the findings from Sykownik et al. [78] where the pace of interaction was less critical. These differences highlight the additional challenges in VR, such as the need for precise coordination and real-time communication, which are less pronounced in non-immersive environments.

6.4 Impact of Shared Control on User Experience

Collectively, the shared control mode enhanced participants' user experience compared to the single-player mode. In our examination of qualitative data, we observed that participants demonstrated a preference for shared control mode when performing the first two tasks (*Control* and *Balancing Tasks*). However, the shared control did not enhance user experience in the *Shooting Task*. This could be due to the fact that the *Shooting Task* was a fast-paced action game. As prior research has shown, shared control mode reduces participants' engagement in fast-paced action games [43].

Furthermore, in the shared control mode, novice participants may benefit from the knowledge and expertise of their experienced game partners [53], enhancing their overall task performance. This improvement in task performance in the shared control mode, especially for novice players, can be attributed to the prior knowledge and proficiency of experienced players enabling them to quickly navigate and perform the tasks [83]. Additionally, previous studies showed that the shared control in 2D games had effectively fostered peer engagement [65]. However, the increased error rates observed in the shared control mode during the *Shooting Task* might be due to the fact that shared control amplified the challenges of the task [46], potentially increasing the difficulty of aiming at and shooting the targets.

We further observed participants subconsciously using their non-engaged hand with their VR hand during the *Control Task* and *Balancing Task*. This shows their brain's innate tendency for synchronized bilateral motor coordination. This phenomenon poses a challenge in an environment where control is asymmetrically distributed. However, our behavioural observations revealed a gradual minimization of the movement of their non-engaged hand, particularly towards the end of the experiment in the *Shooting Task*. This adaptation showcases their brain's ability to adjust to new control schemes and realign motor responses to fit the constraints of the shared control mode [39]. This finding demonstrates participants' progressive acceptance of the shared control concept, indicating that they became more accepting of the idea that their virtual hand is controlled by their game partner [39]. This result was also confirmed with an increase in levels of agency and body ownership towards the end of the gaming experience. Our findings revealed that participants reported higher values in agency and body ownership towards the end of the gaming experience compared to the start of the process in the shared control mode. This insight suggested that fostering a prolonged shared control experience through multiple rounds of co-play could effectively enhance the sense of agency and body ownership in shared control scenarios.

6.5 Comparison with Existing Shared Control Models

Drawing from foundational principles established by non-immersive shared control models, our approach extends these concepts into the VR domain, introducing additional engagement, performance, agency, and body ownership. In the study by Sykownik et al. [78] on shared control in 2D environments, the authors provide a useful benchmark. In their work, shared control primarily facilitated task execution without significantly altering the user's sensory experiences. In contrast, our VR setup not only requires users to collaborate but also to adapt to the immersive environment, which dramatically influences both the strategy and the interaction dynamics.

As participants navigated through the tasks and gained experiences, the shared control mode in VR not only enhanced their gaming experience but also provided better immersion and virtual embodiment. This finding could be leveraged to improve cooperative strategies and learning outcomes. This extension of findings by Sykownik et al. [78] into VR showcases the potential of immersive technologies to transform traditional shared control paradigms by enhancing user engagement and emotional responses. The increased user experience in the shared control mode implies the unique contributions of VR to shared control scenarios. Particularly, the results indicated that the shared control offered deeper immersion and a more compelling sense of presence, which are integral in VR but not essential in 2D interfaces.

6.6 Shared Control Applications in Serious Games

Shared control has also been used in applications outside entertainment. For instance, a large body of scientific work studied the effect of shared control on learning [2, 16], rehabilitation [75, 76], and serious games [45]. Serious gaming stands at the intersection of immersive experiences [74], cognitive load management [70], and heightened engagement [86].

The serious games often required gradual progression in the intensity and complexity of exercises to ensure steady recovery [86]. In the context of serious games, incrementally converting training mechanics within shared control modes could have enhanced both user motivation and efficiency. Hence, the integration of shared control in serious games could have the potential to enhance processes like rehabilitation. For example, in the Cognitive-Behavioral Therapy (CBT) area, literature reviews indicate that shared control has potential benefits for Obsessive-Compulsive Disorder (OCD) and Autism Spectrum Disorders (ASD). Peris et al. [58] emphasize the effectiveness of family-based interventions in pediatric OCD, underlining the importance of family collaboration in therapy. Valeri et al. [80] demonstrate the success of parent-mediated cooperative therapy in ASD, showcasing a model where therapists and parents share control and responsibility, tailoring therapy to individual needs. These studies highlight the relevance and effectiveness of shared control approaches in these specific therapeutic contexts, aligning with serious games' potential for treatments like CBT [66] and Play Therapy for Childhood Trauma [54].

Additionally, our findings show that shared control improved the efficiency of novice users when they played with experienced players. This finding aligns with prior research [48] and implies that in future studies, experienced players could act as coaches or trainers if shared control is part of the rehabilitation process. Moreover, rehabilitation could be emotionally taxing [69]; hence, shared control could be used to elicit positive emotions and improve users' emotional well-being. For instance, our results indicated that shared control could elevate "Positive Affect" and diminish "Negative Affect", providing a positive and encouraging environment for players.

6.7 Alternative Configurations and Future Directions in Shared Control

Our study focused on each user controlling one arm of the avatar; however, this can be expanded to other shared control strategies in future such as sharing the same arm (i.e., forearm vs upper arm) or even torso or lower limbs. Depending on the context, different fusion strategies such as averaging movements [25] and divisional control [10] can be utilized to enhance interactions. Time-multiplexed control, where control alternates between users based on contextual cues could reduce cognitive load and enhance focus during specific tasks [55]. These are important future directions that need to be investigated to determine optimal setups for various applications, enhancing the versatility and impact of shared control in VR. This exploration would broaden the theoretical understanding of shared control dynamics and its practical utility in collaborative virtual environments.

6.8 Translating Findings into Design Guidelines

Informed with findings from our research, we identified three design guidelines for designing Virtual Reality games that allow multiple players to interact in a VR setting in a shared control mode. We argue that these strategies could potentially serve as valuable insights and support for upcoming research and the development of systems aimed at exploring shared control within the VR gaming contexts.

- *Finding a Trade-off Between Competence and Positive Affect.* When designing VR games to be played in shared control, we need to aim to strike a balance between enhancing player "Competence" and fostering positive emotions. Our results suggested that fostering player "Competence" can enhance player engagement. Therefore, it is crucial to develop game scenarios that enhance players' sense of "Competence" at a certain level while maintaining a sense of accomplishment and "Positive Affect".
- *Promoting Sustained Cooperation.* Encouraging repeated cooperation and interaction enables players to gradually accept sharing control. It is, therefore, beneficial to implement features that empower players to feel in control of their virtual avatars and partner-controlled elements.
- *Customising Task Selection.* It is essential to consider the nature of the tasks while selecting the VR game to be played in shared control. Tasks that involve coordination and cooperation (e.g., *Balancing Task*) can be more suitable for shared control modes. Furthermore, it is crucial to allow for customizing the task by incorporating an appropriate gameplay mechanism, game pace, and game dynamics to achieve optimal player immersion and richer collaboration.

7 LIMITATIONS AND FUTURE WORK

Our study has several limitations that should be noted to inform future research. The number and types of game tasks we used were strictly controlled. In traditional video games and VR games, players' preferences and game type details (e.g., difficulty levels) may be more diverse. Nevertheless, we argue this control was introduced to exclude any potential confounding effects on the experiment and to solely understand the effect of a shared control on the game experience. In future work, it is important to consider how the game can deliberately control the difficulty to ensure it feels 'fair' to the player. Additionally, future research will explore how the collaborative nature influences engagement and affects a shared control game environment, e.g., a multiplayer condition.

Our participant pool also resulted in several limitations. For instance, the restricted age range of the participants limits the diversity, primarily including individuals in their late teens to early twenties, which could affect the generalizability of our results. Our participants were also not familiar with each other in terms of their gaming experiences, and participants' experience may change as they become more familiar with one another. This is a prospective area for research to look into in future investigations [63]. Additionally, we suggest in future research, it is necessary to provide greater clarity for participants about each of the questions of the Avatar Embodiment Questionnaire and Game Experience Questionnaire to avoid misunderstandings or confusions.

The laboratory setting of our study may also limit the naturalistic behaviours of participants, potentially influencing the outcomes. Task counterbalancing was employed to reduce order effects; however, this method introduces its own challenges and potential biases. Specifically, counterbalancing can affect participants' learning and fatigue levels differently, depending on the task sequence [11]. Nevertheless, we argue that counterbalancing still minimises the impact of any potential fatigue or learning effects. However, acknowledging these methodological constraints is crucial for interpreting the study results within the controlled experimental conditions.

The utilization of the Game Experience Questionnaire (GEQ), especially with recent criticism [41], presents a limitation in capturing the full spectrum of immersive experiences in VR in a reproducible manner, as it does not specifically assess deep immersion or embodiment, which are crucial in VR environments. Future studies could benefit from incorporating Immersion Experience Questionnaires (IEQ) [32] or other more VR-focused tools to gain deeper insights into how immersion affects user experience in shared control settings. This additional measurement could provide a comprehensive understanding of the shared control in overall gaming experience.

Furthermore, we recognize a promising research direction in playing VR games in the shared control mode for accessibility or rehabilitation applications. Precisely, playing games in a shared control mode holds particular promise for players with physical challenges, enabling another player to join and assist in the gaming environment, thus increasing accessibility and fostering social interaction and teamwork. We also anticipate to provide a more inclusive gaming experience, allowing individuals with various physical limitations to engage in gaming activities [31, 47]. Drawing inspiration from initiatives like the 'Two-In-One' system by Yamagami et al. [89], which aims to supplement a user's input to complete tasks, we seek to establish a direction that further enhances the inclusivity of our gaming system. Additionally, we intend to expand our research to explore shared control over the full avatar, focusing on other bodily components. Finally, while we did not employ the rubber hand illusion in this study, future research might consider a comparative analysis between our findings and those from the rubber hand illusion to provide a comprehensive understanding of shared control in the VR contexts.

8 CONCLUSION

In this work, we investigated the effect of the shard control mode on the user experience, including user satisfaction, performance, agency and body ownership through a series of VR games – the *Control Task*, the *Balancing Task* and the *Shooting Task* in a user study with 48 participants. Our findings demonstrate that the shared control mode improved certain factors of the user experience in VR games, such as the "Challenge", "Sensory and Imaginative Immersion", and "Positive Affect" and decreased "Negative Affect". Furthermore, our results show that the shared control significantly enhanced the performance of novice user when played in tandem with experienced users. Our findings also reveal that the longer participants shared their virtual hands, the more their sense of agency and body ownership of the hands increased. These findings contribute to understanding and enriching the knowledge base of using shared control in VR. This knowledge is paramount for research and design to inform the creation of shared control systems that improve user experience with potential applications in gaming and rehabilitation.

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