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ORIGINAL ARTICLE

Understanding user experience, task performance, and task interdependence in symmetric and asymmetric VR collaborations

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Abstract

Asymmetric collaboration is an important topic for the research of multiuser collaborative systems. Previous works have shown that by providing different abilities, devices or content to different users, users can take advantage of the unique features of each side and collaborate effectively with each other. However, there is limited work comparing the differences between asymmetric and symmetric Virtual Reality (VR) collaboration systems. How task complexity may affect symmetric and asymmetric VR collaboration is also unclear. In this paper, we present a comparative study that investigated how user experiences and task performance vary in symmetric and asymmetric VR collaboration. In addition, we also explored how task interdependence correlates with user experience and task performance. Participants were asked to collaboratively perform 3D object selection and manipulation tasks in pairs. A within-subjects study was conducted, where participants used PC and PC, VR and VR, and PC and VR, respectively in three conditions. Our results revealed that the asymmetric collaboration using both PC and VR showed the best results in closeness of relationship, social presence and task performance; the PC symmetric collaborative system showed the worst user experiences and task performance. Both user experience and task performance showed a positive correlation with task interdependence. We discussed the effects of the collaborativ mode and device on the user experience and task performance, and the implications for future symmetric and asymmetric VR collaboration systems.

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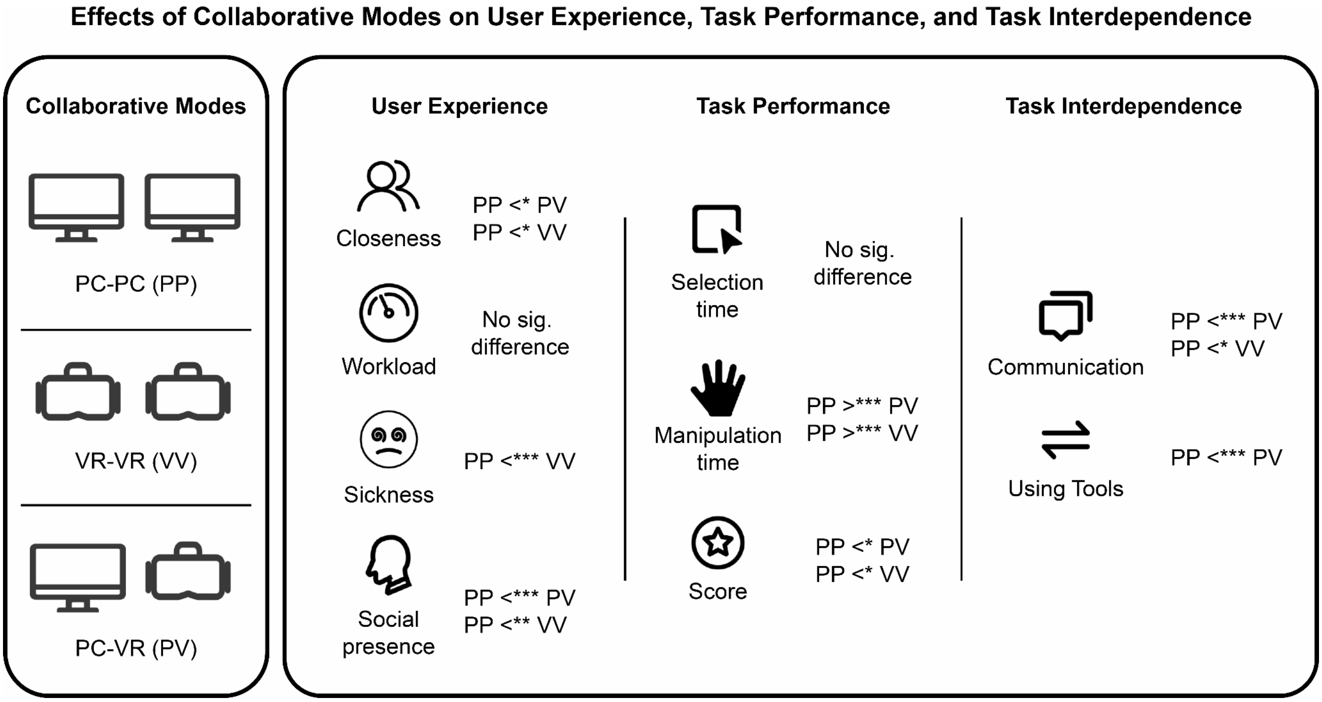
Graphical abstract



Keywords Virtual reality · Asymmetric collaborations in VR · Symmetric collaboration in VR · Selection and manipulation · Task interdependence

1 Introduction

With the increasing maturity of Virtual Reality (VR), novel interface methods like asynchronous collaboration (Pidel 2020) and asymmetric collaboration (Ouverson and Gilbert 2021) are designed to overcome the limitations of time, space and device features in multi-user applications. Asymmetric VR collaboration is an emerging form that has been explored by researchers to meet the needs of co-located or remote users using different types of technologies to access Virtual Environments (VEs). Different from symmetric VR collaborations, where users usually work with the same devices and abilities, asymmetric collaborations allow users to collaborate with different devices and system settings, which will lead to the use of distinct interaction techniques, varied access of content and control, and different perceptions of reality and virtuality. In recent years, asymmetric VR collaboration studies have been developed in different fields and proven effective. For example, Strak et al. (2021) designed a telemedicine guidance system with the combined use of VR and AR. Their study showed that the asymmetric approach is more effective than traditional video methods in a preclinical scenario. Other research has also shown the feasibility and benefits of using asymmetric VR in indoor space design (Sugiura et al. 2018), teaching (Nebeling et al. 2021), museum experience (Li et al. 2023), and engineering guidance (Clergeaud et al. 2017).

However, existing asymmetric collaboration research mainly focuses on the design and evaluation of collaboration systems for a specific scenario. There were few evaluation studies of fundamental 3D selection and manipulation tasks in symmetric and asymmetric collaborations. Despite some comparative studies, they sometimes show contradictory results. For example, in the study comparing the use of VR-VR and VR-tablet, Agnès et al. (2022) found that the devices had no effect on creativity scores in painting tasks. However, Drey et al. (2022) found that VR-VR showed a better user experience in learning than the asymmetric mode using VR and tablet. Heldal et al. (2005) compared the differences when using desktop, immersive projection, and head-mounted displays (HMDs) in a 3D cube puzzle collaborative system. This work showed that users had the overall highest task performance, presence, copresence and usability when both were using immersive projections and the lowest task performance, presence, copresence and usability when both were using desktops. Asymmetric modes fell in the middle area. Li et al. (2021) compared two conditions of Shared Virtual Reality (SVR) and Hybrid Virtual and Augmented Reality (HVAR) in a virtual museum environment. The authors found that users perceived greater presence in the SVR condition than in the HVAR condition. In addition, VR users perceived greater spatial presence while AR users perceived greater social presence. Overall, these comparisons studied various tasks, which all involved basic 3D selection and manipulation tasks. However, there is no study that systematically examined the fundamental 3D selection and manipulation of task performance and user experience when using symmetric or asymmetric devices in collaborations.

Three-dimensional object selection and manipulation are extremely important in works that involve creating and modifying virtual objects, such as 3D modelling, interior design, game design, and architectural design. Nowadays, these works are mainly conducted using Personal Computers (PCs), but an increasing number of works are starting to incorporate VR in the design pipeline to obtain immersive visual effects (Ibayashi et al. 2015; Thoravi Kumaravel et al. 2020; Kim et al. 2019). These tasks are essentially 3D selection and manipulation tasks, which have been studied heavily in Human-Computer Interaction (HCI) research. Specifically, direct manipulation being the most used method in VR simulates grabbing and manipulating objects in the real world. In the meantime, many other manipulation methods in VR shared similar mental models with those used in a PC, such as *widgets* (Mendes et al. 2016), *7-handle* (Nguyen et al. 2014), and *3-DoF hand* (Mendes et al. 2014). These similarities indicate a feasible transition from using PC to VR as productivity devices. However, a recent study (Zhang et al. 2023) showed that even using the same interaction technique, PC and VR showed different performance and user experience in 3D object selection and manipulation tasks. The study showed that compared to the PC, VR showed a higher selection efficiency but similar manipulation efficiency. Several users in the study mentioned that using VR was more tiring, although no significant difference in workloads was found between the PC and VR. Given the growing need for VR in productivity works, there is an opportunity to design collaborative systems that take advantages of both the PC and VR. Combining the high immersion and freedom of VR with the reliability and popularity of the PC, it is likely to improve the user experience and work efficiency. Asymmetric VR collaborative systems could, to a certain extent, mitigate the limitations of VR HMDs, such as reducing simulator sickness and alleviating the physical discomfort of wearing an HMD.

In collaboration, task interdependence refers to the interdependence caused by the exchange of information or resources, as defined by Thompson (1967). It has been discussed widely in research works about companies (Hart and Estrin 1991), communities (Li et al. 2022), and group works (Barbosa et al. (2017), but limited work has investigated task interdependence in asymmetric collaborations. In existing experimental studies, task interdependence is often enforced by providing users with different abilities or roles. For example, *Operation Sting* includes different roles such as a conman, muscle man, hacker and executive (Nasir et al. 2013). The study showed that users who played this game as an ice-breaker showed higher communication interest for future work than those who attended traditional ice-breaking activities. Harris and Hancock (2019) studied 4 combinations of characters and skills in *Beam Me 'Round, Scotty! 2*. They found that users experienced greater social connectedness and individual experience in higher interdependence conditions. These results provide design references for setting task interdependence in collaboration systems with different roles. In addition to the roles, which are more relevant to the design of game mechanisms, devices can also be a contributing factor to task interdependence. For example, it was found that adding biometric feedback to devices in a collaborative game can increase users' task interdependence (Karaosmanoglu et al. 2021). However, the understanding of task interdependence using different devices, especially VR and the PC, was limited. Thus, we try to explore how device-based collaborative mode affects users' task interdependence and understand its relationship with the user experience and task performance.

To fill the research gaps, we present a comparative study that investigates the differences in the user experience and task performance between collaborative modes (PC–PC, PC–VR, and VR–VR) in a series of fundamental 3D selection and manipulation tasks. The main contributions are three-fold.

- We presented an empirical evaluation of the user experience and task performance of the three collaborative modes when performing 3D selection and manipulation tasks. We further contributed to the understanding of devices by comparing the user experience and task performance using a PC and VR, respectively.
- Our study contributed to the understanding of task interdependence in multi-device collaborations and unveiled the user preferences of device usage for 3D selection and manipulation tasks.
- We discussed the features of different collaborative modes, devices and task complexity, which have led to useful findings and design implications for future collaborative systems in various fields such as design, education, and games.

2 Related work

2.1 PC and VR in collaborative systems

The device is one of the most important factors affecting user experience and interaction results, whether in symmetric or asymmetric collaboration systems. Thus, confirming the features of various devices before system designing is necessary. PCs and mobile devices (e.g., touchscreens) are two of the most commonly used interactive devices in traditional interactive systems. The PC control is mediated by a set of mouse and keyboard and requires a high demand for users' hand-eye coordination. Thus, novice users need more cognitive effort to learn it (Vigouroux et al. 2009). For skilled users, on the other hand, it is a reliable tool, especially in tasks that require operational precision (Zhang et al. 2023). In contrast, control methods of mobile touchscreens using fingers or stylus are more direct and easier to learn for novice users (Im et al. 2015; Park and Han 2010). However, it may lead to low efficiency when tasks require complex operations. In 3D selection and manipulation tasks, tablets showed the lowest work efficiency and highest workload compared to the PC and VR (Zhang et al. 2023). Aside from the screen size, finger occlusion of vision and the deviation between users' expected contact point and the actual finger position are also important reasons that led to this situation. Thus, considering the effect of the device on task performance in object selection and manipulation tasks, we chose to combine the PC and VR to develop asymmetric VR collaboration systems.

Among an emerging interactive device, VR HMDs is one of the most popular devices and has been applied in various fields, such as education (Nebeling et al. 2021), training (Tiator et al. 2018), gaming (De Marsico et al. 2020), and culture heritage (Tennent et al. 2020). VR HMDs involve users in virtual environments with high immersion, but also isolate users from the real world (Tennent et al. 2020) and can lead to simulator sickness (Kolasinski 1995). Therefore, how to minimize these issues when applying VR to various fields is a topic worth exploring. The control methods is one of the most important factors affecting user experience and task performance. In the past studies, except using hand-held controls, VR gloves (Gebhardt et al. 2022), eye-tracking (Luro and Sundstedt 2019), depth cameras (Greuter and Roberts 2011), and motion capture devices (Hoffard et al. 2022) were also used for VR controls. Some studies tried to find the highest efficiency device among them. For example, In an anatomical learning system, Fahmi et al. (2020) compared users' acceptability, satisfaction, learnability, and haptic feedback among VIVE controller, Leap Motion, and Senso gloves. The results showed that the VIVE controller was significantly better than the Leap motion and Senso glove in other aspects, except that the Senso glove provided greater haptic feedback. Thus, the controller-based method is still the best choice for most commercial VR HMDs (such as HTC VIVE and Meta Quest) and VR applications (Fahmi et al. 2020; Luro and Sundstedt 2019). Previous studies have provided insights into the features of traditional interactive devices and VR and pointed out that they vary in acceptability, learnability, and usability. Combining the results from previous research and the topic of 3D object selection and manipulation of this project, we finally chose the PC and VR as interactive devices.

2.2 Symmetric and asymmetric VR collaborative systems

Collaborative VR systems could be defined by various dimensions. The criteria for identifying symmetry and asymmetry in collaborative systems are diversified, and these classification dimensions are always proposed from collaborative mechanisms and showed as the differences in interactive ability (Ouverson and Gilbert 2021). In this work, we classified and explained collaborative systems into symmetric ones and asymmetric ones by devices (Gugenheimer et al. 2017; Mai et al. 2018; Ibayashi et al. 2015) and ability (Thanyadit et al. 2018; Wang et al. 2020 and discussed them in this section. We also discussed the existing comparative studies that focused on the differences between symmetric and asymmetric collaborations.

2.2.1 Symmetric VR collaboration systems

Symmetric VR collaboration systems provide users with the same abilities and require them to collaborate with the same devices. The biggest feature of this collaborative mode is the equal relationship between system users. Thus, participants can adopt equal communication methods in the task. In addition, such VR supported symmetric collaborative system can also improve the users' communication interests and their work results. For example, Jackson et al. (1999) showed that a VR-based multi-person collaborative education system can arouse students' interest and provide them with a high presence and pleasant user experience. Users of Doležal's work (2017) gave similar feedback after using a multiplayer VR geography education system. *CollaVR-Lap*, a laparoscopic liver surgery training system, also got positive feedback from surgeons (Chheang et al. 2019): the exploration mode in this system helped users understand and observe the structure of organs, and the surgical mode laid a good foundation for understanding and communication between doctors. Adding advanced technologies to support traditional collaborative works gives users more choices in terms of form, availability, usability and vitality. However, the features of the devices also limit the application of these collaborative systems, especially in distinctive technology systems, like VR and AR. Asymmetric collaboration is one method to deal with this limitation.

2.2.2 Asymmetric VR collaboration systems

The "asymmetric" in the asymmetric collaboration was defined as "*the capacity of individuals in a group to have different means to visualize and interact with virtual content*" (Ouverson and Gilbert 2021). Device-based asymmetry is a common asymmetric collaboration form. For example, *Virtual Makerspaces* (Radu et al. 2021) showed a remote multi-user online collaborative system. Users can join in the VEs based on real-time scanning of real space, generating content, and remotely discussing in real-time by using PC, AR, or VR. *Dollhouse VR* (Ibayashi et al. 2015) introduced an interior decoration system. Users could achieve an external view and an internal view of the virtual space together through a large screen and a VR HMD. These asymmetric collaboration systems expanded the systems' available environment and increased the users' achievable information by allowing multiple devices to join in the collaborative tasks. In the *Dollhouse VR*, designers could discuss and verify the rationality of interior decoration by combining the macro view on the interactive large screen and the first view of VR. This kind of multi-device asymmetric collaborative system expands systems' compatibility and reduces use restrictions. Thus, users could select devices and cooperate according to their needs and conditions, to achieve a good user experience and task performance. Collaborators can also have different devices and abilities together, which means users were assigned different roles or given different abilities in one system. For example, Kangas et al. (2018) designed a guidance system which allows experts to guide mechanics in performing mechanical repairs remotely. In this system, the scene captured by the maintenance personnel could be generated into a VE through a 360-degree camera. Meanwhile, experts could join in this VE and provide guidance, in real-time, by wearing a VR HMD. Maintenance personnel can see the experts' activities in the VE through a projector. Similarly, the telemedicine guidance system developed by Strak et al. (2021) also allows experts to guide medical staff remotely using VR HMD. These medical staff could receive expert advice and practice through using AR HMDs. Compared to video guidance systems, this kind of asymmetric remote guidance system using VR can give users a better sense of immersion while providing high user experience and work efficiency. Except for the applications in guidance systems, this method was also used in game (Gugenheimer et al. 2017), teaching (Thanyadit et al. 2019), exhibitions (Ishii et al. 2019), and science restoration (Süncksen et al. 2019). Overall, asymmetric collaborative systems provide users with more options than symmetric systems from devices, interaction methods and working scenarios. Users with different knowledge or skills could collaborate more easily and efficiently. Thus, how to match devices and tasks in asymmetric collaboration systems is a valuable question to explore.

2.2.3 Comparative studies of symmetric and asymmetric collaboration systems

Previous studies have provided insights into the features of symmetric and asymmetric collaborative systems and pointed out their acceptability, usability, and application fields, respectively. However, there is only limited research focusing on the differences between symmetric and asymmetric collaborative systems. For example, Heldal et al. (2005) used a 3D cube puzzle task to compare the differences among desktop (D), immersive projection technology systems (I) and head-mounted display (HMD) when using symmetric and asymmetric systems. In the four scenarios: I-I, I-HMD, I-D, and D-D. I-I showed the highest degree of presence and copresence. It is also the easiest mode to see and manipulate objects, followed by I-HMD. I-D and D-D showed similarly unsatisfying results. The results of this study strongly support the idea that devices can affect collaboration results. However, this study did not discuss the differences between symmetric and asymmetric collaborations. Besides, due to the lack of comparisons of the HMD-HMD and HMD-D, the conclusions of this work are not applicable to the HMD based VR research. Grandi et al. (2019) compared the performance of AR-AR, VR-VR, and VR-AR configurations in an object manipulation task. Their findings indicated that the collaborative mode did not affect participants' social presence across the three conditions. However, the efficiency of collaboration varied significantly: the VR-VR setup resulted in the shortest task completion time, followed by VR-AR, with the AR-AR setup being the slowest. These two studies strongly support the idea that devices affect collaboration results.

Agnès et al. (2022) compared the relationship between creativity and behaviour when users use symmetric (VR-VR) and asymmetric (VR-desktop) methods in a drawable virtual environment. The results showed that users communicated more in the asymmetric situation and preferred to work independently in the symmetric situation, but the difference in collaborative mode had no effect on the users' creativity scores. One limitation of this project is that PC users in the asymmetric situation do not have the ability to interact with VE as they do in the symmetric situation. Thus, whether the change of user behaviour comes from ability or collaborative mode should be further explored.

Drey et al. (2022) used a forest animal learning system to compare the user experience between the symmetric (VR-VR) and asymmetric (VR-tablet) systems. VR-VR showed better presence, immersion, player experience, and motivation. The interview results also show that the symmetric approach is more popular with users. The lack of perception of the collaborator's behaviour is an important reason why VR-tablet showed bad results. As the asymmetric system did not provide avatars for tablet users, VR users could not obtain real-time information about the tablet users' behaviours, which caused communication barriers.

Existing comparative studies focused on the effects of collaborative modes on user experience, task performance, and creativity in 3D cube puzzle tasks (Heldal et al. 2005), object manipulation (Grandi et al. 2019), 3D drawings (Agnès et al. 2022), and learning systems (Drey et al. 2022). These comparisons studied various tasks, which all involved basic 3D selection and manipulation tasks. However, the differences in task performance and user experience using symmetric or asymmetric devices have not been systematically studied. Thus, we hope to explore the differences between device-based symmetric and asymmetric collaborative systems on user experience, task performance and task interdependence through a series of generic 3D selection and manipulation tasks based on the PC and VR.

2.3 Task interdependence in collaborations

Interdependence is an important factor in group work. Mohr (1971) defined it as "*the extent to which work unit members have one-person jobs and the degree of collaboration required among unit members to produce or deliver the finished product or service of the unit.*" The interdependence caused by the exchange of information or resources during collaboration was named task interdependence (Thompson 1967). Based on this work, more researchers explored and defined task interdependence in detail and proposed the classification principle. Although Tal Katz-Navon and Miriam Erez described task interdependence as a continuous variable (Katz-Navon and Erez 2005), researchers prefer to use three (Harris et al. 2016; Kiggundu 1981) or four (Thompson 1967; Saavedra et al. 1993) typical dependency patterns to represent the level of users collaborate with each other. We explain them by the classification standard proposed by Harris et al. (2016).

Mirrored interdependence is typical in daily work, wherein users rely on each other in identical ways. It can be seen as the minimum level of interdependence because users do not have the necessary interaction among collaborators. Such as the collaborative mode in classic games: *Contra* (1987) and *Battle City* (1985). In unidirectional interdependence, user B's work is completely dependent on user A's result and does not reciprocate to user A. Thus, users under this interdependence level usually have different roles and are responsible for different parts of the task in a prescribed order in real work. Thomas explained it with a two-person crew working with an anti-aircraft gun (Thomas 1957). Assembly line work is also a classic example. Bidirectional interdependence can be considered as the highest degree of interdependence because it requires users to cooperate closely to achieve the final goal. In this interdependence level, collaborators always have differences with each other, which include different knowledge (Nasir et al. 2015), abilities (Harris and Hancock 2019) or use different devices (Gugenheimer et al. 2017). Thus, these collaboration systems provide high closeness and work efficiency to users, but also increase the design burden because of the lack of consistency between different systems.

In computer-supported cooperative work (CSCW) research, the explorations that focus on task interdependent are always done in game-based systems. According to the analysis of popular collaborative games, Rocha et al. (2008) identify six design patterns: "shared goals", "synergies between goals", "complementarity", "synergies between abilities", "abilities that can only be used on other players" and "special rules for players of the same team". These patterns describe game mechanics that induce dependency in games and could be used for reference in other collaborative scenarios. For example, in *Operation Sting*, Nasir et al. (2015) provided complementary roles (e.g., thief, hacker) for players who had the same knowledge to promote collaboration. *Beam Me 'Round, Scotty!* also used a similar way: Players collaborate by playing characters with different abilities. An interesting finding is even the experimental design did not compare the difference between high interdependence and low interdependence, participants expressed the positive effects of interdependence on their experience. Their work in 2019 (Harris and Hancock 2019) further explored the effects of task interdependence on user experience and task performance. The high interdependence condition showed higher connectedness, engagement, individual player experience and mode ranking than the low interdependence condition. Beznosyk et al. (2012) distinguish "closely-coupled" from "loosely-coupled" casual games and found that closely-coupled games rated higher overall in engagement. However, because this work compared different casual games with each other, it is hard to distinguish what effects are due to the game and what effects are due to interdependence. Gerling and Mandryk (2014) built two interdependent games to explore social play as an opportunity to improve caregiving relationships. They found that dependence between players appeared to foster communication between the players.

Previous studies have explored the factors and system settings that influence task interdependence in collaboration. However, there is still a lack of exploration to identify the relationship of task interdependence with task performance and user experience in asymmetric VR collaborations. Exploring this relationship will help improve the user experience and work efficiency in asymmetric collaborative systems. Therefore, this is meaningful work for collaborative system design in both research and actual production.

3 Methodology

3.1 Research questions

In this research, we ask the following research questions:

RQ1 Do collaborative modes (PC-PC, PC-VR and VR-VR) affect user experience (specifically, closeness of relationship, workload, simulator sickness, and social presence) in collaboration?

RQ2 Do collaborative modes (PC-PC, PC-VR and VR-VR) affect task performance in collaboration?

RQ3 Is there a relationship between task interdependence and user experience in collaboration?

RQ4 Is there a relationship between task interdependence and task performance in collaboration?

3.2 Independent variables

Two independent variables were examined in this study: collaborative mode and task complexity.

3.2.1 Collaborative mode

This independent variable is about the use of devices. It includes three conditions:

- PC and PC (PP): each user uses a PC during collaboration;
- PC and VR (PV): one user uses a PC and the other one uses the VR HMD;
- VR and VR (VV): each user uses a VR HMD.

3.2.2 Task complexity

This variable is determined by the placement of the wall in the experimental environment (see Sect. 3.5.4). It includes two conditions:

- With wall (WW): high task complexity;
- No wall (NW): low task complexity.

3.3 Dependent variables and measures

The dependent variables of this research include task performance and user experience. We adopted both subjective and objective measures. Specifically, the user experience was measured using validated questionnaires from existing literature (see Table 1). Users' task performance data were collected using instrumented automated data collection through C# scripts in Unity.

3.3.1 User experience

Closeness of Relationships (C1) The We measured the closeness of relationships using the Inclusion of Other in the Self (IOS) questionnaire (Woosnam 2010). It is a single-question questionnaire that uses two circles to represent the users and the intersection of the circles to represent the users' closeness of relationships. Users evaluate it using a 7-point Likert scale, where 7 shows the greatest intersection size and indicates the closet relationships.

Workload (W1–W6) The unweighted NASA Task Load Index (NASA-TLX) (Hart 2006) was used to measure users' workload. It consists of six questions that assess mental demand, physical demand, temporal demand, performance, effort, and frustration. Questions were rated on a scale between 0 and 20. Each dimension had the same weight and the sum of the six dimensions was reported as the workload.

Simulator Sickness (SS1–SS16) The Simulator Sickness Questionnaire (SSQ) (Kennedy and Lilienthal 1993) is a sixteen-question questionnaire designed to measure a user's degree of simulator sickness. Users were asked to rate each question on a scale from 0 to 3 (0: no, 1: Slight, 2: Moderate, 3: Severe). The scoring standard consists of three dimensions: nausea, oculomotor and disorientation. The final score is a weighted result of the three dimensions (see Kennedy and Lilienthal 1993).

Social Presence (SP1–SP17) Social presence is a key element in collaborative works to promote interaction and a sense of community. We used the social presence module of the Game Experience Questionnaire (GEQ) IJsselsteijn et al. (2013), which consists of three subdimensions: empathy, negative feelings, and behavioural involvement. We use a

Table 1 Questions to measure the closeness of relationships, workload, simulator sickness, and social presence dimensions of user experience

No	Type	Question	Scale
C1	Closeness of relationship	Which picture best describes the relationship with your collaborator?	1–7 Low–high
W1	Mental demand	How mentally demanding was the task?	0–20 Low–high
W2	Physical demand	How physically demanding was the task?	
W3	Temporal demand	How hurried or rushed was the pace of the task?	
W4	Performance	How successful were you in accomplishing what you were asked to do?	
W5	Effort	How hard did you have to work to accomplish your level of performance?	
W6	Frustration	How insecure, discouraged, irritated, stressed, and annoyed were you?	
SS1	Nausea and oculomotor	Please rate the severity of general discomfort	0–3 None-severe
SS2	Oculomotor	Please rate the severity of fatigue	
SS3	Oculomotor	Please rate the severity of headache	
SS4	Oculomotor	Please rate the severity of eyestrain	
SS5	Oculomotor and disorientation	Please rate the severity of difficulty focusing	
SS6	Nausea	Please rate the severity of increased concentrating	
SS7	Nausea	Please rate the severity of sweating	
SS8	Nausea and disorientation	Please rate the severity of nausea	
SS9	Nausea and oculomotor	Please rate the severity of difficulty concentrating	
SS10	Disorientation	Please rate the severity of your fullness of head	
SS11	Oculomotor and disorientation	Please rate the severity of blurred vision	
SS12	Disorientation	Please rate the severity of dizziness-eyes open	
SS13	Disorientation	Please rate the severity of dizziness-eyes closed	
SS14	Disorientation	Please rate the severity of vertigo	
SS15	Nausea	Please rate the severity of stomach awareness	
SS16	Nausea	Please rate the severity of burping	
SP1	Empathy	I empathized with the other	1–7 Strongly disagree–strongly agree
SP2	Behavioural involvement	My actions depended on the other actions	
SP3	Behavioural involvement	The other's actions were dependent on my actions	
SP4	Empathy	I felt connected to the other	
SP5	Behavioural involvement	The other paid close attention to me	
SP6	Behavioural involvement	I paid close attention to the other	
SP7	Negative feelings	I felt jealous about the other	
SP8	Empathy	I found it enjoyable to be with the other	
SP9	Empathy	When I was happy, the other was happy	
SP10	Empathy	When the other was happy, I was happy	
SP11	Negative feelings	I influenced the mood of the other	
SP12	Negative feelings	I was influenced by the other moods	
SP13	Empathy	I admired the other	
SP14	Behavioural involvement	What the other did affected what I did	
SP15	Behavioural involvement	What I did affected what the other did	
SP16	Negative feelings	I felt schadenfreude/malicious delight	
SP17	Negative feelings	I felt revengeful	

7-point Likert scale is used to evaluate the 17 items instead of the original 5-point Likert scale to ensure a consistent scale measurement in this work.

Based on the review of related works (see Sect. 2), we propose the following hypotheses for RQ1:

H1a There is a difference in the closeness of relationship when using different collaborative modes (Harris and Hancock 2019).

H1b There is no difference in workload when using different collaborative modes (Zhang et al. 2023).

H1c There is a difference in simulator sickness when using different collaborative modes (Martirosov et al. 2022).

H1d There is a difference in social presence when using different collaborative modes (Chen et al. 2022).

3.3.2 Task performance

Selection Time We recorded the objects that collided with users' head position raycasting (see Table 2, column Head). This gives an indication of users' gaze positions. When the raycasting collided with the selection area and the controllers were not holding any object, it was considered as selecting objects (see Table 2, column Head, row 2). We calculated the total time of selecting objects in each session for analysis.

Manipulation Time The grabbing of objects was indicated by the controller activities (see Table 2, column Hold_L and Hold_R). When the user grabbed an object and the object overlapped with the detection area, it was recorded as a manipulation state (see Table 2, column Manipulate, row 5). We counted the time spent manipulating objects in each session for analysis.

Score When an object overlapped with its corresponding target transform position and rotation, the object and its corresponding target area were dismissed. Meanwhile, the score was increased by one (see Table 2, column Score, row 6).

The following hypotheses are proposed for RQ2, based on the findings in related works:

H2a Users will show greater individual task performances using VR than PC in selection tasks (Zhang et al. 2023).

H2b Users will show greater individual task performances using direct control (VR) than indirect control (PC) in the manipulation task (Wang et al. 2023; Rodrigues et al. 2023).

H2c Users will show the greatest group task performances using PV (PC - VR) (Zhang et al. 2023).

3.3.3 Task interdependence

Frequency of Communication The frequency of communication is an external manifestation of their task interdependence and social closeness Depping and Mandryk (2017). When users work closely with each other, they need to exchange information and identify goals frequently. In this experiment, we recorded the participants' conversations during the experiment. Each sentence that participants spoke was treated as an instance of communication and calculated the total number of communication between each group. The frequency number was considered as the frequency of communication.

Frequency of using Transmission Tools The last column of Table 2 indicates the use of transmission tools. By default, the value displayed in this column is "No"; when an object was placed into the transmission tools, the system will record a "Yes" (see Table 2, column Tools, row 4). The frequency of using transmission tools equal to the number of "Yes" appeared in each session. This is another data used to measure the collaborative relationship between users. It also represents the level of collaboration between users.

The following hypotheses are proposed for RQ3 and RQ4, as implicated in the previous works:

Table 2 Example CSV records for the experiment

Time	Scene	State	Hold_L	Hold_R	Head	Manipulate	Score	Tools
hh:mm:ss	PV_NW	Waiting	None	None	None	None	0	No
hh:mm:ss	PV_NW	Start	None	None	B_0_1	None	0	No
hh:mm:ss	PV_NW	Start	None	B_0_1	B_0_1	None	0	No
hh:mm:ss	PV_NW	Start	None	None	None	None	0	Yes
hh:mm:ss	PV_NW	Start	None	None	B_0_1	B_0_1	0	No
hh:mm:ss	PV_NW	Start	None	None	None	None	1	No
hh:mm:ss	PV_NW	Start	None	None	None	None	5	No

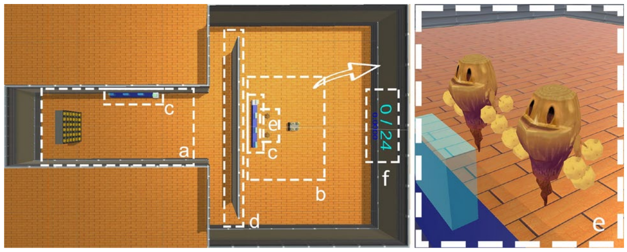


Fig. 1 A top-down view of the experimental environment. **a** The object selection area; **b** the manipulation area; **c** transmission tools supporting a quick transfer of objects between the two areas; **d** the area displaying a wall or no wall in two task conditions; **e** users' avatars; **f** timer and score board

H3 A positive correlation exists between task interdependence and user experience in collaboration (Harris and Hancock 2019).

H4 A positive correlation exists between task interdependence and task performance in collaboration (Puck and Pregernig 2014).

3.4 System development

Hardware and Software Our proof-of-concept prototype was built using a PC with Intel® Core™ i9-11900K CPU @ 3.50GHz, 64GB RAM, NVIDIA GeForce GTX 3090 graphics card with 24GB RAM. Another PC with Intel® Core™ i9-10980K CPU @ 2.40GHz, 32GB RAM, NVIDIA GeForce GTX 3080 graphics card with 16GB RAM was used to assist in prototype testing. The systems were built in Unity (version 2021.3.7) and two packages: *VR Interaction Framework*[1] and *Photon*,[2] which are available on the Unity Assort Store. We used Rhino 7.0 to build the 3D models and the virtual scenes.

System Setup We adopted two PCs and two VR HMDs to set up the experimental conditions. Specifically, the PCs have a resolution of 3840 × 2160 and a refresh rate of 60 Hz. We used two Meta Quest 2 (1920 × 1832 resolution for each eye, 72 Hz refresh rate) as the VR HMD devices. We set up C# scripts to capture objective user behaviour data. The program records the data every 0.1 s, which is exported as CSV files of each session for further analysis. Table 2 shows some example lines of user behaviour data. The details are explained in Sect. 3.3.2.

1 https://assetstore.unity.com/packages/templates/systems/vr-interaction-framework-161066.

2 https://assetstore.unity.com/packages/tools/network/pun-2-free-119922.

Table 3 Control methods when using PC and VR

Operation	Using PC	Using VR
Change viewing perspective	Mouse movement	Head movement
Move around in the VEs	W A S D keys	Teleport and-steer using the thumbstick
Point and select an object	Screen center pointing	Controller raycasting
Confirm selection	Space key	Grip button
Manipulate an object	I J K L U O keys	Virtual hand

3.5 Experimental environment and tasks

A top-down view of the experimental environment is shown in Fig. 1. The environment consists of six main parts, which we detail below.

Within the VE, two users in a pair need to work together on selection and manipulation tasks. They were given the following instructions:

> This experiment consisted of 6 sessions. Each session has 24 target objects in total and it will stop at 200 seconds. Within the 200 seconds, please work together to select and manipulate as many cubes as possible. You can identify them according to their features (colours, patterns and variations), because each of them is different and there are always 24 cubes corresponding to the target objects. When one cube overlaps with the target objects, the cube will be replaced with a new one and the score board is added by one. You can always talk to each other during this experiment.

Using either VR or a PC, users could move around in VE, select target objects from the selection area, and manipulate objects to align them with the target transform position and rotation. Table 3 shows the PC and VR control methods.

3.5.1 Object selection area

This area consists of a shelf with 36 cubes and a transmission table (see Fig. 2a–b). The cubes were randomly selected from a sample pool of 40 cubes (4 colours × 5 patterns × 2 variations). Upon the start of the experimental session, 36 non-duplicated cubes were randomly placed on the shelf.

3.5.2 Manipulation area

This area shows the target objects along with a transmission table (see Fig. 2c). After having the target object with the correct colour, pattern and variation, users need to manipulate the transform position and rotation of the object to make it overlap with the target transform (see Fig. 3). To facilitate

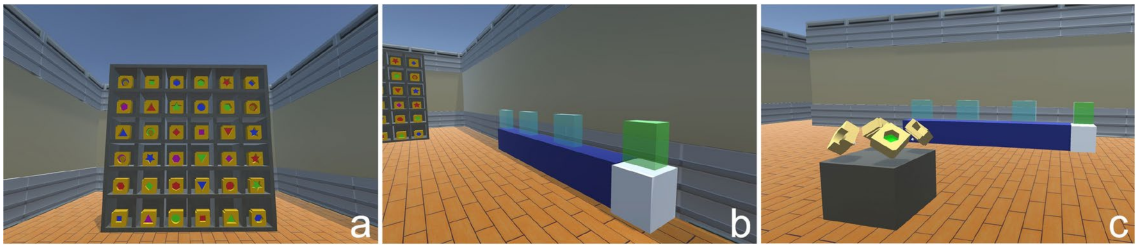


Fig. 2 Screenshots of the **a** shelf with selection targets and **b** transmission tools in the object selection area; **c** object manipulation area with transmission tools. Objects on the blue portals are transmitted to the other table; an object on the green portal is transmitted back to the shelf

Fig. 3 Figures showing the manipulation methods when using **a** VR controllers and **b** PC mouse and keyboard. **c** An incorrect target object with the red sign; **d** a correct but not aligned object with the orange sign; **e** a correct and aligned object with the green sign

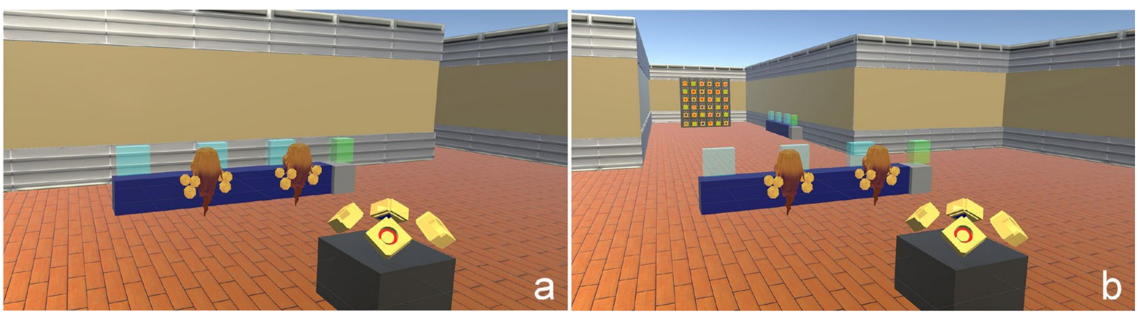


Fig. 4 Screenshots showing the experimental environment of the **a** with the wall and **b** no wall condition

the manipulation, we set three colour signs (see Fig. 3c–e). Red means the object does not match the target transform; orange means the object is correct but not correctly aligned; green means the correct object has been properly aligned with the target transform. We set up a threshold of 10% for the transform position and rotation. Upon a successful manipulation task, the target is replaced with a new one and the score is added by one.

3.5.3 Transmission tools

We implemented transmission tools to improve collaborative efficiency (see Fig. 2b–c). This is inspired by the setting of "town portal" in *Warcraft 3* (2002) and the teleportation in VR (Liu et al. 2018). By using these transmission tools, users do not needs to move cubes by moving themselves, but only place them into the transmission tools. Each transmission tool comprises 3 blue portals and 1 green portal (see Fig. 4). When a user puts a object into a blue portal, the objects will be transmitted to the corresponding portal on the other transmission table. The object placed on the green portal is transmitted back to its original position on the shelf.

3.5.4 Wall

Between the object selection area and the manipulation area, we use a wall set up to distinguish the two task complexities, following the design of (Siau et al. 2017). Having a wall will block users' sight and increase the uncertainty and potential movements across zones, leading to a higher task complexity. Thus, we set the with wall condition (WW) as the complex condition and the no wall condition (NW) as the simple condition (see Fig. 4).

3.5.5 Avatars

To help users understand the behaviours of their collaborators, we set an avatar[3] for each participant (see Fig. 1e). The positions and rotations of these avatars are updated in real-time according to users' control of their movements.

3.5.6 Task time and score

To keep users informed about their task progress, we set a timer on the wall to show the duration of the experiment. It stops when the time reaches 200 s. The score board displays the successfully completed task trials in real-time during the experiment.

3.6 Experimental procedure

We conducted a study that took place in a 3 m × 3 m space in a university lab. After a brief introduction, we collected participants' consent and asked them to fill out a pre-experiment questionnaire. Then, participants familiarised themselves with the devices and adjusted the device to a comfortable physical setting, including the sensitivity of the mouse and the strap fit and lens position of the VR HMD.

Before the experiment, participants went through two tutorials to familiarise with the system's control methods with PC and VR, respectively, until users were sure they had sufficient familiarity. The experiment consists of six sessions. A Latin square design was applied to avoid the influence of experimental order on the results. Participants were asked to complete a questionnaire (see Table 1) after completing a set of collaborative modes to evaluate their user experience. Then, they were encouraged to rest fully and inform the researcher when they were ready for the next experimental session.

After completing all six experimental sessions, the two participants in every group were invited to participate in a voluntary interview. The entire experiment lasted approximately 70 min. The experimental procedure is summarised in Fig. 5. This study is approved by the University Ethics Committee.

3.7 Participants

We had 36 participants (13 female, 23 male) who voluntarily signed up for the study, with an average age of 22.14 ($SD = 2.45$). Participants were asked to rate their usage frequencies and familiarity with the PC and VR. Most participants ($N = 35$) use a PC almost every day. About half of the participants ($N = 20$) use VR less than once per month, 16 participants used VR more than once per month. On a 5-point Likert scale, participants were very familiar with a PC (4.36 ± .93) and moderately familiar with VR (3.19 ± 1.12).

4 Results

4.1 Analysis methods

In total, we collected 216 questionnaire samples (36 participants × 6 experimental conditions) about user experience. In addition, CSV log files and audios have been recorded for the analysis of task performance (see Sect. 3.3.2) and task interdependence (see Sect. 3.3.3). Specifically, we processed the log files to analyse the selection time, manipulation time, score, and the frequency of using transmission tools; the audio recordings of all experimental sessions were analysed to calculate the frequency of communication. No significant outliers were found in the data, and we did not exclude any data from the experiment.

Statistical analysis was performed using IBM SPSS Statistics 26. The Shapiro–Wilk tests of normality and the Q–Q plots showed that the distributions of workload, empathy,

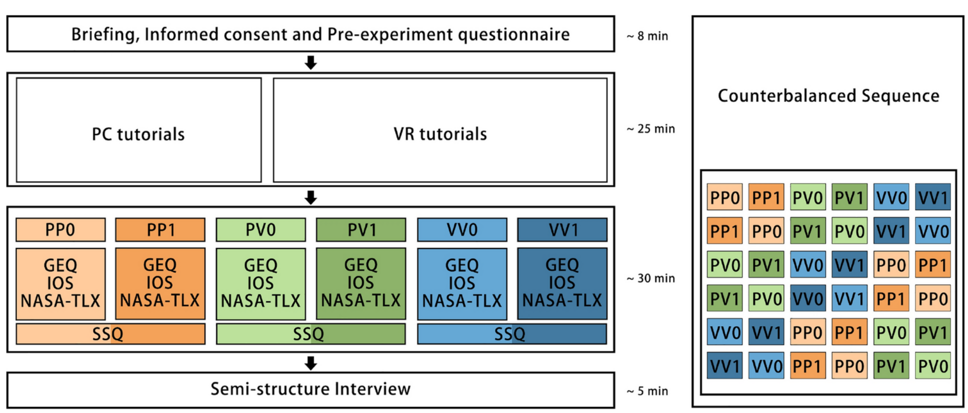


Fig. 5 An example experimental procedure and the counterbalanced sequence of sessions. The experiment consisted of six sessions: PP0 (PP-NW), PP1 (PP-WW), PV0 (PV-NW), PV1 (PV-WW), VV0 (VV-NW), VV1 (VV-WW). PP: both users use PC; PV: one person use PC and the other one use VR; VV: both users use VR; NW: no wall in the scene; WW: with a wall in the scene

[3] https://assetstore.unity.com/packages/3d/characters/food-monsters-character-and-animation-pack-1-88227.

score, frequency of communication, and frequency of using tools in each combination of the related groups were approximately normally distributed. We performed repeated measures ANOVA to analyse the effects of the collaborative mode (PP: PC and PC, PV: PC and VR, and VV: VR and VR) and task complexity (WW: with wall and NW: no wall) on these measures. The distributions of other measures of user experience (i.e., closeness of relationship, negative feelings, behavioural involvement, simulator sickness) and task performance (i.e., selection time and manipulation time) did not meet this assumption. Therefore, we used the Friedman tests and Wilcoxon signed-rank tests for the analysis. Correlation analysis was conducted to understand their relationship with task interdependence. Greenhouse-Geisser correction was applied when the collected data did not satisfy the sphericity test assumption. Bonferroni adjustment was applied for post-hoc tests to avoid inflated Type I errors. We report Bonferroni-adjusted p-values, i.e., multiplying the observed (uncorrected) p-value by the number of comparisons made, which is compared against the threshold value of 0.05.

4.2 User experience

4.2.1 Closeness of relationships

A Friedman test showed a significant difference in the closeness of relationships under different collaborative modes, $\chi^2(2) = 12.347, p = 0.002, W = 0.086$. Post hoc analysis revealed significant differences between PP-PV ($p = 0.026$) and PP-VV ($p = 0.018$). The closeness of relationships was significantly lower in PP (PC and PC), compared to PV (PC and VR) and VV (VR and VR) (see Fig. 6, left). A Wilcoxon signed-rank test showed that the closeness of relationships in WW (with wall) was significantly greater than NW (no wall), $Z = -4.458, p < 0.001, r = 0.303$. The results support H1a: Users felt higher closeness of relationship in PV and VV than PP.

4.2.2 Workload

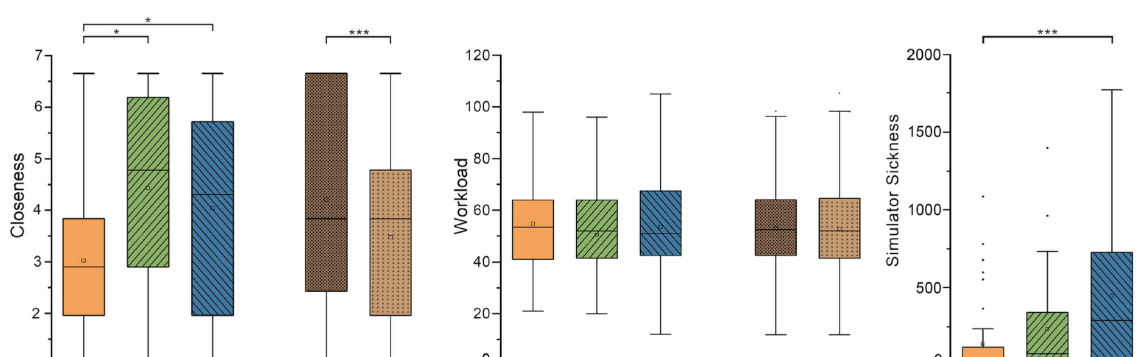
A two-way repeated measures ANOVA showed no significant interaction between the collaborative mode and task complexity on workload, $F(2, 70) = 0.39, p = .681, \eta^2 = 0.011$. Further analysis showed no significant effect of collaborative mode ($F(2, 70) = 1.64, p = .201, \eta^2 = 0.045$) and task complexity ($F(1, 35) = 0.046, p = 0.831, \eta^2 = 0.001$) on workload (see Fig. 6, middle). The results support H1b: There is no difference in workload when using PP, PV and VV.

4.2.3 Simulator sickness

A Friedman test showed a significant difference in the level of simulator sickness under different collaborative modes, $\chi^2(2) = 22.472, p < 0.001, W = 0.312$. Post hoc analysis revealed a significant difference between PP-VV ($p < 0.001$). The level of simulator sickness was significantly higher in VV (VR and VR) than PP (PC and PC). The results support H1c: Users felt higher simulator sickness in VV than PP.

4.2.4 Social presence

Psychological Involvement—Empathy A two-way repeated measures ANOVA showed no significant interaction between the effects of the collaborative mode and task complexity on empathy, $F(1.35, 47.26) = 1.19, p = 0.310, \eta^2 = 0.033$. Further analysis showed that collaborative modes had a significant effect on empathy, $F(2, 70) = 3.39, p = 0.039, \eta^2 = 0.088$. Post hoc analysis revealed no significant differences in pair-wise comparisons of social presence when using different collaborative modes (see Fig. 7, left). The



Collaborative Mode			Task Complexity		Collaborative Mode			Task Complexity		Collaborative Mode		
PP	PV	VV	WW	NW	PP	PV	VV	WW	NW	PP	PV	VV
3.14	4.64	4.22	4.39	3.61	54.68	50.50	53.46	53.00	53.77	134.89	230.69	445.29
0.25	0.30	0.31	0.26	0.20	2.90	2.53	2.94	2.46	2.51	44.28	53.07	86.75

Fig. 6 Box-plots and table of means and standard deviations showing the results of closeness of relationships (left), workload (middle), and simulator sickness level (right)

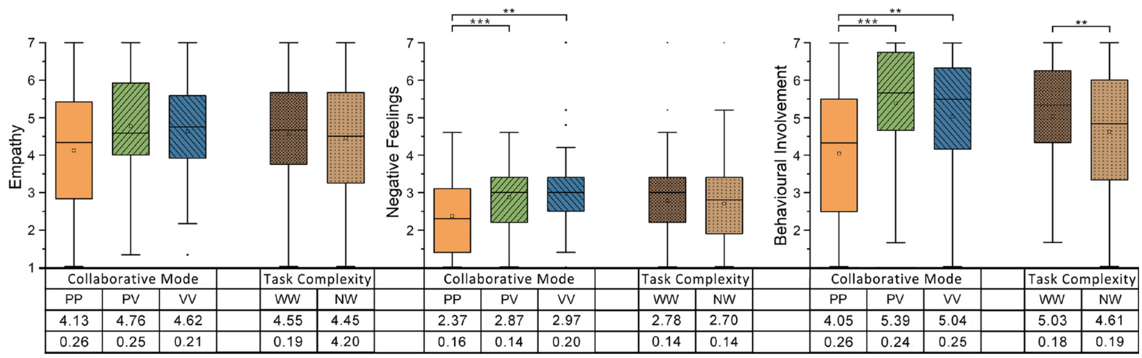


Fig. 7 Box-plots and tables of means and standard deviations showing the results of social presence, including measures of empathy (left), negative feelings (middle), and behavioural involvement (right)

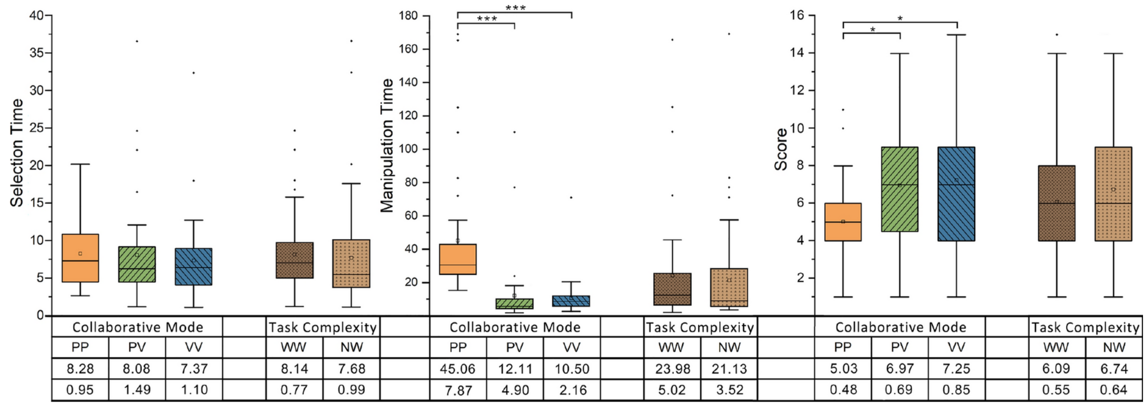


Fig. 8 Box-plots and tables of means and standard deviations showing the results of selection time (left), manipulation time (middle), and score (right). Time was measured in seconds

effect of task complexity on empathy was insignificant, $F(1,35) = 1.72, p = 0.198, \eta^2 = 0.047$.

Psychological Involvement—Negative Feelings A Friedman test showed a significant difference in negative feelings under different collaborative modes, $\chi^2(2) = 22.428, p < 0.001, W = 0.156$. Post hoc analysis revealed significant differences between PP-PV ($p < 0.001$) and PP-VV ($p = 0.001$). The users' negative feelings were significantly lower in PP, compared to PV and VV (see Fig. 7, middle). A Wilcoxon signed-rank test did not show a significant effect of task complexity on negative feeling, $Z = -1.815, p = 0.070, r = 0.123$.

Behavioural Involvement A Friedman test showed a significant difference in the behavioural involvement under different collaborative modes, $\chi^2(2) = 19.428, p < 0.001, W = 0.135$. Post hoc analysis revealed significant differences between PP-PV ($p < 0.001$) and PP-VV ($p = 0.002$). The behavioural involvement from highest to lowest was PV, VV, and PP (see Fig. 7, right). A Wilcoxon signed-rank test showed that the behavioural involvement was significantly higher in WW than NW, $Z = -3.153, p = 0.002, r = 0.215$. Overall, these results support H1d: Users felt lower negative feelings and behavioural involvement in PP than PV and VV.

4.3 Task performance

4.3.1 Selection time

A Friedman test showed no significant difference in the selection time under different collaborative modes, $\chi^2(2) = 0.056, p = 0.973, W = 0.001$ (see Fig. 8, left). A Wilcoxon signed-rank test showed the effect of task complexity on selection time was insignificant, $Z = -1.029, p = 0.304, r = 0.099$. The results reject H2a: There is no difference in selection time when using PC and VR.

4.3.2 Manipulation time

A Friedman test showed a significant difference in the manipulation time under different collaborative modes, $\chi^2(2) = 49.189, p < 0.001, W = 0.683$. Post hoc analysis revealed significant differences between PP-PV ($p < 0.001$) and PP-VV ($p < 0.001$). The manipulation time was significantly longer in PP, compared to PV and VV (see Fig. 8, middle). A Wilcoxon signed-rank test showed the effect of task complexity on manipulation time was insignificant, $Z = -1.038, p = 0.299, r = 0.010$. The results support H2b: Users used less time manipulating objects when using VR than a PC.

4.3.3 Score

A two-way repeated measures ANOVA showed no significant interaction between the effects of the collaborative mode and task complexity on the score, $F(2, 34) = 0.53, p = 0.595, \eta^2 = 0.026$. Further analysis showed that collaborative mode had a significant effect on the score, $F(2, 34) = 6.04, p = 0.006, \eta^2 = 0.256$. Task complexity had no significant effect on the score, $F(1, 17) = 2.26, p = 0.151, \eta^2 = 0.121$. Post hoc analysis revealed significant differences in PP-PV ($p = 0.013$) and PP-VV ($p = 0.016$). The score was significantly lower in PP, compared to PV and VV (see Fig. 8, right). The results reject H2c: Users showed similar scores when using PV and VV.

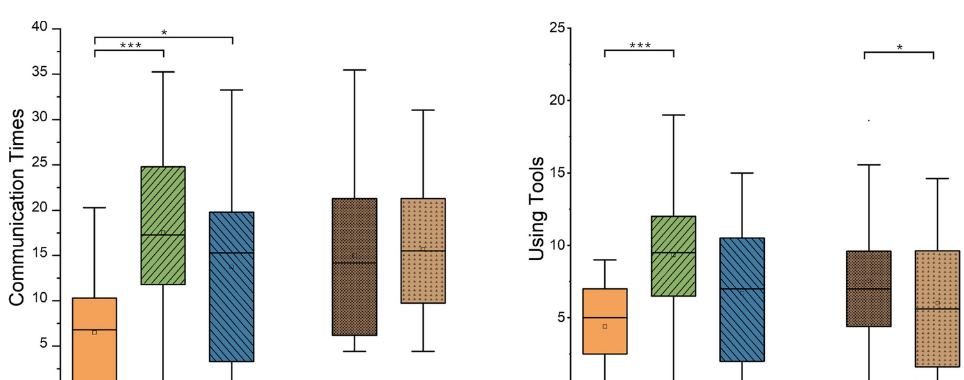
4.4 Task interdependence

4.4.1 Frequency of communication

A two-way repeated measures ANOVA showed no significant interaction between the effects of the collaborative mode and task complexity on the frequency of communication, $F(2, 34) = 0.30, p = 0.740, \eta^2 = 0.009$. Further analysis showed that collaborative mode had a significant effect on communication frequency, $F(2, 34) = 14.39, p < 0.001, \eta^2 = 0.454$. Post hoc analysis revealed significant differences in PP-PV ($p < 0.001$) and PP-VV ($p = 0.010$). The communication frequency from highest to lowest was PV, VV, and PP (see Fig. 9, left). Task complexity had no significant effects on communication frequency, $F(1, 17) = 0.84, p = 0.371, \eta^2 = 0.260$.

Correlation with User Experience A partial correlation analysis whilst controlling the effect of collaborative mode showed that users' communication frequency correlates positively with users' closeness of relationships ($r = 0.310, p < 0.001$), empathy ($r = 0.280, p < 0.001$), negative feelings ($r = 0.265, p < 0.001$) and behavioural involvement ($r = 0.410, p < 0.001$). However, zero-order correlations showed that there was a statistically significant positive correlation between communication frequency and closeness of relationships ($r = 0.363, p < 0.001$), empathy ($r = 0.306, p < 0.001$), negative feelings ($r = 0.315, p < 0.001$) and behavioural involvement ($r = 0.456, p < 0.001$), indicating that collaborative mode had very little influence in controlling for the relationship between communication frequency and closeness of relationships, empathy, negative feelings and behavioural involvement.

Correlation with Task Performance A partial correlation analysis whilst controlling the effect of collaborative mode showed that a negative correlation between users' communication frequency correlates and manipulation time ($r = -0.259, p = 0.007$), but no significant correlation between users' communication frequency and score ($r = 0.127, p = 0.194$). Zero-order correlations showed that there was a statistically significant negative correlation between communication frequency and manipulation time ($r = -0.357, p < 0.001$) and a statistically significant positive correlation between communication frequency and score ($r = 0.190, p = 0.050$). This means that the collaborative mode had little influence in controlling the relationship between communication frequency and manipulation time and score. Both controlled ($r = 0.021, p = 0.828$) and zero-order ($r = 0.003, p = 0.976$) correlation analysis showed no correlation between users' communication frequency and selection time.



Collaborative Mode			Task Complexity		Collaborative Mode			Task Complexity	
PP	PV	VV	WW	NW	PP	PV	VV	WW	NW
6.19	17.22	13.47	11.93	12.67	4.39	9.33	6.69	7.57	6.04
1.21	1.90	2.11	1.44	1.30	0.55	0.89	1.02	0.73	0.71

Fig. 9 Box-plots and tables of means and standard deviations showing the results of the users' frequency of communication (left) and frequency of using tools (right) during the experiment

4.4.2 Frequency of using transmission tools

A two-way repeated measures ANOVA showed no significant interaction between the effects of the collaborative mode and task complexity on the frequency of using transmission tools, $F(2, 34) = 0.15, p = 0.861, \eta^2 = 0.018$. Further analysis showed that both collaborative mode ($F(2, 34) = 14.12, p < 0.001, \eta^2 = 0.458$) and task complexity ($F(1, 17) = 5.98, p = 0.026, \eta^2 = 0.047$) have significant effects on the frequency of using transmission tools. Post hoc analysis revealed that the frequency of using transmission tools was significantly greater in PV than PP ($p < 0.001$). For different task complexities, the frequency of using transmission tools in WW was significantly higher than NW ($p = 0.026$) (see Fig. 9, right).

Correlation with User Experience A partial correlation analysis whilst controlling for collaborative mode showed that users' frequency of using transmission tools correlates positively with users' closeness of relationships ($r = 0.331, p < 0.001$), empathy ($r = 0.301, p < 0.001$), negative feelings ($r = 0.289, p < 0.001$) and behavioural involvement ($r = 0.445, p < 0.001$). However, zero-order correlations also showed that there was a statistically significant positive correlation between users' frequency of using transmission tools and closeness of relationships ($r = 0.374, p < 0.001$), empathy ($r = 0.323, p < 0.001$), negative feelings ($r = 0.329, p < 0.001$) and behavioural involvement ($r = 0.480, p < 0.001$), indicating that collaborative mode had very little influence in controlling for the relationship between users' frequency of using transmission tools and closeness of relationships, empathy, negative feelings and behavioural involvement. Thus, these results support H3: There is a positive correlation between task interdependence and user experience.

Correlation with Task Performance A partial correlation analysis whilst controlling the effect of collaborative mode showed that users' frequency of using transmission tools correlates negatively with manipulation time ($r = -0.235, p = 0.015$), but no significant correlation between the frequency of using transmission tools and score ($r = 0.173, p = 0.076$). Zero-order correlations showed that there was a statistically significant negative correlation between users' frequency of using transmission tools and manipulation time ($r = -0.235, p = 0.001$) and a statistically significant positive correlation between the frequency of using transmission tools and score ($r = 0.222, p = 0.022$). The results indicated that collaborative mode had little influence in controlling for the relationship between users' frequency of using transmission tools and manipulation time and score. Both controlled ($r = 0.017, p = 0.860$) and zero-order ($r = 0.003, p = 0.979$) correlation analysis showed no correlation between users' frequency of using transmission tools and selection time. Overall, these results support H4: There is a positive correlation between task interdependence and task performance.

4.4.3 Observations about task interdependence

Based on our observations, users formulate task interdependence with similar task load for two collaborators according to task types and device features. Some worked closely with each other and assigned the task load based on the task type (selection and manipulation), while others chose to work independently and divide the task load based on the number of target objects, showing a low (mirrored) interdependence. For example, in PP, users need about 8 s to select a correct object and 45 s to overlap it with the target object. If they choose high (bidirectional) interdependence and assign one user in selection and the other in manipulation, the user who is responsible for selection needs to wait about 37 s before starting the next task, which will lead to a large difference in the two users' task load. Therefore, most groups of collaborators work in low interdependence in PP. That is, each of them worked independently on the selection and manipulation of two objects. In VV, there is only 3 s difference between one-time selection and manipulation. Thus, users could decide whether to use low or high interdependence according to their personal preferences. We found slightly more groups of users worked with high interdependence than low interdependence under this condition. In PV, although the selection time of PC and VR were similar, almost all users chose to work with a high task interdependence: VR users were responsible for manipulation, and PC users were responsible for selection. This is related to the features of PC and VR, which we discuss in Sect. 5.2.

4.5 Interview

At the end of the experiment, 16 groups of participants (32 users) volunteered to participate in the interview. The other 2 groups of participants skipped the interview. Figure 10 shows the interview questions and their results.

According to the results of Q1, all participants thought the device affected their user experience, but 4 of them thought the effects were limited. Specifically, users' preferences were balanced for using a PC ($N = 12$) or VR ($N = 9$) for selection tasks (Q2). On average, participants who preferred the PC for selection tasks were less familiar with VR ($M = 2.83, SD = 1.19$) than participants who preferred VR ($M = 3.11, SD = 1.05$) or found them similar ($M = 3.64, SD = 0.81$). However, the difference was not statistically significant. When manipulating objects (Q3), nearly all participants ($N = 31$) preferred VR.

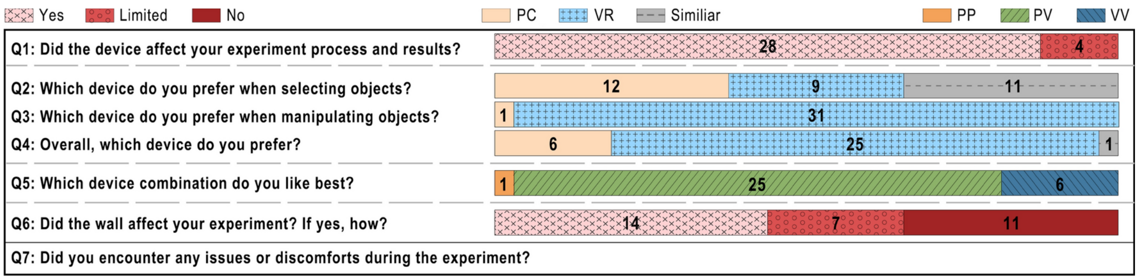


Fig. 10 Semi-structured interview questions and results

Overall, most participants ($N = 25$) preferred VR in the selection and manipulation tasks; one participant found the use of a PC and VR was similar; 6 participants preferred using the PC. The six users expressed different degrees of unfamiliarity or discomfort with VR in Q7, such as the perception of simulator sickness and the weight of HMDs. When asked the collaborative mode they prefer (Q5), 25 participants chose PV, 6 participants chose VV, and only 1 participant chose PP. We found that participants who preferred VV reported lower SSQ in VR ($M = 220.57, SD = 244.31$) than participants who preferred PV ($M = 529.46, SD = 582.77$), yet the data sample was too limited to show statistical significance.

Regarding the effect of task complexity (Q6), 14 participants reported that the wall affected their task interdependence: participants tended to divide tasks between them (work in high interdependence) in WW, while they tended to work alone (work in low interdependence) in NW. Eleven participants thought the wall did not affect their experiment process and task interdependence; the other 7 participants thought the wall affected their user experience, but it did not affect their task interdependence. In addition to user experience and task interdependence, participants also reported the effect of the wall on their work efficiency ($N = 4$).

In the last question (Q7), we received some subjective feedback. By simulating the manipulation method in the real world, VR was found easy to learn and use ($N = 4$), but the simulator sickness ($N = 4$) and discomfort caused by the device weight ($N = 4$) were unavoidable. The negative feedback mainly came from the manipulation task: participants had difficulty when continuously rotating the object ($N = 5$) and determining the exact position of the object ($N = 3$). Seven participants mentioned the movement in the experiment: 4 participants thought movements in VR were harder than the PC; 1 participant expressed the opposite feeling; 2 participants thought there was no significant difference between the PC and VR when moving around in the experimental environment. Some participants ($N = 7$) mentioned that the task objects seemed alike, which increased their communication difficulty.

5 Discussion

Our study examined the users' task performance and user experience through a task consisting of selection and manipulation. We also reported the users' subjective preferences of device use. In this section, we first discuss our findings about the three RQs we proposed in Sect. 3.1. We also discuss some additional findings based on our observations and users' subjective feedback.

5.1 Asymmetric collaborative mode improves user experience

In response to RQ1, our results showed that participants felt higher closeness and social presence in the asymmetric collaborative mode using a PC and VR than in the symmetric mode of PC and PC. These results supported H1a and H1d. This finding is related to higher communication frequency and task interdependence when users work in the asymmetric collaborative mode (PV). Similar findings were also reported in Harris and Hancock (2019). Users expressed their feelings in the interview: *"The asymmetric modes bring me a stronger sense of collaboration. I felt we were strongly dependent on each other. The other two modes did not provide such experience to me"* (*p16*). *"We can collaborate with each other easily in asymmetric mode"* (*p15*). In addition, users did not report significant differences in workload when using different collaborative modes. H1b is supported, which is consistent with the findings in Zhang et al. (2023). Besides, the results showed that using the asymmetric mode (PV) significantly reduced the physical discomfort of simulator sickness on users compared with VV, supporting H1c. It allowed users who are prone to simulator sickness to participate in collaborative processes using PCs. As users reported in the interview: *"I love the asymmetric mode because I can use a PC without affecting our productivity"* (*p16*). *"I'm very sensitive to motion sickness. I like the PC and VR mode because it allows my friend to have an immersive experience and high work efficiency when I have to use PC"* (*p23*). The freedom from device selection allows users to achieve an overall greater user experience while maintaining their work efficiency. The popularity of PV was evident in participants' subjective feedback. Most participants ($N = 25$) reported that PV is their favourite collaborative mode. For example, *p4* said: *"The asymmetric mode is my favourite"*; *p23* said *"Even I used VR and got severe simulator sickness, I still think the asymmetric mode is the best one"*. To conclude, PV is the preferred collaborative mode in 3D object selection and manipulation tasks which showed the greatest sense of closeness and social presence.

5.2 Collaborative mode affects task performance

Asymmetric collaborative mode showed the overall highest score and manipulation task performance, showing support for H2c. Regarding selection tasks, three collaborative modes showed similar task performance, H2a is not supported. However, the asymmetric mode (PV) and VR symmetric mode (VV) showed higher manipulation efficiency in manipulation tasks than PC symmetric mode (PP), supporting H2b. These results are highly related to the device features of a PC and VR. We observed that when participants allocated tasks among them, almost all users used VR to manipulate objects and PC to select objects in PV. The similar selection performance of PC and VR explains the reason why PV and VV showed an overall similar task performance.

Compared to PP and VV, the PC and VR showed similar selection performance, but VR showed greater manipulation performance. These results conflict with those of Zhang et al. (2023), and we discuss two potential causes of these differences. The main reason is the manipulation method. The direct manipulation method in VR is simpler and faster than the three-axis based manipulation method (Rodrigues et al. 2023). Participants found the lack of intuitive correspondence between keyboard control and objects' transform location and rotation made the PC manipulation more challenging. As *p15* reported, *"After adjusting several times, I had no idea which button corresponded to which direction, so I had to experiment again and again."* Similarly, *p22* commented that *"It is so hard for me to match the buttons with the objects' direction."* Thus, this may lead to inefficiency when using the PC to manipulate objects. The second reason is that participants found the selection tasks simple and straightforward. Although we set two task complexities, the challenge of the wall can be mitigated if participants distribute the workload and stay in the two areas. *p20* reported that *"I did not find any obvious difference between them when selecting objects"*. *p16* also commented that *"There is no difference between VR and PC when making selections because they are both easy"*. Overall, the asymmetric collaborative modes consisting of PC and VR achieved comparable task performance as the symmetric VR mode in the selection and manipulation tasks. Both PV and VV showed a greater performance than the symmetric PC mode.

5.3 Task interdependence correlates positively with user experience

In our work, task interdependence is indicated by the frequency of communication and the use of transmission tools. A high task interdependence is shown when participants had a high frequency of communication and frequent use of the tools. The analysis of their correlation to user experience showed that task interdependence correlates positively with the closeness of relationships, empathy, and behavioural involvement, which partially support H3. However, task interdependence also showed positive correlations with negative feelings. This finding was implied in D'Oliveira and Persico's work (2023), where they explained that collaborations under high task interdependence would constrain users' working process and may lead to conflicts due to the strong dependence on each other.

5.4 Task interdependence correlates positively with task performance

Regarding to task performance, task interdependence showed a negative correlation with manipulation time and a positive correlation with the score, supporting H4. This means that users can manipulate more efficiently in high interdependence conditions. We observed that a high task interdependence saved users' time in correcting errors. When a user realised a wrong cube was transmitted for manipulation, they can quickly describe the look of the correct cube to their collaborator and get it without any movement. However, in the case of mirrored (low) interdependence with no communication or not using the transmission tool, they had to travel to find the right cube and then went back to the manipulation area, which led to a decreased task performance.

5.5 Limitations and implications for future work

Our study has some limitations that need to be addressed and explored in future works. First, our work mainly contributes to understanding the use of PC and VR, but not other interactive devices like tablets or augmented reality. They are also important parts of interactive systems and should be explored in future work. Second, we use direct manipulation in VR and three-axis manipulation based on key controls in PC. This is, in some sense, not a fair comparison. However, considering the most commonly adopted 3D interaction approach used in PC and VR, they are the most representative ones. The understanding is needed when adopting the two types of devices in the design of collaborative tasks in the future. Third, we set a relatively strict target offset in manipulation tasks (10%), as we are motivated by the need for precise control in asymmetric VR interaction and collaboration. It is expected that users' task performance may differ if the offset is made more lenient. Future work can explore appropriate offsets for different application areas. Fourth, we would like to point out that the GEQ was measured using a 7-point Likert scale in this work, but not the original 5-point Likert scale. This adjustment was made to ensure a consistent scale measurement in our study. While this affects the comparability of our study with others' work, previous research has demonstrated ways to transform the scale (https://www.ibm.com/support/pages/transforming-different-likert-scales-common-scale) to facilitate a valid comparison. Finally, our sample has some limitations. Participants' age groups lack diversity and about half of them were frequent VR users. This led to the limited coverage of participant demographics. Thus, our findings should be generalised with caution.

The findings of this study have several implications for the design and development of collaborative systems.

– For collaborative systems using either PC or VR, asymmetric collaboration is a viable alternative for tasks involving object selection and manipulation. Users preferred the asymmetric mode that exhibited higher levels of closeness of relationship, social presence, task performance, and task interdependence. It also reduced the probability of simulator sickness than the VR-VR symmetric mode and resulted a good user experience and task performance.
– Tasks in asymmetric collaborative systems should be designed with a consideration of the device features. For example, object manipulation tasks are well-suited and preferred to be conducted in VR. For tasks that exhibited comparable performance and user preferences (e.g., object selection), the systems should support allocation of these tasks among devices and users.
– As an important indicator of user experience and task performance, task interdependence should be carefully designed in asymmetric collaborations. Closely-coupled tasks encourage user communication and could potentially improve their closeness of relationships, empathy, behavioural engagement, and task performance. However, this could also lead to negative feelings such as jealousy. Compared to forming a high interdependence by limiting user abilities, the task interdependence spontaneously formed by users based on their device characteristics and own preferences will allow for more adaptive collaborative behaviours.

6 Conclusion

In this study, we present a comparative analysis that explores the distinctions among collaborative modes (PP, PV, and VV) and devices (PC and VR) in a series of 3D object selection and manipulation tasks. The motivation for this work stems from identifying differences between symmetric (PP and VV) and asymmetric (PV) collaborative systems in 3D object selection and manipulation tasks, offering insights for the future design of such collaborative tasks. Through our empirical evaluation, we observed significantly different user experiences and task performances among users employing collaborative modes, devices, and task complexities. Specifically, the asymmetric mode (PV) exhibited higher levels of closeness of relationship, social presence, task performance, and task interdependence. The asymmetric mode also reduces the probability of simulator sickness than VR collaborative mode (VV) while ensuring a good user experience and task performance. There is no noticeable difference in workload among the three collaborative modes. Regarding the features of PC and VR, we found that the direction control of VR excels in manipulation, but it is prone to causing simulator sickness; PC is effective in selection tasks while the manipulation of objects proved to be complex. Additionally, we found task interdependence showed a positive correlations with user experience and task performance. Based on these findings, we provided several design recommendations for device selection and system design in collaborative system development. Our results and the recommendations derived from the user study can assist researchers and designers in developing future collaborative systems related to 3D object selection and manipulation, especially in asymmetric collaboration systems involving PC and VR.

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Author contributions S.Z. implemented the system, conducted the experiment, and wrote the main manuscript text. Y.L. conceived the idea, supervised the study design, reviewed the data analysis, and revised the manuscript. All authors reviewed the study design and the manuscript.

Data availability Anonymized data will be made available upon request.

Declarations

Competing interests The authors declare no competing interests.

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