# Mixed Interaction: Evaluating User Interactions for Object Manipulations in Virtual Space

**Abstract**

This paper presents an evaluation of a potential new interaction mode in virtual reality (VR) to determine whether it provides any positive impact in terms of how users interact with content. We evaluated the user experiences for 3D object manipulation across three modes of interaction. Interaction using controllers and gestures are used as baselines from which to gauge the potential value of the new mode of interaction, where a single controller and gestures are combined. This paper reports on a user study that captures quantitative and qualitative data related to a variety of object manipulation tasks in a Virtual Environment (VE). We investigated the impact of this new interaction mode with 40 participants across a number of interaction tasks, with the quantitative evaluation indicating that generally, the mixed mode of interaction resulted in task completion times consistently faster than gesture-based interaction and, in some cases, faster than with the use of controllers alone. A qualitative evaluation of the user experience indicated potential application areas for the new mode of interaction.

**Keywords:** Virtual Reality, Object Manipulation, Human-Computer Interaction, User Experience, Multi-Modality, User Interfaces.

## 1 Introduction

The rapid growth of virtual reality (VR) technologies has resulted in a similarly rapid increase in the capabilities and features of virtual environments (VE). Such VEs now support a wide range of different body movement tracking and modes of interaction with virtual elements. A number of interaction task studies have started to explore the efficacy of different modes of interaction. However, there are relatively few studies of interaction tasks that focus on virtual 3D object manipulation comparing different interaction modes. Therefore, this study aims to explore how people tend to perform 3D object manipulation in a VE when there are options of a direct interaction using a Leap Motion gesture-based device, an indirect interaction using a hand-held controller, and a mix of direct and indirect interactions in manipulating 3D objects.

In this paper, we present the results of evaluating a mixed interaction mode that can be used in a variety of VR applications. We conducted a user study to compare the established interaction modes using controllers and gestures with the new mixed interaction mode, where the user tasks involved solving a number of different puzzles in VR. There are three different puzzles in the user study, the first one uses a sliding puzzle, the second one uses a wood block tower puzzle, and the third uses an interlocking puzzle. A comprehensive analysis evaluates each interaction task with a mixed-methods approach. We collected quantitative data such as time measurements and task completions from the user interaction tasks and qualitative data from the user experience to evaluate the user preferences.

An important factor considered in this study is the handedness of the participants. Handedness, or the preference for using one hand over the other, can significantly influence the performance of participants in different interaction modes. Therefore, we hypothesise that participants may prefer to use their dominant hand for tasks requiring precision and control. This hypothesis will be tested in our study, providing insights for designing efficient VR interaction systems.

# 2 Background and Related Work

## 2.1 Interaction in VR

Gerhard and Norton (2022) stated that "[t]he emergence of VR as a medium presents new, unique ways of interacting with computers. Being able to digitally generate and display content that a user's mind may interpret as a three-dimensional space introduces new ways to create and improve the way we interact" (p. 5). VR as a medium is an exciting new development in digital interaction, and it opens up several possibilities for how we interact with computers and how designers create content (Murray, 2011). The most apparent advantage of VR is that it allows users to interact with the digital world in a way that more closely resembles real-life interactions (Moustafa & Steed, 2018). VR users can move around in virtual spaces, reach out and touch objects, and experience them much more immersive than traditional screens (Jones, 2017). Nevertheless, VR HCI and human factor engineering researchers have struggled with questions about which interaction technique works best for navigation and manipulation tasks (D. Bowman et al., 2008).

### Direct and Indirect Interaction

Direct and indirect interactions are different interaction styles in a virtual environment. Indirect interaction requires users to wait for a response or to interpret a result between input and output while interacting with an object (Jerald, 2016). In contrast, direct interaction allows users to directly manipulate an object using physical gestures (Jang, Vitale, Jyung, & Black, 2017). For example, a direct interaction occurs when the user picks up an object by holding it in their hands, whereas an indirect interaction occurs when the user picks up an object by pressing a button on a controller. An indirect interaction requires the user to think more deeply about interacting with the system and how their actions will affect it (Seinfeld, Feuchtner, Maselli, & Müller, 2021). Furthermore, indirect interaction also requires the users to be more aware of their environment and the context of the interaction in order to interpret the output and make the correct input accurately (Jerald, 2016).

Some researchers focused on direct manipulation to review each interaction mode's interaction task performance and degree of immersion. McMahan, Gorton, Gresock, McConnell, and Bowman (2006) compared three interaction techniques with different levels of immersion settings. Their results show that the 3D interaction techniques had more impact on object manipulation than the levels of immersion. Jang et al. (2017) investigated the impact of direct manipulation in anatomy learning. Their results suggest that direct manipulation facilitated embodiment in anatomy learning, allowing participants to maintain an apparent reference during interactions. Caputo and Giachetti (2015) used a Leap Motion controller to evaluate four hand gesture modes for manipulating 3D objects in VR.

Yang (2019) mentioned that, ideally, humans could use the most natural human senses to perceive sensory information and manipulate the contents in a virtual environment. On the other hand, LaValle (2020) explained that there are a variety of objects, including different sizes, weights, and flexibility in the real world. The wide variety of object settings makes manipulating virtual objects more challenging when applying the sensorimotor relationship from the real world to the virtual environment. However, most of the studies are mainly focused on gesture-based interaction modes. It is thus necessary to evaluate the impacts of controllers, which are currently the most popular input devices in the VR industry when it comes to similar interaction tasks, to facilitate ongoing development.

According to Marriott et al. (2018), no single input method is suitable and perfect for all tasks, as mentioned in the existing works reviewed in the previous section. New inter-action techniques must be designed and provide guidance based on empirical evidence. Finding a suitable interaction mode for particular tasks is not easy in VR development today (Li, Huang, Tian, Wang, & Dai, 2019). Although existing studies have shown an extensive evaluation of menu designs (Jeong, Jung, & Im, 2016; Kwon, Kim, & Nam, 2017; Santos, Zarraonandia, Díaz, & Aedo, 2017), there are limited evaluations focused on different modes of interaction.

## Multimodality

VR is a medium that aims to simulate the sensations humans experience and interact with the physical world (Gerhard & Norton, 2022). However, several studies have shown that performing different interaction tasks in a large virtual space over extended periods may cause fatigue (Iskander, Hossny, & Nahavandi, 2018; LaViola, 2000; Wang et al., 2019). Therefore, there is space to explore new knowledge that ideally works with different interaction modes and integrates with the VR multimodality system.

Multimodal interaction is an advanced technique involving multiple input modalities (Mohamad Yahya Fekri & Ajune Wanis, 2019). It enables users to interact more naturally and efficiently by combining various sensing methods such as visual, audio, haptics, speech, and gestures (Burdea, Richard, & Coiffet, 1996; Li, Wu, et al., 2019). By utilising these multiple modalities, users can have a more seamless and intuitive experience when interacting with the computer (Suarez Fernandez et al., 2016). Multimodality can alter how users perceive the virtual world around them and manipulate their experience to reduce physical movements and simulation sickness (Martin, Malpica, Gutierrez, Masia, & Serrano, 2022). Researchers suggest that the main issue may be related to the integration between VR and HCI (Olmedo, Escudero, & Cardeñoso, 2015).

Appropriate design choices will majorly impact the usability results (Bossavit, Marzo, Ardaiz, De Cerio, & Pina, 2014). In order to make sure the design choices are appropriate, usability testing should be applied throughout the design process. Usability testing can be used to evaluate the ease of use, effectiveness, and satisfaction of the design (D.A. Bowman, Gabbard, & Hix, 2002; Ramaseri Chandra, El Jamiy, & Reza, 2019).

Generally, designers should follow established design principles within their area of expertise (Lidwell, Holden, & Butler, 2003). However, as no specifications suggest integrating VR multimodality systems, the challenges of VR multimodal interactions remain unsolved. VR can potentially investigate the synergy between different modalities in real-world scenarios, providing a more thorough understanding of communication than studies focusing solely on a single modality. Despite each modality's advantages and drawbacks, it is possible to explore whether mixed interactions can address these issues or supplement individual modalities. Moreover, further research is needed to understand better the extent to which different modalities should be incorporated into a unified VR system.

## 2.2 Modes of Interaction in VR

The modes of interaction in VR and design techniques are closely related to the field of HCI (Sutcliffe et al., 2019). HCI is an essential field of study that examines how people interact with technology, such as computers and VR. It involves the design, evaluation, and development of interactive systems and the creation of user interfaces. The role of HCI in VR helps to minimise user cognitive effort and to focus on the user tasks in a 3D virtual environment (Araújo et al., 2016) with a variety of interactive modes and research examples such as follow:

### Handheld Controller

A tracked handheld controller with buttons and switches is an ideal way to provide users with a more immersive experience in VR (Choi, Ofek, Benko, Sinclair, & Holz, 2018). Physical controls and haptic feedback can enhance the sense of presence by visually co-locating the controller in a virtual space with the user (Spanlang et al., 2014).

### Gesture Interaction

Gesture interaction provides a natural interactive experience in the VR experience by capturing users' movements through sensors (Li, Huang, et al., 2019). Some research described that the use of the hand is more common in communication than other parts of the human body (Li, Huang, et al., 2019), as most users express their feelings and thoughts through hand gestures (Murthy & Jadon, 2009). Furthermore, when compared to traditional interaction methods such as using controllers alone, gesture interaction is perceived to be much more natural and intuitive, closely mirroring human expression (Cabral, Morimoto, & Zuffo, 2005; Li, Huang, et al., 2019; Sudha, Sriraghav, Abisheck, Jacob, & Manisha, 2017). Users can use hand gestures to interact with objects in the virtual environment, and this can create a more immersive and engaging experience in the VR environment.

### Haptic Glove

The haptic glove works by using a combination of sensors and actuators to detect pressure, movement, temperature and other data. The collected data is then transferred to a computer and translated into haptic feedback, such as a vibration or pressure sensation (Foottit, Brown, Marks, & Connor, 2016; Pamungkas & Ward, 2016). Haptic gloves bring a sense of touch through haptic feedback, where the hand can perceive details through vibrations of varying frequencies (Perret & Vander Poorten, 2018).

### Eye-gaze Interaction

Real-time eye tracking, now incorporated into devices like the HTC Vive Eye or the Meta Quest Pro, enables users to navigate user interfaces through eye movements (Piumsomboon, Lee, Lindeman, & Billinghurst, 2017). This technology not only provides insights into user behaviour and preferences for improved user experience but also serves as an alternate input for VR, offering a more intuitive and engaging user experience (Hansberger et al., 2019).

### Speech Interaction

Speech recognition allows users to communicate with computers. Speech is beneficial when the users are busy coordinating with their hands, feet, and eyes (Jacob, Leggett, Myers, & Pausch, 1993). It can control devices, give commands, or search for information. Using speech recognition, users can interact with computers more naturally, as it can control devices and give commands more effectively than typing (O'Shaughnessy, 2003; Schalkwyk et al., 2010).

In VR, interaction modes can be combined using principles like equivalence, complementarity, and redundancy. Equivalence uses modalities with the same expressive power. Complementarity enhances functionality by using different modalities together. Redundancy employs multiple similar modalities concurrently for a consistent user experience(Costa & Duarte, 2011). By using these principles to combine modalities in VR, we could potentially enhance both the immersive quality and user engagement.

## 2.3 The Case for Mixed Interaction

This study focuses on user interactions for object manipulation by indirectly manipulating 3D objects with a controller or manipulating 3D objects with Leap Motion. Based on the existing literature, a controller can provide tactile or vibrational feedback when the user interacts with an object or presses a button. However, using a controller for extended periods can cause arm fatigue and discomfort due to its size and weight (Chang, Kim, & Yoo, 2020; Iqbal, Latif, Yan, Yu, & Shi, 2021). Additionally, the controller can strain the user's hands and wrists over time. Gesture interaction is a more natural form for users, allowing them to use hand gestures to interact with objects in the virtual environment (Li, Huang, et al., 2019). However, studies have indicated that time performance is slower when using gesture interaction than other interaction types.

In this research, mixed interaction refers to using direct and indirect interaction simultaneously in the same virtual environment. It allows users to interact with the virtual environment using a mix of interaction modes such as a controller and gesture interactions. Mixed interaction combines the advantages of both direct and indirect interaction, allowing users to use their natural movements and gestures while also using a controller to achieve precise and accurate control. Only one research was found on mixed interaction lately. Wagner, Stuerzlinger, and Nedel (2021) attempted to evaluate interaction modes for data manipulation study using virtual hand interaction with grabbing and stretching action and virtual ray pointer with actions assigned to controller buttons and mixed. The results from 15 participants show that mixed interaction did not significantly increase workload or decrease system usability or task ease. Nevertheless, 60% of the participants prefer using mixed mode for different low-level tasks over the other two modes, and 40% of participants explained that mixed mode is confusing. The researchers suggested that designers can decide on interaction modes that favour a specific task, and they believe integrating different modes of interaction is necessary for data manipulation in the future to overcome the limitations of specific interaction modes.

Therefore, the effectiveness of mixed interaction should be evaluated and compared with other user interface designs and modes of interaction. These studies should also focus on understanding the complexity and difficulty of the tasks in order to investigate the effects of mixed interaction. Furthermore, the impact of mixed interaction on user engagement and satisfaction should be further examined. It is still necessary to conduct further research to determine the best combination of interaction modes for different VR interaction tasks. The results of this research can be used to provide insights for future research in the area of mixed interaction for VR.

# 3 Method

This study uses mixed methods to explore the connections between user performances and behaviours. When combined with mixed methods, the results can produce multi-aspect outcomes with the scientific ground, allowing researchers to integrate qualitative and quantitative data within one study (Ivankova & Wingo, 2018).

Structured observations provide a more reliable and valid method of measuring behaviour than other methods, such as self-reports (Martinko & Gardner, 2019). Data triangulation is a method of analysing large amounts of data to identify patterns or trends to answer a specific research question (Wilson, 2014). In this study, recordings of an individual's task performance can best be achieved through triangulation (Polit & Beck, 2017). This study involves collecting data from a number of interactive tasks relating to different types of puzzle to understand the user interaction process. This data was collected through task completion, observation, and talk-aloud verbal data. Combining these data is a triangulation process that gives a more detailed understanding of user interaction.

### 3.1 Study Design

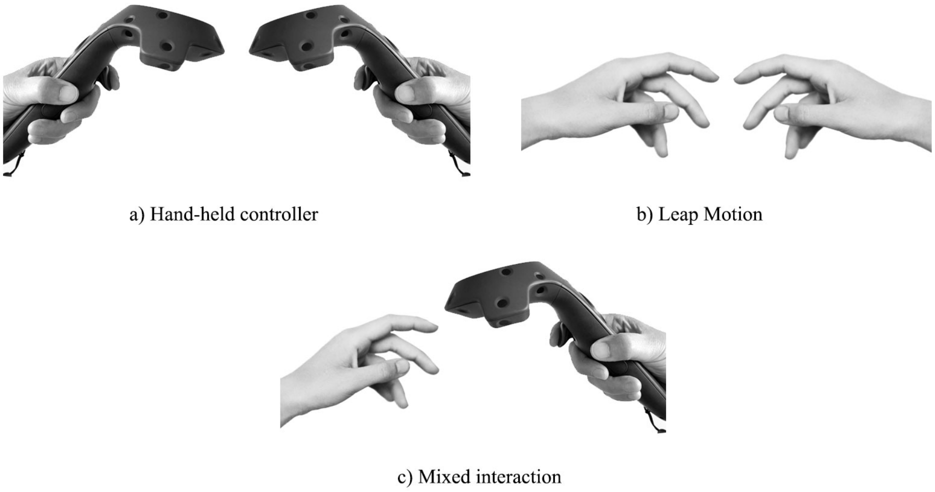
This study compares three interaction modes: indirect, direct, and a mix of both (mixed). The interaction mechanism of each interaction mode is different. Figure 1 describes the mechanism to select and grasp an object in different modes:

a) Indirect mode, participants use a controller in each hand and pull the trigger button to select and grasp an object. to the desired location. This can also be done with one hand or both hands;

b) Direct mode, participants use both hands freely in front of the Leap Motion sensor to select and grasp an object via pinch gestures. They can use one hand or both hands, depending on the complexity of the task and their personal preference;

c) Mixed mode, participants use one controller with its push button and one hand freely with gestures to perform those actions.

In the mixed interaction mode, the choice of which hand gets the controller is determined by the participant's preference. Before starting the mixed interaction, participants were asked which hand they preferred to use the controller with. This approach ensures that the interaction mode is tailored to each participant's comfort and ease of use, thereby enhancing the overall user experience.


a) Hand-held controller

b) Leap Motion

c) Mixed interaction

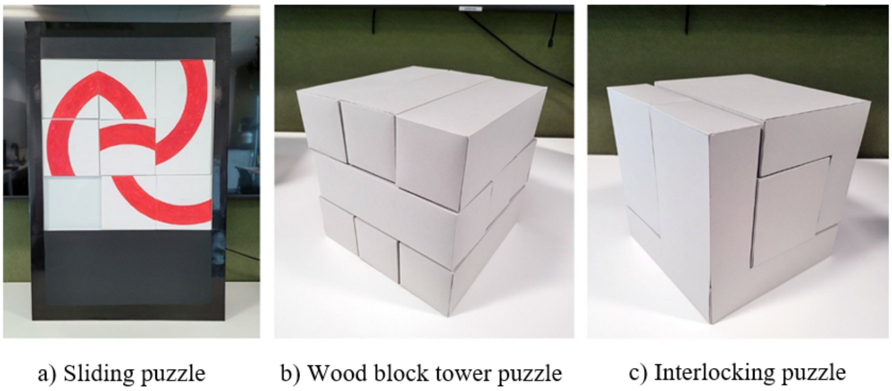
**Fig. 1** The Interaction Mechanisms

The puzzles that are the basis of the interaction tasks were built using the Unity3D game engine with SteamVR Plugin and Ultraleap Unity Plugin. The applications are displayed in an HTC Vive headset with controllers and tracked with Vive base stations V2.0. The concept of mixed interaction is based on having a controller and a Leap Motion within an application.

Participants were invited to solve three physical puzzles before using the VR applications. The aim of comparing three physical puzzles to a VR puzzle was to understand how long it took to complete each task. In order to ensure that the task completion time would only be impacted by the interaction mode and not by the puzzle itself, all participants were asked to construct the physical puzzles before attempting the VR puzzle.

### 3.1.1 Physical Puzzles Setup

Three physical puzzles were produced that are precisely the exact sizes as in the virtual environment. In Figure 2, a) The sliding puzzle, b) The wood block tower puzzle, and c) The interlocking puzzle. These puzzles were used to allow participants to become familiar with the interaction tasks prior to attempting them in the virtual environment as a means of reducing the cognitive load on the participant and therefore allowing task completion times to be representative of the mode of interaction used and not impacted by the need to learn the task.



a) Sliding puzzle b) Wood block tower puzzle c) Interlocking puzzle

**Fig. 2** Physical Puzzles

### 3.1.2 VR Setup

An HTC Vive headset with a Leap Motion mounted on top was given to each of the participants in the user study, and they were asked to stand in the middle of the room during the user study. The participants were located in a virtual environment with three different puzzles on the tables in a 3m x 3m room surrounded by walls (See Figure 3).

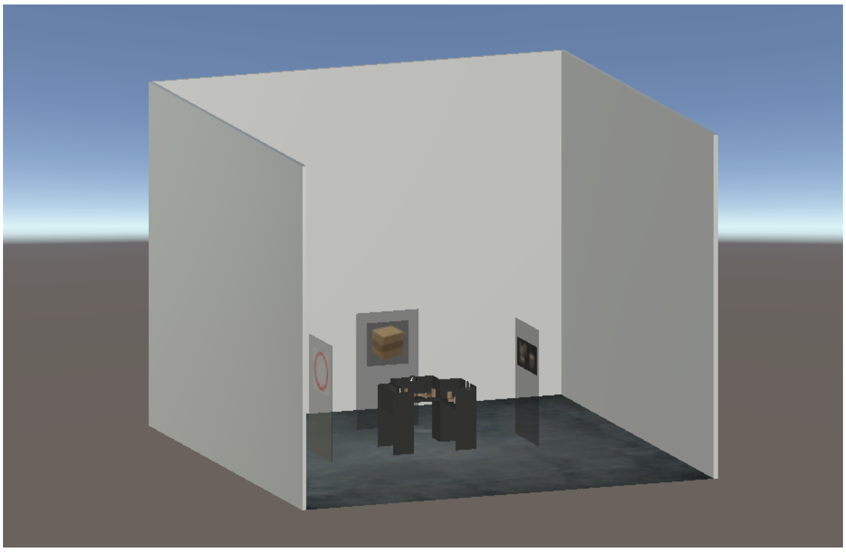


**Fig. 3** Room Setup in Unity3D

The participants were asked to complete the puzzles that focused on three basic object manipulations: grasp, hold, and move the wood blocks to match the poster with hints in front of the participants as closely as possible, as seen in Figure 4.

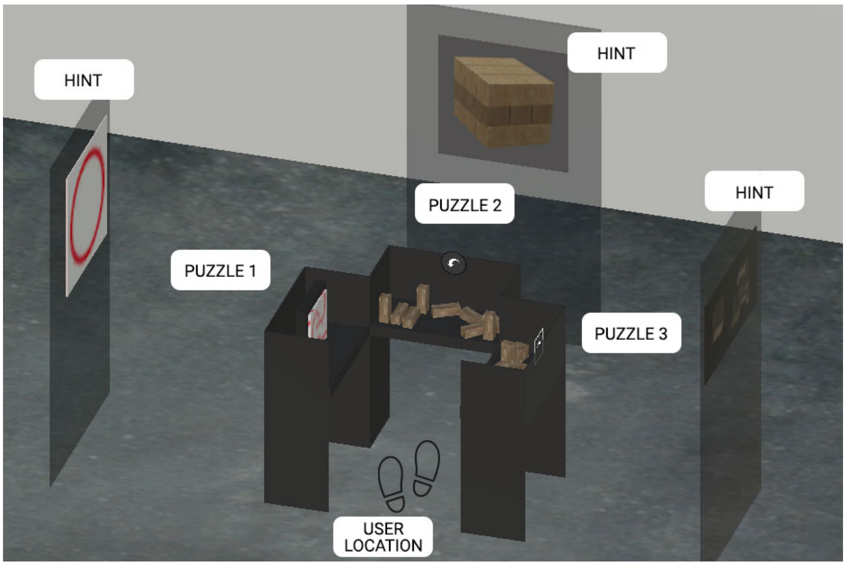


**Fig. 4** Posters in front of each Puzzle

### 3.1.3 Task Design

The order of presentation of the three puzzles and the interaction modes was designed to gradually increase the complexity of the tasks. Participants started with the simplest puzzle and interaction mode and progressed to more complex ones. This was done to allow participants to gradually acclimate to the VR environment and the interaction tasks. The participants began by using a controller to finish the three puzzles, then used a Leap Motion to complete the same puzzles and finally used a mix of both interaction modes to complete the three puzzles.

1. Puzzle 1 (Sliding Puzzle, see Figure 5): For this puzzle, the participants were required to slide each puzzle piece until the picture of a circle was formed.

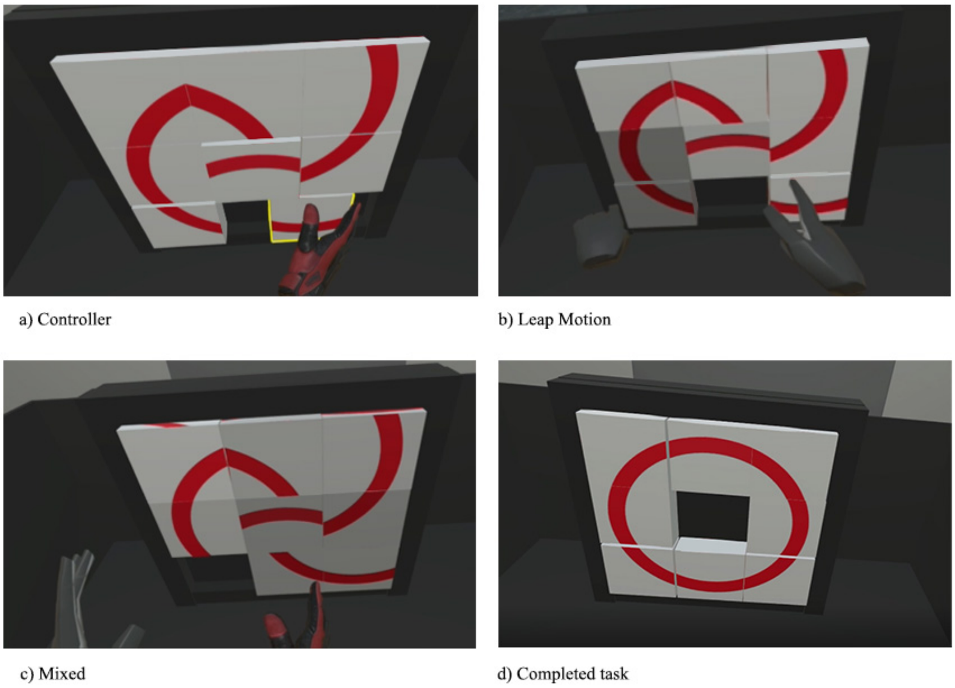


**Fig. 5** Puzzle 1 with Different Interaction Modes: a) Gloved hand for controller mode. b) Low polygon hand for Leap Motion mode. c) Combination of both for mixed mode. d) A circle is formed.

2. Puzzle 2 (Wood Block Tower, see Figure 6): For this puzzle, the participants were required to stack up each wood block until it formed a tower. This involves careful placement of each block on top of the other, maintaining balance and stability. The button on the top allows participants to reset the puzzle when they accidentally drop a wood block out of a reachable area in the room, for example, behind the table or wall.

a) Controller

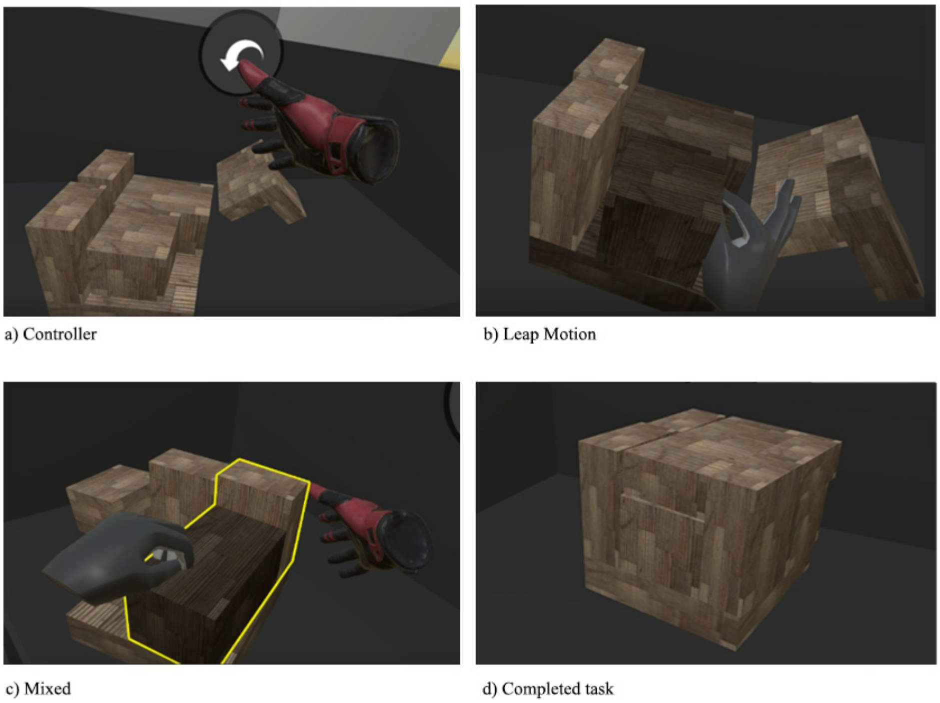
b) Leap Motion

c) Mixed

d) Completed task

**Fig. 6** Puzzle 2 with Different Interaction Modes: a) Gloved hand for controller mode. b) Low polygon hand for Leap Motion mode. c) Combination of both for mixed mode. d) A wood block tower is formed.

3. Puzzle 3 (Interlocking Puzzle, see Figure 7): For this puzzle, the participants were required to manipulate each wood block until it formed a cube. This involves not just stacking, but also aligning and interlocking the blocks in a way that they fit together to form a three-dimensional cube. The button on the top allows participants to reset the puzzle in case they accidentally drop a wood block.


a) Controller

b) Leap Motion

c) Mixed

d) Completed task

**Fig. 7** Puzzle 3 with Different Interaction Modes: a) Gloved hand for controller mode. b) Low polygon hand for Leap Motion mode. c) Combination of both for mixed mode. d) A cube is formed.

### 3.1.4 Participants

40 participants were randomly recruited through email and posters. We did not specify age during recruitment. The study required participants to attend a 30-minute session. There were 20 participants with previous VR experience and 20 without VR experience. Only 1 participant had prior Leap Motion experience. The experiment took place in a study room on campus, and the participants were asked to complete several universal interaction tasks in VR. There were three VR applications in the user study, and the manipulation tasks centred around the use of hold, grasp, rotate, and move actions. The participants were asked to manipulate the objects across three applications with 1) a hand-held controller, 2) a Leap Motion controller 3) Mixed controllers.

Quantitative data were collected from screen recording of task completion time, and qualitative data were collected from observation. Quantitative and qualitative data are analysed statistically, and data from the structured observation and talk-aloud protocol provide insights for prototype development in the future. The study design did not include counterbalancing. This means that the experience gained from earlier tasks could influence the performance in later tasks. This is another limitation of the study design and was also factored into the data analysis. Future research could benefit from implementing counterbalancing to reduce such effects.

# 4 Results

## 4.1 Participant Use of Hand(s) Measures

The user study recorded how participants used their hands across different VR applications. The data, presented in Table 1, shows the percentage of participants who used both hands approach in each interaction mode for each puzzle.

For Puzzle 1, 68% of participants used both hands in the physical puzzle. When using a controller and Leap Motion, the percentages dropped to 60% and 55% respectively. However, in the mixed mode, 78% of participants used both hands, the highest among all four modes.

In Puzzle 2, all participants used both hands in the physical puzzle, similar to the mixed mode where 93% of participants used both hands.

For Puzzle 3, 98% of participants used both hands in the physical puzzle. The mixed mode also saw a high percentage of both hands use at 78%, more than the other two interaction modes.

Overall, the use of both hands was most common in the physical puzzles across all modes, with the controller and Leap Motion modes seeing slightly lower usage.

**Table 1** Use of Hand(s) Analysis

| | Physical | Controller | Leap Motion | Mixed |
|---|---|---|---|---|
| Puzzle 1 | 1 hand: 32% | 1 hand: 40% | 1 hand: 45% | 1 hand: 22% |
| | 2 hand: 68% | 2 hand: 60% | 2 hand: 55% | 2 hand: 78% |
| Puzzle 2 | 1 hand: 0% | 1 hand: 25% | 1 hand: 20% | 1 hand: 7% |
| | 2 hand: 100% | 2 hand: 75% | 2 hand: 80% | 2 hand: 93% |
| Puzzle 3 | 1 hand: 2% | 1 hand: 30% | 1 hand: 27% | 1 hand: 22% |
| | 2 hand: 98% | 2 hand: 70% | 2 hand: 73% | 2 hand: 78% |

### Task Completion and Performance

Time completion data was measured during the puzzle study. The Shapiro-Wilk test was used to verify the normality of the data. Levene's test was used in the puzzle study to verify the normality of the dataset. The results from the Shapiro-Wilk test indicated that none of the data was normally distributed. The Kruskal-Wallis test was therefore used to test for statistical significance across the three modes of interaction on each task. The Kruskal-Wallis test is a non-parametric test alternative to one-way ANOVA suitable for testing the difference among three or more independent groups on non-normally distributed data (McKight & Najab, 2010). Whilst the Kruskal-Wallis test is intended for continuous data, it is commonly used for analysing ordinal data. In addition, as a non-parametric test, it is more robust to data that is not normally distributed. Dunn's test was applied for nonparametric pairwise multiple comparisons following a Kruskal-Wallis test to see the group difference (Dinno, 2015).

## Puzzle 1

In Puzzle 1 (Figure 8), the range and the interquartile range of mixed mode are the narrowest among the two interaction modes, indicating the participants' performance was more stable during the mixed mode. The mixed mode shows the best median in time completion among the two interaction modes. Moreover, the shortest task completion time (6 seconds) is recorded in the mixed mode in Puzzle 1. In contrast, the longest task completion (90 seconds) and the widest range and interquartile range are noted in controller mode.

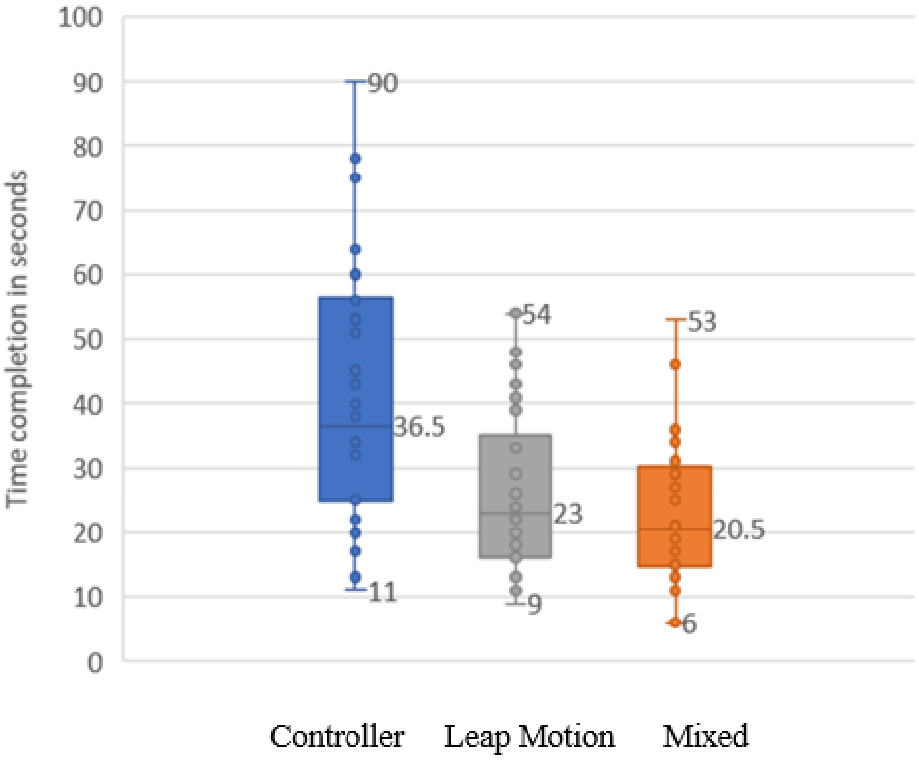


**Fig. 8** Participant Time Completion in Puzzle 1

The Kruskal-Wallis test indicates that a statistically significant difference exists in task completion time for Puzzle 1 ($p < 0.001, \alpha = 0.05$). The controller has a considerably greater median of task completion times; however, the Kruskal-Wallis test results only indicate a difference between the groups, but not where that difference lies.

Dunn's post hoc test was applied to determine where the significant differences lie. The post hoc test indicates no significant difference between the task completion times using the Leap Motion and mixed interaction. However, there are significant differences between the controller and both the Leap Motion and mixed interaction.

## Puzzle 2

The following box and whisker graph in Figure 9 shows the task completion time results in Puzzle 2. The range and the interquartile range of mixed mode are the narrowest among the two interaction modes, indicating the participants' performance was more stable during the mixed mode. Also, the shortest task completion time (23 seconds) is recorded in mixed mode, whereas the longest task completion is recorded in Leap Motion mode (232 seconds). The range and the interquartile range of Leap Motion are broader and higher than the other modes, which means the task performance varied among the participants during the user study.

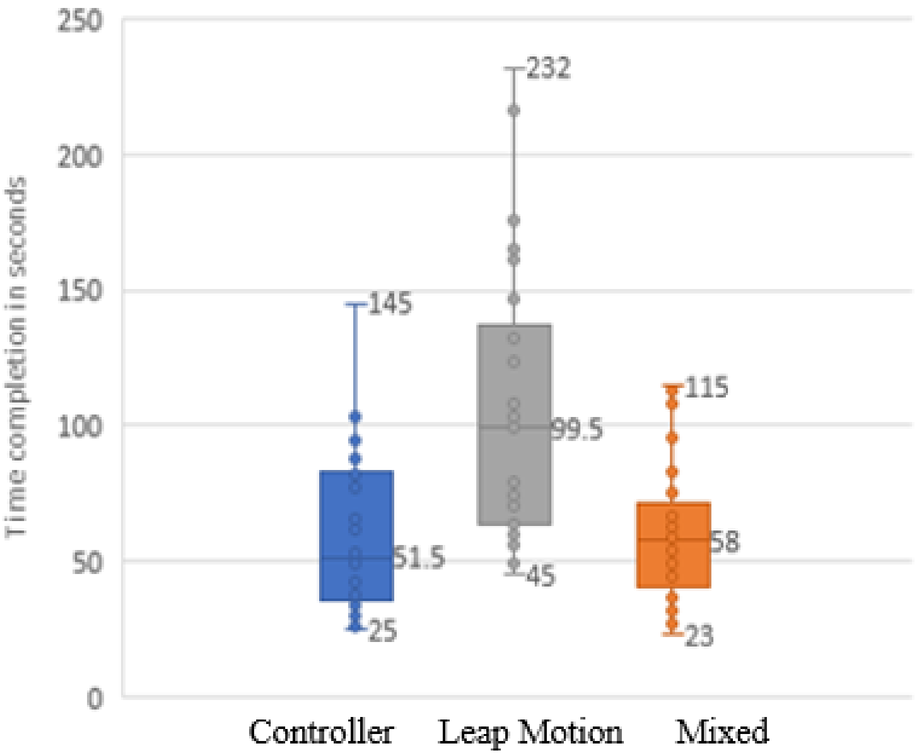


**Fig. 9** Participant Time Completion in Puzzle 2

The Kruskal-Wallis test indicates a statistically significant difference in task completion time for Puzzle 2 ($p < 0.001, \alpha = 0.5$). The median task completion time of the Leap Motion is very much slower, whereas the others are comparable for Puzzle 2.

The application of Dunn's post hoc test indicates no significant difference between the task completion times using the controller and mixed interaction. However, there are significant differences between the Leap Motion and both the controller and mixed interaction.

### Puzzle 3

In Figure 10, the range and the interquartile range of mixed-mode are the narrowest and faster than the two interaction modes, indicating the participants' performance was more stable during the mixed mode. The interquartile range of the controller is wider than the other modes, and the task performance is not as stable as the other modes during the user study. However, the shortest task completion time (6 seconds) is recorded in controller mode, and the longest task completion is also recorded in controller mode (91 seconds).

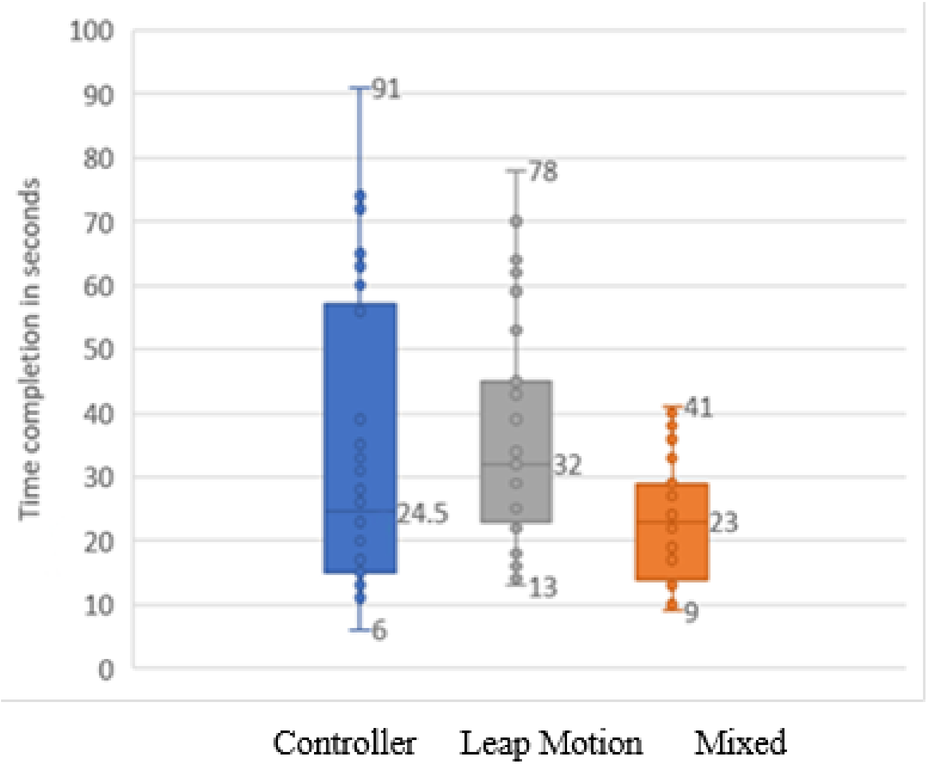


**Fig. 10** Participant Time Completion in Puzzle 3

The Kruskal-Wallis test indicates a statistically significant difference in task completion times for Puzzle 3 ($p = 0.019, \alpha = 0.05$). Mixed interaction's median task completion time is faster than the controller and Leap Motion for Puzzle 3. Dunn's post hoc test was used to determine where the significant differences lie. The post hoc test indicates no significant differences in task completion times between the controller and both the Leap Motion and mixed interaction. However, there is a significant difference between the Leap Motion and mixed interaction.

## 4.2 Structured Observation Summary

Structured observation allows the researcher to take notes while the participants share their comments and feelings during the user study. Information needs are created from an individual's performance, emotions and cognitive needs (Taherdoost, 2019). The purpose of structured observation is to capture some actions and activities which are hard to communicate verbally (Schalkwyk et al., 2010). A list of target reactions created by the observer included "Frustrated", "Confident", "Interested", "Uncertain", "Determined", "Engaged", "Vexed", "Excited", "Annoyed" and "Infuriated". The reactions from the participants were recorded on observation form by the observer during the user study. The total numbers of each reaction are summarised in Table 2. During the user study, 18 participants showed their interest in Leap Motion. A total number of 27 participants are more confident when using a mixed (14 participants, 35%) controller (13 participants, 32%) than Leap Motion (5 participants, 12%). Participants were generally more engaged when using a controller and mixed than Leap Motion.

**Table 2** Observation Summary

| | Controller | Leap Motion | Mixed | | | |
|---|---|---|---|---|---|---|
| | Numbers of participants | % | Numbers of participants | % | Numbers of participants | % |
| Frustrated | 4 | 10% | 4 | 10% | 4 | 10% |
| Confident | 13 | 32% | 5 | 12% | 14 | 35% |
| Interested | 10 | 25% | 18 | 45% | 5 | 12% |
| Uncertain | 1 | 2% | 2 | 5% | 3 | 7% |
| Determined | 1 | 2% | 1 | 2% | 4 | 10% |
| Engaged | 7 | 18% | 3 | 8% | 7 | 17% |
| Vexed | 3 | 8% | 2 | 5% | 1 | 3% |
| Excited | 1 | 3% | 2 | 5% | 1 | 3% |
| Annoyed | 0 | 0% | 1 | 3% | 0 | 0% |
| Infuriated | 0 | 0% | 2 | 5% | 1 | 3% |

## 4.3 Talk-aloud Verbal Summary

The purpose of notetaking through observations is to capture participants' comments to remind the observer about the activities, and the field notes require accuracy and no bias (Yang, 2019). Some verbal data in Table 3 suggested some helpful ideas for further development. It is worth paying attention when the participants revealed the advantages and disadvantages of a controller and a Leap Motion during the mixed interaction mode. For example, User 3 expressed that some movements performed better with a controller, but some are better with a Leap Motion. Similarly, Users 13 and 14 also stated it is easier to grasp and place an object with a controller but quicker and easier to rotate objects with a Leap Motion. While some participants were concerned with the importance of having a physical controller during the interactions, for example, User 8 felt unusual with Leap Motion when there was no physical object to touch during the tasks. Whereas User 17 felt that the controller was too heavy to perform the tasks, and User 30 felt that the controller was too tiring to use compared to a Leap Motion. Furthermore, some interesting comments on mixed interaction mode gave insights into developing the prototype for the next study. User 24 expressed that the mixed interaction is intuitive, and User 27 expressed that it is interesting but requires more practice. Moreover, User 23 suggested that mixed interaction can potentially be used in shooting games, in which the user can hold a gun using a controller and load the ammo using Leap Motion.

**Table 3** Verbal Data from the Puzzle Study

| User ID | Comments |
|---|---|
| 3 | ”Controller is better in some movements, but some are better with my own hands.” |
| 7 | “I found that a bit easier to have controller in my dominant hand.” |
| 8 | “It’s kinda weird of not having anything that you can physically touching (Leap Motion)” |
| 13 | ”Use controller to grasp, use Leap Motion to rotate is quicker.”<br>”Move object over to another hand with your own hand is easier with leap” |
| 14 | ”Use controller to grasp, use Leap Motion to rotate is quicker.” |
| 17 | “With the controller, it always feels heavier.” |
| 19 | “The Leap is easier in puzzle 1, but harder in puzzle 3.” |
| 23 | “Come back with thoughts in mixed interaction, I can see the potential in shooting games, I like shooting games, will be nice to use the controller,like holding a gun with the controller because you need some weight and feel like holding a real gun but load the gun with the Leap” |
| 24 | “Mixed interaction is very intuitive.” |
| 27 | ”Need practice in mixed interaction, it’s interesting” |
| 30 | “The controller is so cool, but I’m tired”<br>“Leap Motion is so cool, and I quickly did it.” |
| 34 | “It’s hard to slide with a controller.” |
| 37 | “Able to decide which interaction mode to use in the three puzzles, e.g., Leap to slide, mixed for the tower, controller for interlocking puzzle” |

# 5 Discussion

The objective of the puzzle study is to understand the strengths and weaknesses of a controller, Leap Motion, and mixed interaction modes by collecting qualitative and quantitative data from the user study. This preliminary analysis provides initial insights into user performance and user experience in VR interaction developments. However, it’s important to acknowledge that other analysis methods might yield more comprehensive insights and should be considered for future studies. Overall, the findings from this study helped understand the user experience of mixed interaction compared to direct and indirect interaction. This underscores the need for further research to fully explore the potential of mixed interaction modes in VR.

### Participant Use of Hand(s) Measures

The findings of the puzzle study support conclusions derived from other studies on this topic. The findings of this study indicate that using two hands to complete the physical and VR puzzles is the preferred method for task completion time. These results align with previous research conducted by Drogemuller et al. (2020), where the study of one-handed and two-handed VR navigation revealed that the two-handed approach was more efficient and faster. Moreover, the use of hand(s) measures in this study also indicates that the percentage of using both hands during the mixed modes is greater than the controller and Leap motion modes. This result is consistent with the findings of Olmedo et al. (2015), who found that the main issue with VR and HCI integration may be related to the efficiency of the integration. In HCI, the relationships between users and computers are shaped through interfaces, allowing users to express themselves effectively through different media or tools (Rantamaa et al., 2022). The study results highlight the potential of mixed interaction to improve user experience in VR applications. According to Glonek and Pietruszka (2012), a mixed-reality interface seeks to unify the physical and digital realities by creating seamless transitions between them and allowing the co-existence and interaction of real and virtual objects and environments in real-time. The results of the studies discussed herein support the multimodality notion proposed by Burdea et al. (1996) and Li, Wu, et al. (2019), which suggests that incorporating multiple sensing methods enables users to interact more naturally and efficiently. According to the results, users achieved better performance outcomes when using both hands simultaneously for their tasks than when using only one hand.

The results indicate that the participants feel more comfortable and natural when using both hands in physical and virtual environments. Using both hands also suggests that users are more likely to explore the available tools and options and find the most intuitive solution to the puzzle. It is likely because both hands can offer more control and precision, allowing users to explore all possible combinations of objects or movements (Nanjappan et al., 2018). Furthermore, using both hands can increase the user's sense of engagement with the puzzle, as they can physically and mentally interact with the objects or movements.

### Task Completion and Performance

From the Puzzle Study, the mixed mode shows the best median in time completion among the two interaction modes for Puzzle 1. The results indicate that mixed interaction is better for completing Puzzle 1 quickly than the controller and Leap Motion. However, the median of the controller has better results in Puzzle 2. In Puzzles 1 and 3, the interquartile range of the controller is wider than the other modes, and the task performance is not as stable as the other modes during the user study. The controller mode likely requires the user to interact physically with the system, meaning that the user's performance may vary depending on the individual's physical capabilities and experience level. The controller mode involves more complex physical movements than the other modes, indicating a larger interquartile range. This is supported by studies such as those conducted by Lou, Li, Hansen, and Du (2021), which found a hand-adaptive UI more efficient and less physically demanding. Furthermore, from the talk-aloud verbal summary, User 30 felt that the controller mode was more tiresome than Leap Motion, which could contribute to the more extensive interquartile range observed for this type of interaction. This is in line with the assertion by Jerald (2016, p. 284) that indirect interaction requires more cognitive effort from users, as they need to interpret the output of the interaction before entering the appropriate data to affect the system.

Meanwhile, Kangas, Kumar, Mehtonen, Järnstedt, and Raisamo (2022) and Nanjappan et al. (2018) found that hands-based manipulation of simple objects is advantageous for one-hand manipulations. However, controller-based manipulation was found to be more efficient for two-hand manipulations. The present research's results may have been influenced by the extent to which users relied on one or two hands during the experiment. Therefore, it is essential to consider the balance between control type and hand preference when performing similar studies in the future.

## Structured Observation Discussion

The user study indicated that Leap Motion is less well-received than the controller and mixed interaction modes. It could be due to various reasons, such as the lack of familiarity with the technology and the lack of precision compared to a controller and mixed modes. However, the participants did find some advantages with Leap Motion, such as natural and the ability to use it for more immersive experiences. The results described by Jang et al. (2017) demonstrate that direct manipulation can facilitate embodiment in anatomy learning. Previous studies have shown that hand movements are the most common form of body language when communicating (Lidwell et al., 2003), as gestures and other hand signals are used to express feelings and thoughts (Nanjappan et al., 2018). The participants in the study did not demonstrate a high degree of engagement when using Leap Motion technology, indicating that further research is needed to gain insights into the reasons for this. It could include exploring user preferences and motivations for using different input modes and investigating ways to improve user experience and engagement with Leap Motion. For instance, providing better tutorials or visual cues could help users effectively understand how to use Leap Motion in mixed interaction modes.

## Talk-aloud Verbal Discussion

The results of this study demonstrate that the mixed interaction mode can potentially be a valuable and intuitive way of interacting with digital environments. Participants generally expressed positive attitudes towards the mixed interaction mode, suggesting that it is a viable option to consider when developing digital user interfaces.

The mixed interaction mode was reported to potentially reduce arm fatigue and improve task performance, making it suitable for extended use. This aligns with the findings of Mendes, Fonseca, Araujo, Ferreira, and Jorge (2014), and Song, Goh, Hutama, Fu, and Liu (2012), who noted that direct manipulation was more pleasing and in-formal in comparison to indirect manipulation for mid-air interactions. Meanwhile, Rantamaa et al. (2022) also proposed a mechanical redesign of controllers to minimise discomfort and arm fatigue from bulky controllers. The mixed interaction mode, combining direct and indirect manipulation, could serve as a solution by reducing stress on the hands and wrists.

However, some participants found the mixed interaction mode tiring and challenging, indicating a need for further refinement and practice. There was also confusion over various input and output modalities, which could lead to incorrect operations.

Individual differences were evident. For example, User 3 preferred a mixed approach, choosing the interaction mode based on the specific task, while User 30 favoured using Leap Motion, possibly due to its lower physical effort requirement.

These differences highlight the need for flexibility in VR systems. While some users may prefer one interaction mode for all tasks, others may switch between modes depending on the task. This underscores the need for VR systems to support multiple interaction modes, allowing users to choose the one that best suits their needs.

# 6 Conclusion

This puzzle user study aimed to explore the user experience of mixed interaction compared to direct and indirect interaction. The puzzle user study intends to determine the strengths and weaknesses of different modes of interaction. The data obtained from the user study includes the participant's behavioural measures, task performance, usability, mental workload, and user preferences. The data from the puzzle user study showed how participants perceive mixed interaction. The questionnaire data analysis indicated that participants prefer using a controller over a Leap Motion and mixed in general. Participants show their interest in mixed interaction, and their comments suggest potential ideas to develop further in the next study. Overall, the findings added knowledge and insights into the development of mixed interaction and existing VR interaction literature.

This study has provided valuable insights into the impacts of direct and indirect interaction in VR. However, a comprehensive understanding of the effects of combining multiple interaction modes in VR settings and their implications in diverse contexts requires further investigation. Moreover, examining the impact of different interaction modes on user experience and performance, encompassing task completion time, user satisfaction, and engagement, is of utmost importance.

In addition to puzzle-solving tasks, future research could explore the application of these interaction modes in more sophisticated and less controlled tasks. For instance, virtual training simulations, virtual design applications, virtual gaming environments, and virtual social platforms could all benefit from the mixed interaction mode. These potential applications could provide a broader context for evaluating user experience and performance, encompassing task completion time, user satisfaction, and engagement.

The development of novel and improved interaction techniques for VR applications is also imperative. In particular, exploring the effectiveness of mixed interaction mode, as suggested by participants, presents a promising avenue for further research. Ultimately, such research endeavours are critical to enhancing the effectiveness and efficiency of VR applications, ensuring that users develop the requisite skills to interact with virtual environments seamlessly and intuitively.

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