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Effect of Hand and Object Visibility in Navigational Tasks Based on Rotational and Translational Movements in Virtual Reality

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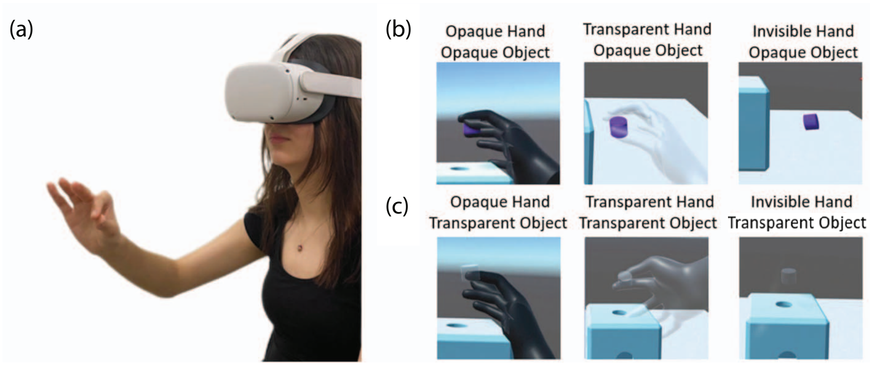

Figure 1: Experiment Design: (a) a participant wearing a Virtual Reality (VR) headset while navigating a cylindrical object in the VR environment under different visibility (transparency) settings: (b) an opaque object can grasped with an opaque hand, a transparent hand, or an invisible hand, or (c) a transparent object can be grasped with an opaque hand, a transparent hand, or an invisible hand.

Abstract

During object manipulation in Virtual Reality (VR) systems, realistically visualizing avatars and objects can hinder user performance and experience by complicating the task or distracting the user from the environment due to possible occlusions. Users might feel the urge to go through biomechanical changes, such as re-positioning the head to visualize the interaction area. In this paper, we investigate the effect of hand avatar and object visibility in navigational tasks using a VR headset. We performed two user studies where participants grasped a small, cylindrical object and navigated it through the virtual obstacles performing rotational or translational movements. We used three different visibility conditions for the hand avatar (opaque, transparent, and invisible) and two conditions for the object (opaque and transparent). Our results indicate that participants performed faster and with fewer collisions using the invisible and transparent hands compared to the opaque hand and fewer collisions with the opaque object compared to the transparent one. Furthermore, participants preferred to use the combination of the transparent hand avatar with the opaque object. The findings of this study might be useful to researchers and developers in deciding the visibility/transparency conditions of hand avatars and virtual objects for tasks that require precise navigational activities.

Index Terms: Human-centered computing—Human Computer Interaction (HCI); Human-centered computing—Virtual Reality

1 Introduction

Virtual reality (VR) has evolved as a cutting-edge technology that allows individuals to engage in three-dimensional experiences within virtual settings generated by computer systems. VR technology has a great potential to build realistic virtual worlds that mirror real-world experiences [42] — especially for applications in the fields of education [29, 49, 50], healthcare [37], architecture [14], engineering [3, 15, 35], and entertainment [30].

Interacting with digital content in three-dimensional (3D) immersive space allows users to manipulate virtual objects, explore virtual environments, and engage in realistically rendered simulations [38]. Conventionally, these interactions are performed through VR controllers, tracking users' real movements accurately and receiving triggered-base commands. However, these interactions do not occur in the VR environments as in real life (e.g., grasping an object by triggering the controller click instead of applying forces from opposite locations through virtual fingertips). Such trigger-base interaction ultimately limits the nature of the interaction — in other words, users have a more natural and intuitive experience when utilizing their hands in virtual reality [12, 25]. Integrated with Head-Mounted Displays (HMDs), hand tracking technology captures real-time hand movements through embedded cameras, ensuring accurate tracking and display of gestures and movements [2].

Designing effective hand control and visualization techniques is one of the foundational elements of VR [22, 34, 44, 54]. Additionally, optimizing the virtual grasping methods significantly improves the overall user experience [13, 16, 43]. Thus, developers, researchers, and practitioners have previously aimed to align how individuals perceive and interact with the real world with the virtual world [4]. In the real world, healthy humans visualize their limbs and body parts (e.g., hands) to be completely opaque and obscuring the actual interaction with the physical objects to be interacted with. Thanks to their ability to interpret their surroundings through their other senses, they are capable of performing almost any interaction (e.g., grasping, pushing buttons, or moving objects) [24]. With the goal of achieving realistic and immersive virtual environments, designers might allow users to visualize completely visible, opaque objects and hand avatars. Unfortunately, opaque hand avatars might potentially obscure the view of small objects from the user's perception, causing confusion and frustration [40]. One option is to render the hands completely invisible, such that users' attention can be directed to

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the object instead. Despite its potential, users might find it difficult to interact with these objects when there is no visual representation of their hand movements. This is even more prominent when interacting with small objects, where coherent and realistic perceptions of virtual objects are distributed. Finally, a transparent hand avatar might allow participants to visually follow their hand movements in a lighter and less obscuring manner [52].

The second visual component to be adjusted is how to render the information about the object to be grasped to improve the VR interactions. In real life, the opaque hands occlude the objects (especially if they are small) during manipulation tasks as the user looks at their hand and the object simultaneously. It is quite possible that the users complete the manipulation tasks by interpreting the movements and position of the hand, making the visual information coming from the object irrelevant and unnecessary. It is possible to design the VR interaction as realistically as possible by rendering the visual object to be completely visible (opaque). Yet, it is also possible to render its visuality to be transparent [52].

In this paper, we investigate how visualization methods for hand avatars and objects, including their transparency, affect user performance and experience in the virtual environment. To assess this effect, we designed a custom-made virtual task that requires participants to use fine motor dexterity skills and focus on eye-hand coordination during rotational or translational hand movements. Our contributions are centered around a comprehensive exploration of the role of hand visibility and object visibility conditions in VR environments, particularly within navigation-based tasks. These investigations offer valuable insights into how varying levels of transparency influence user interactions and experiences.

2 Previous Work

2.1 Hand Avatar Representations

2.1.1 Form and Shape

The form and shape of the virtual hand avatar representations have been investigated in terms of their impact on user performance. Gruber et al. [19] investigated how different hand representations affect user performance while typing on a virtual keyboard using *(i)* no visual hand, *(ii)* inverse kinematic model ,*(iii)* sphere-based fingertip visualization, and *(iv)* video hands, displaying the actual hands through a blended video. Participants made the least error using the spherical fingertip visualization and chose video hands as the most realistic representation. Aslandere et al. [5] investigated the hand rendering conditions during VR flight simulators while participants pressed buttons using *(i)* an opaque hand and *(ii)* a hand with cylindrical shapes for half of the finger and a sphere representing the palm. Participants were more accurate with cylindrical shapes, where they could easily see the buttons.

The form and shape of the virtual hand avatar representations have also been investigated in terms of their impact on user experience (and emotions). Argelaguet et al. [4] focused on the agency and ownership while using *(i)* an abstract ball, *(ii)* an "iconic" joint hand, and *(iii)* a virtual hand while performing a pick-and-place task in scenarios wherethe user's hand avatar in danger. Their results indicated a higher agency with less accurate depictions due to a less noticeable disparity between the VR representation and the actual movements.Similarly, Lin et al. [31] explored the impact of six distinct virtual hand appearances on own-body perception – considering realism, render styles, and pain sensitivity. The virtual hand illusion was found to be the weakest for non-humanoid block models and strongest for realistic human hand models, with significant variability in participant responses.

Lougiakis et al. investigated the impact of three virtual hand representations (the sphere's abstract form, the controller's 3D model, and the virtual hand) on user embodiment while moving a cube in a lifelike environment [33]. Participants' motor performance decreased with the sphere compared to 3D controllers and virtual hands while the controller outperformed the other two for the positioning performance, but there was no discernible difference in mediation. Moreover, the virtual hand was the most preferred representation with the strongest sense of ownership.

2.1.2 Visibility

Ricca et al. [47] investigated how the user's real hand depiction affects motor skill development and subjective experience during tool-based virtual training. The same experiment was then extended to a two-week study as a between-subjects experiment — where participants were divided into a visualization and a control group [48]. Each group received training, while the visualization group received additional guidance that involved visualizing their hands while performing the tool-based pick-and-place activities. Both studies did not indicate a significant change in users' hand representation and control on tool-based motor skill training. The participants of the longitudinal study exhibited minor improvements with visible hand representation only in object rotation accuracy, an evaluation metric related to the deviation between the cube and the target.

Borgwardt et al. [9] evaluated visible and invisible hands during VR Frisbee simulations. Participants reported better sensation of control using visible hands, especially in secondary activities (e.g., picking up the disc), but they did not exhibit a significantly increased throwing accuracy. While the visibility of the hand affected the sense of control, it did not affect the total perceived presence or body ownership. The authors suggested that visual representations of limbs alone may not be sufficient for precise control tasks like throwing while holding a virtual object. Veldhuizen et al. [51] explored the effectiveness of semi-transparent and interpenetrable hands in addressing challenges like occlusion and delicate manipulation in VR. Their results indicate substantial improvements in precise manipulation, highlighting the potential advantages of these hand representations. Lastly, Voisard et al. [52] examined three hand visualization styles – transparent, opaque, and invisible in a VR-based Purdue Pegboard Test. The outcomes of the study reveal that an invisible hand visualization enhances task repetitions compared to opaque visualization, thus improving user motor performance.

2.2 Object Representations

Examining the effect of object visibility, Palmer et al. [41] investigated the impact of object visibility during a pick-and-place task in a between-subject experiment where *visible object* group could visualize the object during the whole experiment while *invisible object* group lost the objects' visual feedback after the grasp. In the meantime, participants received haptic feedback on their wrists regarding how much they squeezed the object between their fingers. The visible object group performed the task significantly better than the invisible group in all evaluation metrics.

Several studies also explored the simultaneous variation of hand and object visibility conditions in virtual environments. One prominent study by Buchmann et al. [11] introduced a system exploring the use of partially transparent virtual hands and objects, employing a fixed camera and alpha-blending to overlay frames on a background image. User experiments reveal that users prefer transparency levels of 0.6 and 0.8, balancing transparency and usability, and higher transparency levels negatively affect depth perception and hand control. The paper also discusses selective transparency, rendering specific object parts less transparent, which users appreciated but raised concerns about obscuring background details. These findings provide insights into virtual reality technology development.

3 Motivation & Hypotheses

The visibility conditions have been previously investigated in terms of accuracy, task completion time, and user experience [11, 20]. However, the impact of the hand visibility and object visibility conditions, thus the presence of a possible occlusion, has never been examined from the perspective of possible collisions during tasks that require fine motor dexterity skills and advanced eye-hand coordination. In addition, the literature lacks a systematic evaluation of user performance under such visibility conditions for different movement behaviors independently (i.e., during rotational movements from the wrist or translational movements from the arm or the torso). In other words, examining different movement behaviors separately might provide detailed insights into how grasping occlusion and visibility levels impact the accuracy and efficiency of users' performance in navigation tasks and, thus, propose better virtual hand interaction techniques. Furthermore, the literature still lacks an empirically proven perspective on the level of visibility of hand avatars and manipulated objects in terms of navigational tasks in a cross-referenced manner.

The main focus of this study is to investigate the effect of opacity variations on a virtual avatar hand and the grasped object during virtual navigational tasks. Our motivation is to seek answers to the following research questions (RQ):

- **RQ1:** Does using alternative rendering methods (transparent or invisible) for the hand avatar improve user performance over visually rendering opaque (completely visible)?
- **RQ2:** Are there benefits of using transparent hand avatars over completely invisible ones?
- **RQ3:** Does the visibility of objects to be grasped affect these perceptual differences caused by the hand visibility conditions?
- **RQ4:** Are there perceptual differences when participants perform navigational tasks that are based on either orientation or translation-based movements?

We hypothesize that altering opacity in hand avatars and objects significantly affects user performance in navigational tasks. We expect **participants to exhibit an enhanced motor performance in terms of collisions with transparent or invisible hands and to prefer using transparent hands.** We also think that **the visibility of objects contribute to perceptual differences, such that the combination of a transparent hand and an opaque object create a more effective interaction scenario.** These hypotheses are grounded in the notion that users would benefit from an improved sense of direction, obstacle avoidance, and task performance as they can partially see their hands and the target/environment from all angles easily to avoid hitting obstacles and plan their next moves.

In this paper, we investigated the research questions through user experiments with different hand visibility (*opaque*, *transparent*, and *invisible*) and object visibility conditions (*opaque* and *transparent*). We conducted two experiments: (I) Participants were asked to grasp a cylindrical object and place it inside a toolbox in the correct orientation; (II) Participants were asked to grasp the same object and navigate it through a virtual maze.

4 Methodology

4.1 Physical Setup

Fig. 1 (a) shows the experiment design, where participants wear an Oculus Quest 2 headset. The cameras on the headset use hand-tracking technology to track the participant's hands. The user's hand movements are directly mapped to the avatar hand movements, ensuring a natural experience. We implemented our VR application on a system running on an 11^{th} Gen 2.5 GHz Intel(R) Core(TM) i7-11700F desktop PC with 32 GB RAM and an NVIDIA GeForce GTX 3070 graphics card. For the virtual environment, we used Unity version2020.3.21f1. We also used the Auto-Pose feature of Oculus Interaction SDK, which offers a realistic grasping or interaction by preventing fingers from entering objects [13,43,44]. The experiment was performed in a quiet room dedicated to user studies and isolated from other sections of the laboratory, allowing the participants to focus on the task better.

4.2 Experiment Conditions

In this paper, the perceptual differences between different hand and object visibility conditions are investigated. With this goal, we designed three visibility conditions for the hand:

- **Opaque Hands** are visually rendered as black and fully opaque, as on the left side of Fig. 1 (b-c). This approach offers a mid-way between realism (i.e., it occludes the object and the environment behind it) and virtualism (i.e., the animated black texture is still not realistic).
- **Transparent Hands** are visually rendered as transparent, as at the center of Fig. 1 (b-c). They have an opaqueness level of 15% and a transparent texture instead of a black one. The level of transparency has been set based on pilot studies in which participants can 'barely see the location of the hand avatar' but also 'comfortably see through without the hand occluding the view'. This approach allows participants to visualize the real-time location of their virtual hand avatar while seeing the object and the environment behind it.
- **Invisible Hands** are not visually rendered intentionally, as on the right side of Fig. 1 (b-c). The hands are rendered as opaque before participants grasp the object, but become invisible after a successful grasping.

We also designed two visibility conditions for the object:

- **Opaque Objects** are visually rendered as purple and fully opaque in a cylindrical shape, as in Fig. 1 (b). Similar to opaque hands, this method offers a mid-way between realism and virtuality.
- **Transparent Objects** are visually rendered as transparent in a cylindrical shape, as Fig. 1 (c). Similar to the transparent hand, after trying different levels during the design process, we decided to set an opaqueness level of 15% based on pilot studies, and a transparent material instead of a purple one. This approach allows participants to visualize the real-time location of the object while seeing the environment behind it.

4.3 Experimental Environment

In this paper, we designed and conducted two experiments. In Experiment I, participants were asked to complete a simple navigation task based on "rotational" movements by grasping a small cylindrical object and inserting it into the designated target surface located on a cubical toy box. In Experiment II, participants were asked to complete a larger navigation task based on "translational" movements by grasping the same object and passing it through a virtual custom-made maze without hitting the object against the inner walls of the maze.

4.4 Evaluation Metrics

In both studies, we employed the user performance via:

- **Time** (or task completion time) is recorded from the moment the participant grabs the object until the moment the grasped object is dropped on the table.
- **Number of collisions** is incremented whenever a collision occurs between the grasped object and the walls of the toy box (in Experiment I) or the maze (in Experiment II).

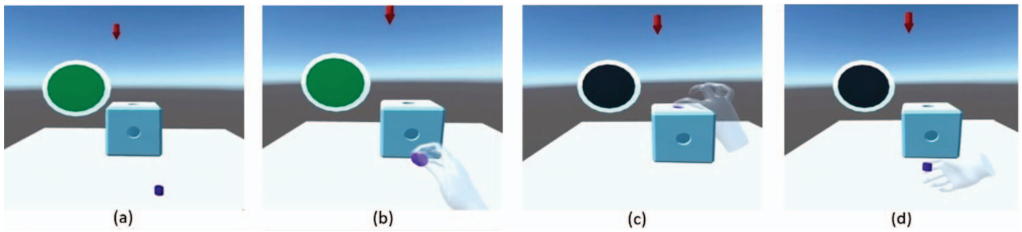

Figure 2: Experiment I: (a) The green light indicates that participants can start the trial, while the red arrow shows the target surface to place the object into, which varies for each trial. The hand and object are rendered opaque at this stage to help them initiate the trial successfully. (b) The participants grasp the object, triggering the visibility conditions to be adjusted accordingly. (c) The participants navigate the object towards the toy box in the direction of the target surface and pass it through the hole. (d) The particiapants navigate the object until placing it on the table, which terminates the trial.

We also asked participants to fill out a 7 Likert scale questionnaire related to their experience and preferences after the experiment. We opted for a custom questionnaire to better understand user preferences, as common ones may not capture these nuances effectively. The questionnaire includes balanced statements: *"It was easy to interact with this visibility." "I like the visibility.", "I found the visibility unnecessarily complex.","I feel that I was successful." "I found the visibility very awkward,", "I felt very confident", "I was so engaged"* . Additionally, participants describe their emotional experience with each condition, selecting emotions from the emotional wheel – an enjoyable emotion tagging tool encouraging users to share their reactions [17,53,55]. In addition to the written comments, we also consider verbal comments provided to the experimenters during the breaks within the experiment trials.

5 EXPERIMENT I: TOY BOX EXPERIMENT BASED ON ROTATION

Participants were asked to grasp a cylindrical object, and a target was given to place it by focusing on the correct orientation of the object — performing "rotational" movements — as accurately and fast as possible. Their success rate depended on how well they could estimate the correct orientation of the object with respect to the given target. This experiment is designed to examine hand avatar conditions and object visibility scenarios where accurate targeting is involved in a virtual environment. Completing this task successfully required participants to pay attention and not exceed the target limits in a very compact area.

Fig. 2 shows the virtual environment we created with a table, a purple cylinder, and a toy box. The toy box has three possible target holes (side, top, and front) in which participants are asked to grasp the objects and place them inside the correct hole via visual arrows, which will be referred to as a target, as fast and with the least collisions with the surface as possible. Each target requires participants to reach the toy box with a different wrist movement, which plays a role in task performance.

5.1 Methodology

5.1.1 Participants

We conducted a user study with 18 participants (8 male and 10 female) from the local university with ages between 18 and 33 (M = 23.11, SD = 4.1). All participants reported being right-handed, while thirteen participants reported their right eye and the remaining five reported their left eye as their dominant eye, which refers to the preference to use one eye more than the other one to accomplish a task [39]. Three participants reported they had never experienced VR; six participants reported 1-3 times, and nine participants reported more than 5 times.

5.1.2 Experiment Design

To test the hypothesis detailed in Section 3, we designed a three-factor within-subject user study with three **Hand Visibility** conditions (3_{HV} = opaque, transparent, and invisible), two **Object Visibility** conditions (2_{OV} = opaque and transparent), and three **Target Surface** conditions (3_{TS} = front, top, and side). Combining these three factors resulted in (3_{HV} X 2_{OV} X 3_{TS} = 18_{EC}) 18 experiment conditions. 18 participants were recruited in the experiment to counterbalance the order of conditions with Latin Square to eliminate any bias effects. The participants repeated all conditions three times (18_{EC} X $3_{rep} = 54_{tr}$), yielding 54 trials. As a result, we obtained (54_{tr} X 18_{part}) 972 data points to perform the statistical analysis.

5.1.3 Virtual Task & Procedure

Upon arrival, participants provided written consent and completed a pre-experiment questionnaire about their demographics. The experimenter explained the task and assisted them in wearing the VR headset. They were intentionally seated to explore diverse perspectives from three viewing angles: top, side, and front. The built-in Oculus hand tracking software allows us to track the participant's hand movements (i.e., position and orientation), which are then visually displayed through hand avatars [23].

For each trial, a green circle indicated that the experiment could be initialized, and a red arrow appeared around the toy box to inform the participants which surface of the toy boy the target is placed on for them to approach with the object (Fig. 2). They grasped the virtual object, rotated it, completely passed it through the designated hole, and dropped it on the table. The event of a successful grasping of the object triggered the navigational timer for each trial separately. The toy box had a mesh collider attached to it, which gave us two benefits: *(i)* the object did not pass through the walls from the outside to inside or inside to outside, and *(ii)* we counted the collisions between the object and the walls of the toy box to record user performance during trials.

5.2 Results

Data were preprocessed through JMP and analyzed using three-way repeated measures (RM) analysis of variance (ANOVA) in SPSS. We evaluated Skewness (S) and Kurtosis (K) to analyze the normality of the data, i.e., when S and K values were within ± 1 [21]. If the data was not normal, log transformation was performed before the statistical analysis [27]. Fig. 3 shows the average time and number of collisions for different hand visibility and object visibility conditions, while Table 1 summarizes the results of the analysis.

5.2.1 Time

Fig. 3 shows the average time to complete the task across all participants, all trials, and all target surfaces on the toy box — categorized based on the hand visibility and the object visibility conditions.

Table 1: RM ANOVA results for the time (s) and the number of collisions in terms of main factors (hand visibility, object visibility, target surface) and their interactions for Experiment I. Significant results are shown in blue.

Parameters	Time (s)	Number of Collisions
Hand Visibility	**F(2,34)=9.205, p<0.05, η^2=0.351**	**F(2,34)=19.331, p<0.001, η^2=0.532**
Object Visibility	F(1,17)=3.871, p=0.066, η^2=0.185	**F(1, 17)=5.350, p<0.05, η^2=0.239**
Target Surface	**F(2,34)=4.926, p<0.05, η^2=0.225**	**F(2,34)=6.916 p<0.05, η^2=0.289**
Hand x Object Vis.	F(2,34)=1.873, p=0.169, η^2=0.099	F(2,34)=2.725 p=0.080, η^2=0.138
Hand x Target Surface	F(4,68)=0.911, p=0.463, η^2=0.050	F(4,68)=2.259 p=0.072, η^2=0.117
Objcet Vis. x Target Surface	F(2,34)=0.473, p=0.627, η^2=0.027	F(2,34)=0.117 p=0.89, η^2=0.007
Hand Vis. x Object Vis. x Target Surface	F(4,68)=0.147, p=0.964, η^2=0.009	F(4,68)=1.081 p=0373, η^2=0.060

Data distribution for time was not normal, so we performed a log transform (S = 0.832, K = 0.463). RM ANOVA results showed a significant effect of hand visibility and target surface, but not for the object visibility and the interactions between the main factors (Table 1).

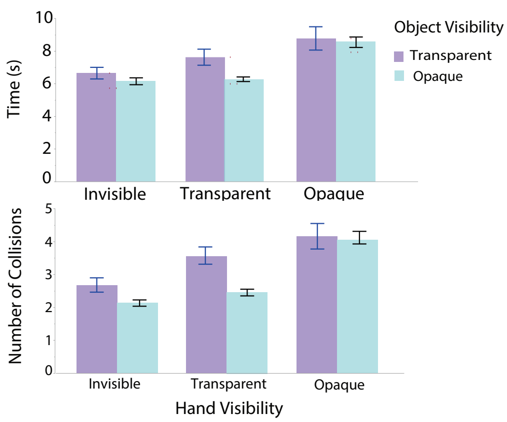

Figure 3: Average for time and number of collisions during Experiment I for different hand visibility and object visibility conditions.

To further investigate the differences between hand visibility and target surface conditions, we performed post-hoc analyses. Fig. 4 (a) details the differences between hand visibility conditions: participants completed the task significantly slower with the opaque hands than with the invisible and transparent hands, but not differently between the invisible and transparent hands. Similarly, Fig. 4 (b) details the differences between target surface conditions: participants completed the task significantly faster while inserting the object on the front surface than on the side and the top surfaces, but not differently between the side and the top surfaces.

5.2.2 Number of Collisions

Fig. 3 shows the average number of collisions across all participants, all trials, and different target holes on the toy box - categorized based on the hand visibility and the object visibility conditions. Data distribution for the number of collisions did not exhibit a normal

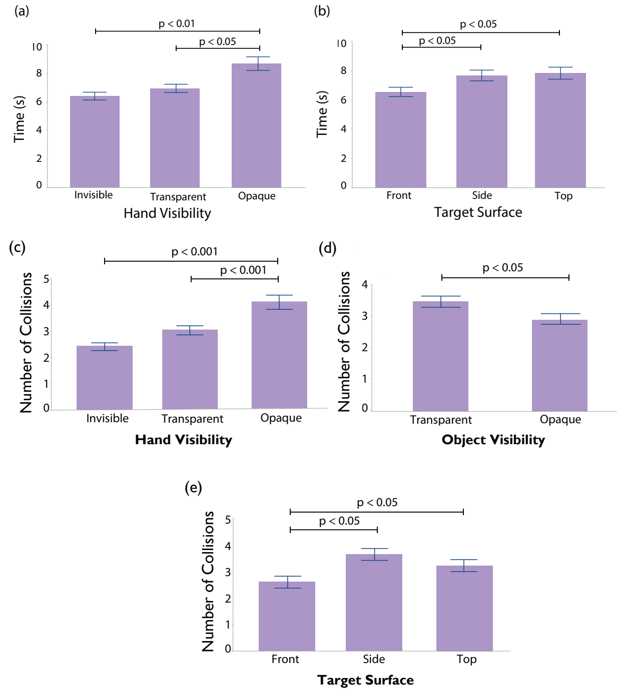

Figure 4: Detailed post-hoc analysis during Experiment I for time between (a) hand visibility and (b) target surface conditions and for the number of collisions between (c) hand visibility, (d) object visibility, and (e) target surface conditions

distribution, so we performed a log transform (S = -0.487, K = 0.439). RM ANOVA results showed a significant effect on hand visibility, object visibility, and target surface conditions, but not on the interactions between the main factors (see Table 1).

To further investigate the differences between hand visibility, object visibility, and target surface conditions, we performed post-hoc analyses. Fig. 4 (c) details the differences between hand visibility conditions: participants completed the task with significantly more collisions with the opaque hands than with the invisible and transparent hand visibility, but not between the invisible and the transparent hands. Fig. 4 (d) shows that participants completed the task with statistically significantly more collisions with transparent objects than opaque objects. Similarly, Fig. 4 (e) details the differences between target surface conditions: participants completed the task with significantly fewer collisions while inserting the object on the front surface than with the side and the top surfaces.

5.3 Subjective Comments

After the experiment, we collected subjective participant feedback through a questionnaire. We asked participants to evaluate each hand visibility and object visibility conditions independently. Regarding hand visibility, 8 participants preferred opaque hands, 5 participants preferred invisible hands, and 5 participants preferred transparent hands. All 18 participants preferred interacting with opaque objects. Then, we asked them to evaluate each visibility condition on a 7-point Likert scale (1: strongly disagree and 7: strongly agree) by giving them the following statements: "It was easy to interact using the hand/object with invisible/transparent/opaque visibility condition", "I felt very confident", "I was very engaged", and "I feel that I was successful". Fig. 5 summarizes the responses of the participants. Overall, the participants preferred interacting with the opaque objects and opaque hands compared to invisible hands,

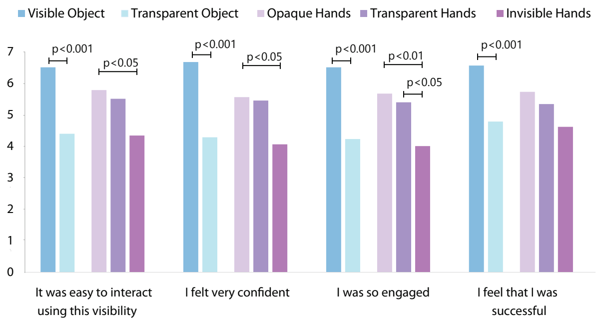

Figure 5: The subjective comments of the participants for hand visibility and object visibility conditions.

while no significant difference was found between the transparent and invisible hand visibility.

Finally, participants were given an emotion wheel to express how they felt about each condition. With the opaque hand condition, 14 participants reported feeling happy, 2 reported disgusted, one reported angry, and one reported surprised. With the transparent hand condition, 14 participants reported feeling happy, and the other 4 reported feeling bad. With the invisible hand condition, 10 participants reported feeling bad, 3 reported curious, and 8 reported happy. On the other hand, while interacting with opaque objects, 17 participants reported feeling happy, and one reported being surprised. While interacting with transparent objects, 10 participants reported bad, 4 reported happy, and 4 reported surprised.

5.4 Discussion

The findings of the toy box experiment (Experiment I) indicate two outcomes: *(i)* time was found to be statistically significantly different for the main factor of hand visibility and target surface conditions, and *(ii)* the number of collisions was found to be statistically significantly different for all main factors (i.e., hand visibility, object visibility, and target surface conditions). Furthermore, the qualitative results state that the participants preferred interacting with the opaque objects while using opaque hands compared to invisible or transparent hands, expressing positive emotions for these conditions.

Regarding hand visibility conditions, participants completed the task significantly slower and with significantly more collisions using the opaque hand compared to the transparent and invisible hands. Furthermore, we observed that using an invisible hand offers the best visibility condition for the participants in terms of time and number of collisions. There might be two possible factors explaining this outcome. Firstly, using opaque hands might resemble real-life activities and interactions more than the other two hand visibility techniques. As a result, participants might not mentally reconcile the hand avatar passing through the toy box while using opaque hands — resulting in slower task completion time. Secondly, these results might shed light on participants' focus while performing such a manipulation task. We speculate that transparent and invisible hands might allow participants to focus better on the object rather than the visual representation of the hand. In other words, opaque hands occluding the object to be grasped might divide their attention and complicate the manipulation task.

Interestingly, the data analysis and subjective comments are conflicting in terms of hand visibility. Participants were significantly faster and made fewer collisions using transparent (or invisible) hands — but the majority of them still preferred using opaque hands over transparent or invisible hands. They commented that using the opaque hand, they *"completed the task faster"*, *"felt more relaxed and confident with the task"* or *"did not have to think about their hand position"*. We observed that the participants who made these comments had very little prior experience with VR, and it is possible that as they get more experienced, they might feel more comfortable and confident also using the other hand visibility conditions. We believe that such a conflict between perceived and actual performance could be improved by adding auditory feedback, which alerts the user whenever a collision occurs [6, 7].

Regarding object visibility conditions, participants completed the task significantly with more collisions using transparent objects compared to opaque objects but not significantly different in terms of time. This can be explained by the simplicity of the experiment task offered to the participants, in which, we only used objects to be picked and placed on the toy box, always through a circular hole. This simplification might lift the challenge of the placement task, and we believe that the results in terms of the object visibility conditions might be different if repeated with more complex shapes.

Regarding target surface location on the toy box, participants completed the task significantly faster and with significantly fewer collisions when they were instructed to insert the object through the front surface compared to the side and top surfaces. We believe that this was because they kept their bodies in front of the front surface during the experiment. For the other surfaces, however, the participants had to move around the toy box slightly, such as leaning on their sides or lifting their heads to get a better look at the side and top surfaces. These movements could increase both the time and the number of collisions [32].

6 Experiment II: Maze Experiment Based on Navigation

Unfortunately, participants' ability to move and navigate through virtual walls in the 3-dimensional world, which requires a fair amount of spatial ability and proprioception [10, 26, 45], could not be extracted from Experiment I. In the second experiment, we evaluated user performance with a navigational task based on "translational" movements: participants were asked to grasp the same cylindrical object and pass it through a virtual maze without hitting the object against the inner walls of the maze. Their success rate depended on how well they could perform linear and translational movements while navigating through a virtual maze.

Fig. 6 shows the virtual environment we created with a table, a purple cylinder, and a transparent maze made of glass tubes. This maze includes 5 segments for vertical movements, 5 for horizontal sideway movements, and 7 for horizontal in-depth movements and it remained consistent across all experiments to ensure the reliability and consistency of the results. Compared to traditional wire loop games, the virtual maze helps us prioritize studying hand visibility by intentionally creating the virtual avatar, occluding the grasped object. Participants are asked to navigate the grasped object through confined walls of the maze performing translational movements, introducing a depth perception challenge in visually intricate environments. The task demands precise fine motor skills and enhanced eye-hand coordination for effective control within the compact space, where avoiding collisions is a key performance factor.

6.1 Methodology

6.1.1 Participants

We conducted a user study with eighteen participants (9 male and 9 female) from the local university with ages between 20 and 31 (M = 22.05, SD = 2.53). The participants who volunteered for the first study were not invited to this study to eliminate any learning effect. All participants were right-handed, while eleven participants reported their right eye, and the remaining seven listed their left eye as their dominant eye. Two participants had no prior experience with VR; ten reported experiencing it 1-3 times, three reported 3-5 times, and three reported more than 5 times. Spatial abilities were evaluated using a test from the STEM Education Research Centre [1, 46], which encompassed questions on Mental Rotation,

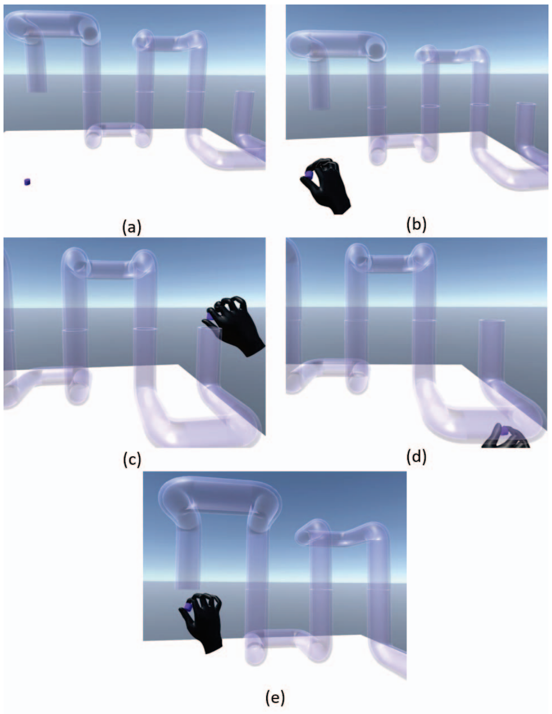

Figure 6: Experiment II: (a) The hand and the object are initiated as opaque to help participants initiate the trial successfully. The experimenter verbally instructs the participant to start the trial. (b) They grasp the object, triggering the visibility conditions to be adjusted accordingly. (c) They enter the maze from the right end of the maze, triggering the trial timer. (d) They navigate it through the maze as quickly as possible while avoiding collisions with the interior walls. (e) They extract it from the left end of the maze and drop it on the table, which terminates the trial.

Spatial Orientation, and Spatial Visualization, resulting in a mean score of 80.83 over 100 and a standard deviation of 13.20.

6.1.2 Experiment Design

We designed a two-factor within-subject study with three **Hand Visibility** conditions (3_{HV} = opaque, transparent, or invisible) and two **Object Visibility** conditions (2_{OV} opaque and transparent). Combining these three factors result in (3_{HV} X 2_{OV} = 6_{EC}) 6 experiment conditions. Participants repeated all conditions three times (6_{EC} X 3_{rep} = 18_{tr}), resulting in 18 trials before completing the experiment. 18 participants were recruited in the experiment to counterbalance the order of conditions with Latin Square to eliminate any bias effects. As a result, we obtained (18_{tr} X 18_{part}) 324 data points to perform the statistical analysis once the experiment was completed.

6.1.3 Virtual Task & Procedure

Before the experiment, participants were first asked to provide their written consent and complete a pre-experiment questionnaire about their demographic information. Then, they were requested to wear the Oculus Quest 2 headset. Similar to the previous experiment, built-in Oculus hand tracking software allowed us to track the participant's hand movements (i.e., position and orientation), which were then visually displayed through avatar hands.

Prior to conducting the experiment, the experimenter explained the task to the participants, emphasizing that collisions were considered detrimental to task performance. Participants were instructed to prioritize completing the task in less time while minimizing collisions and were provided with practice sessions until they felt comfortable with it. they were required to stand up and freely explore and move around the virtual maze.

To study the implications of visualization methods better, we chose manipulation tasks that require fine motor dexterity skills and advanced eye-hand coordination. Initially, we explored various pre-existing task environments, including the pick-and-place task as in [41]. However, we observed that these tasks lacked the incorporation of visual challenges during the object transportation phase, such as the requirement to rotate the object. On the other hand, the wire-loop game is one of the application examples where users move the loop along the wire without creating a collision between those two – requiring a high level of precision where the user has to overcome challenges introduced by visual feedback. It is commonly used for training modalities for physical rehabilitation to recover from physical disabilities [36] or medical training to enhance eye-hand coordination and motion stability [18].

In this experiment, we created virtual environment based on a wire loop game with two modifications. Firstly, in the original game, the loop is fairly big compared to the hand, which does not occlude the loop during navigation. Therefore, it cannot be used to investigate the impact of visualization techniques mentioned in the previous subsection. Instead, we extend the wire loop idea into a tunnel scenario where users are asked to grasp a small object and navigate it through tunnels without colliding with the walls.

Secondly, the original wire loop game requires rotational and translational hand movements interconnected with each other. We deliberately made the choice of separating the "rotational" and "translational" stages of a navigation task in different studies for multiple reasons. *(i)* Participants are allowed to focus on one task at a time, which eliminates any possible confusion and frustration during the trials. We believe that simplifying the task helps participants perform better and helps us obtain more precise data. *(ii)* Dividing the data into two sections significantly reduces the execution time, playing an important role in the mental and physical fatigue of participants. *(iii)* It is expected that hand and object transparency options would show different outcomes and trends while performing different sections of the same task. Dividing these two stages into two experiments allows us to analyze the user performance and user experience in detail and more precisely.

Each trial began with the object located on the left side of the maze, as detailed in Fig. 6. The participants grasped it and navigated it across the maze, starting from the right end and finishing on the left. The successful grasp between the user's hand avatar and the object triggered the navigational timer. The maze had a mesh collider preventing the object from passing through its outer walls. Whenever an object hit the wall, a collision was detected and recorded, and an alert sound was played. Collision detection was achieved using custom logic that measured the distance between the object and the maze tube's center. When this distance exceeded a certain threshold, a collision was recorded. To prevent multiple rapid collisions from being mistaken for a single collision, participants had to exit the collision zone before they could move the object again.

6.2 Results

Fig. 7 shows the average time and number of collisions for different hand visibility and object visibility conditions, while Table 2 summarizes the results of the analysis.

6.2.1 Time

Data for the time had a normal distribution (S = 0.639, K = -0.299). RM ANOVA shows no significant effect of hand visibility and object visibility conditions and their interactions (see Table 2). Fig. 7 shows the average time across all participants and all trials, categorized based on hand visibility and object visibility conditions.

Table 2: RM ANOVA results for time (s) and number of collisions in terms of main factors (hand visibility and object visibility) and their interactions for Experiment II.

Parameters	Time (s)	Number of Collisions
Hand visibility	F(2,34)=0.899 p=0.416, η^2=0.050	**F(2,34)=3.627, p<0.05, η^2=0.176**
Object visibility	F(1,17)=1.951, p=0.180, η^2=0.103	**F(1, 17)=9.784, p<0.05, η^2=0.365**
Hand x Object Vis	F(2,34)=0.93, p=0.748, η^2=0.017	F(2,34)=0.836, p=0.442, η^2=0.047

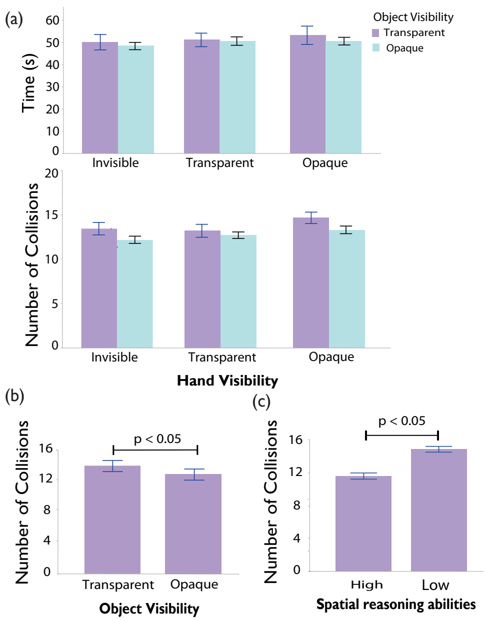

Figure 7: (a) Average time and number of collisions during Experiment II for different hand and cylindrical object visibility conditions.(b) Detailed post hoc analysis for the number of collisions between the object visibility conditions and (c) Spatial ability levels.

6.2.2 Number of collisions

Data distribution for the number of collisions was normal (S =-0.319, K = -0.299). RM ANOVA shows a significant effect on hand visibility and object visibility conditions but not on their interactions (see Table 2). Fig. 7 shows the average number of collisions across all participants and all trials - categorized based on hand visibility and object visibility conditions. Despite the significant overall difference, further post-hoc analysis showed no significant differences between individual pairs of hand visibility conditions.

6.3 Subjective Comments

Similar to our first experiment, we conducted a survey to receive feedback from the participants after the experiment. Participants were asked to evaluate different conditions independently based on hand visibility and object visibility conditions.

Regarding hand visibility, we asked participants to evaluate each visibility condition on a 7-point Likert scale (1: strongly disagree and 7: strongly agree) by giving them the following statements: "It was easy to interact using the hand/object with invisible/transparent/opaque visibility condition", "I felt very confident", "I was very engaged", and "I feel that I was successful". Fig. 8 summarizes the average responses obtained from the participants. Overall, the participants preferred interacting with opaque objects over transparent objects. However, no significant difference was found between different hand visibility conditions.

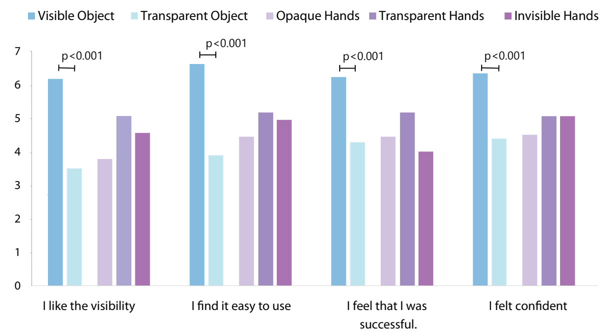

Figure 8: The subjective comments of the participants for hand visibility and cylindrical object visibility conditions.

The participants provided further insightful comments regarding the different hand visibility conditions. About the opaque hand, they made positive comments, such as *"it was comfortable to use because I could see my hand"*, as well as negative comments, such as *"the hand occluding the view caused a distraction"*. For the transparent hand, three participants reported, *"the outline of the hand helped with the task by not occluding the environment but still being able to track my hands"*. For the invisible hand, the participants made positive comments, such as *"it helped me mostly at the corners"* and *"more comfortable to use and better view"*, as well as negative comments as *"not being able to see my hand made me feel I made more mistakes"*. The participants also made further comments about the opaque cylindrical object as *"being able to see the object made me so much more comfortable"*, *"I can track the object easily"*, and *"knowing what I was holding helped me move faster"*.

6.4 Discussion

The findings of the maze experiment (Experiment II) indicate two outcomes: *(i)* time was not found to be statistically significantly different for different hand and cylindrical object visibility conditions, and *(ii)* the number of collisions was found to be statistically significantly differently less while using opaque objects than transparent.

Regarding hand visibility conditions, participants completed the task with no statistically significant difference in terms of time. We observed hand visibility conditions to be statistically different, but further post-hoc analysis revealed no significance when tested independently. Regardless, Fig. 7 indicates that transparent and invisible hands might be slightly better than opaque hands in terms of the number of collisions. Regarding the object visibility conditions, participants completed the task with significantly fewer collisions using opaque objects than transparent objects. We believe that this is because they had a better understanding of the object's position, orientation, and movement within the environment when rendered opaque. The opaqueness of the object increased awareness and enabled participants to adjust their actions and movements accordingly, minimizing the likelihood of collisions.

Furthermore, we categorized participants into low and high spatial ability groups to investigate how it affected their performance. Despite all participants scoring above average, spatial abilities significantly affected collision rates as shown in Fig. 7.c (F(1,7)=20.865, p<0.01, η^2=0.749), but with no effect on task completion time. A detailed examination indicated significant differences in the number of collisions between the hand and object visibility conditions for both low and high-spatial ability groups (p<0.05). These findings emphasize the consistent impact of visibility conditions in the experiment outcomes, even with the spatial ability variation.

Finally, the subjective comments we collected from the participants on hand and cylindrical object visibility conditions support the ANOVA findings: participants agreed that opaque objects are the easiest to interact with – while using transparent or invisible hands. Specifically, all 18 participants found the opaque object to be easy to use, and they felt confident using it independent of hand visibility. However, only 3 participants preferred using opaque hands while using the opaque object, while the rest preferred using transparent or invisible hands. These subjective comments are consistent with the finding that the condition with opaque hands and objects had a larger mean of collisions.

7 General Discussion

In this paper, we investigated the impact of different hand visibility and object visibility conditions on task performance during sorting and navigational tasks based on "rotational" or "translational" movements. Particularly, we combined different hand visibility conditions (opaque, transparent, invisible) and object visibility conditions (opaque and transparent) in two experiment scenarios: a toy box experiment required participants to grasp a cylindrical object and place it inside the holes on the surface of a toy box *(Experiment I)*, and a maze experiment where participants grasped a cylindrical object and navigated it through a maze as fast as possible without colliding with the inside walls *(Experiment II)*.

In both studies, we investigated the impact of using an opaque hand compared to transparent and invisible ones. Our initial hypothesis was that rendering the hand avatars completely opaque might occlude the environment and grasped objects, which might impose a negative impact on user performance. According to our findings, participants exhibited a significantly lower number of collisions in both experiments while using transparent and invisible hands compared to the opaque hand, aligning with the results of Veldhuizen et al. [51] and Voisard et al. [52]. In addition, they completed the tasks significantly faster while using invisible and transparent hands compared to opaque hands during Experiment I, but not Experiment II. With the support of these findings, we can answer *RQ1* as **using transparent or invisible hands improves the user performance of sorting and navigating tasks in terms of the number of collisions and task completion time compared to using opaque hand**.

Furthermore, we compared the user performance in terms of the time and the number of collisions between using transparent and invisible hand avatars. Our initial hypothesis was that transparent hands help participants achieve better results compared to invisible hands by slightly allowing participants to still be able to see and track their hand positions during the tasks. Our results indicate no significant difference between using transparent and invisible hand avatars in terms of the time or the number of collisions, consistent with the results reported by Voisard et al. [52]. However, the subjective comments give us an insight into the impact of transparent hand visibility on enhancing the sense of presence and embodiment; in contrast, comments about invisible hand visibility tend to highlight a lack of visual feedback and realism. Therefore, we can answer *RQ2* as **using transparent hand offers clear benefits over the invisible hand in terms of a more immersive user experience by enhancing the realism and improving the sense of presence, although no benefit was found in terms of user performance.**

We also assessed the impact of different visibility conditions on the object to be grasped during these experiments. In both experiments, participants made significantly more collisions while interacting with a transparent object compared to an opaque object, coherent with the findings of Palmer et al. [41] — even though we observed no difference in task execution time. Yet, it is worth noting that participants consistently reported a heightened sense of realism and embodiment when interacting with the opaque object. We can answer *RQ3* as **interacting with opaque objects compared to transparent ones decreases the number of collisions and increases the sense of realism, but does not shorten the task execution time.** In addition, we observed no significant difference in the interactions between the object visibility and hand visibility conditions.

We investigated the impact of hand visibility and object visibility conditions during a sorting task in the first experiment and a navigation task in the second experiment, which focused on the "placement" and "navigation" stages separately. The findings of both experiments clearly indicate the benefit of using transparent and invisible hands with opaque objects in terms of user experience and the number of collisions. As mentioned before, the user comments about their perceived performance in both studies were found to be different, but this is mostly due to the addition of auditory feedback in the second experiment rather than the nature of the experiment itself. However, we observed that using an opaque hand caused participants to complete the task significantly longer than the other two hand conditions for Experiment I but not for Experiment II. It is possible that the complexity of the task during the maze experiment contributed to the lack of significant time differences across the conditions. Ultimately, we can answer *RQ4* as **different tasks might result in different impacts of hand visibility conditions in terms of the time, but not the number of collisions or user experience.**

In both experiments, participants were instructed to perform specific tasks in a virtual environment using different visibility techniques for their hand avatar and the object to be manipulated. In Experiment II, auditory feedback was used to notify participants when a collision occurred. Even though this feedback helped them self-assess their real-time performance, it is possible that it did not affect the number of collisions — because the feedback came after the collision itself. Instead, they could be notified about a potential collision they are about to make — either via auditory feedback (e.g., car parking alert systems) or via haptic feedback. We speculate that implementing such a "guidance" feedback system might help them perform better and learn to navigate comfortably in the virtual environment [8]. In addition, incorporating haptic devices to simulate the physical touch between the hand avatar and the cylindrical objects could augment the realism of the interaction and alter the user experience of using transparent or invisible hand avatars. However, these hypotheses require further exploration and investigation.

8 Conclusion

In this paper, we analyzed the effect of hand visibility and object visibility on different stages of sorting and navigational tasks in a VR environment to understand how the visual perception of hands and objects influences task performance. We conducted two user studies for different stages of the task (placement and navigation) with 18 participants each. Our results indicate that participants demonstrated enhanced accuracy (fewer collisions) when interacting with transparent or invisible hands paired with an opaque (visible) object. Additionally, our results revealed a significant decrease in task completion time while using the opaque hand compared to transparent or invisible hands.

In the future, we will explore the impact of hand visibility and object visibility conditions on user experience and user performance in application settings other than navigational tasks. We believe that different manipulation or exploration scenarios might indicate different trends than the findings reported in this study. In addition, we acknowledge that the lack of haptics is a big limitation of this study. Including different modalities and methods of haptic feedback could potentially augment user performance and experience [28] and even change the trends between the visibility conditions. We are planning to explore such visuo-haptic scenarios in the future.

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