Subtask-Based Virtual Hand Visualization Method for Enhanced User Accuracy in Virtual Reality Environments

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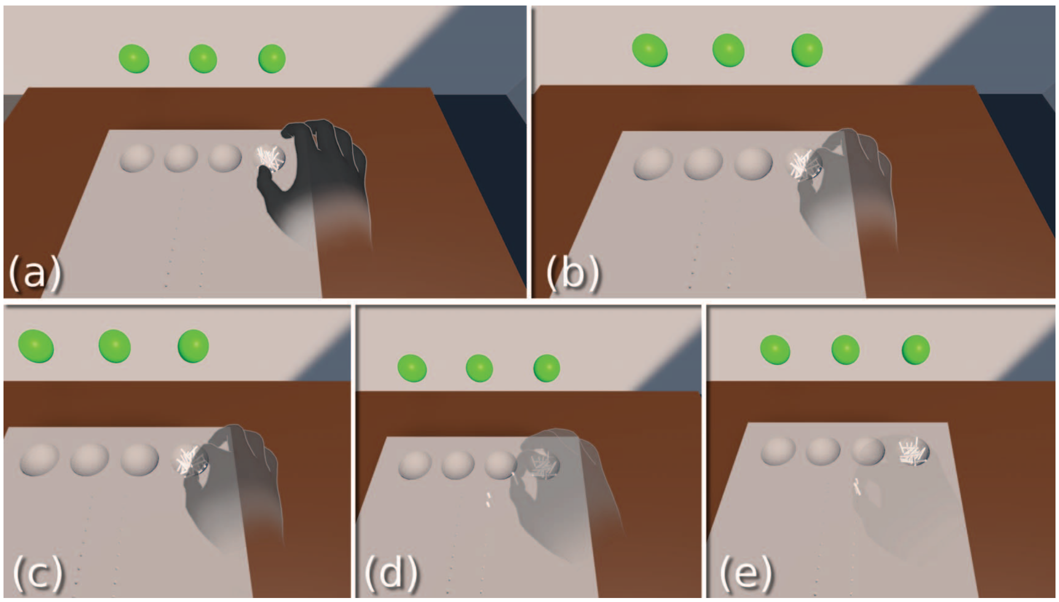

Figure 1: The proposed interaction technique, as demonstrated in the Purdue Pegboard Test (PPT), follows a systematic rendering approach: a) As participants initiate the "reaching" subtask, approaching the target, the virtual hand avatar is presented as opaque. b) When the participants start "grasping", the virtual hand avatar becomes transparent. The opacity of the hand increases with distance. c) While participants are "grasping" the peg, the virtual hand is maintained transparent. During the "transport" phase, as participants move the peg, the hand remains transparent. e) As the transported peg nears the target hole, the hand gradually fades out to become invisible. Throughout the "inserting" subtask, the hand remains completely transparent. Similarly, after successfully inserting the peg into the hole, the virtual hand's opacity gradually increases. This dynamic rendering sequence aims to align with the subtasks of the PPT, aiming to enhance user interaction accuracy and overall virtual experience.

Abstract

In the *virtual hand interaction techniques*, the opacity of the virtual hand avatar can potentially obstruct users' visual feedback, leading to detrimental effects on accuracy and cognitive load. Given that the cognitive load is related to gaze movements, our study focuses on analyzing the gaze movements of participants across opaque, transparent, and invisible hand visualizations in order to create a new interaction technique. For our experimental setup, we used a Purdue Pegboard Test with reaching, grasping, transporting, and inserting subtasks. We examined how long and where participants concentrated on these subtasks and, using the findings, introduced a new virtual hand visualization method to increase accuracy. We hope that our results can be used in future virtual reality applications where users have to interact with virtual objects accurately.

Index Terms: Human-centered computing—Visualization—Visualization techniques—; Human-centered computing—Visualization—Visualization design and evaluation methods

1 Introduction

Virtual Reality (VR) Head Mounted Displays (HMDs) take the human perception of reality to the next level, allowing individuals to immerse themselves in digital worlds. Unlike the constraints of the real world, VR opens the door to numerous possibilities. VR headsets can be used to train people in complex tasks [15], create virtual simulations and test them in a safe environment [12], and even create immersive experiences for entertainment [2]. Additionally, it can be used to help people with medical conditions improve their quality of life [11].

While early HMDs had limited functionalities, recent advancements, such as the finger-tracking feature in modern HMDs, now provide detailed hand avatars. Eliminating controllers from HMDs

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and relying solely on hand-tracking has the potential to significantly enhance user experiences. For example, Shangchen et al. [6] developed a low-jitter real-time hand tracking system that can be used for interaction across various tasks. However, achieving real-time, robust hand tracking still requires the development and implementation of novel methods. Further research is essential to explore more efficient and user-friendly virtual hand interactions in VR.

In virtual environments, realism does not always translate to improved performance. While realistic virtual hand avatar movements contribute to immersion, simplified hand visuals can achieve satisfying performance without sacrificing realism [3]. In VR experiences, ease of use is often more valuable than visual realism, preventing user frustration, which can negatively impact immersion [14]. Creating an immersive experience is possible with simplified hand visuals, and it can also enhance efficiency as rendering detailed hands demands more computational resources. However, allocating the computational budget to improve hand-tracking, is a challenging task [13]. Particularly during fine finger movements, occlusion of fingers or target may lead to unrealistic hand movements, reducing the precision of hand-tracking and potentially harming immersion and the overall user experience.

In a virtual environment, obstructing the view of a target object can make it difficult for the user to locate and interact with that object accurately. This situation also has the potential to disrupt immersion and result in a decline in the user's motor dexterity skills, impacting both gross and fine hand movements. Gross motor skills involve larger muscle groups, while fine motor skills involve smaller muscle groups like fingers. The user facing such a problem may struggle or fail to interact effectively with objects in the virtual environment. In this case, overcoming the challenge of reduced motor dexterity might require an additional cognitive load on the user, leading to mental fatigue and less precise interactions, ultimately causing a decline in overall performance.

The main goal of this study is to explore how hand visualizations affect fine motor skill tasks through the analysis of users' gaze movements. To achieve this, we conducted a pilot study in which participants performed a Purdue Pegboard Test (PPT) within a virtual environment, experiencing opaque, transparent, and invisible hand visualizations. Using the insights gathered from this pilot study, we developed a novel virtual hand visualization method during interaction. We hope that our proposed interaction technique can be used to increase the usability of VR HMD applications.

2 Previous Work

2.1 Hand Visualizations

The effects of virtual hand visualization in VR experiences have been the subject of extensive research, with many studies exploring their effects on participants' manual abilities [20]. One study by Ricca et al. [16] investigated the influence of transparent and opaque hand visuals on motor skills. The findings suggested that providing either transparent or opaque hand visuals did not result in a significant performance difference among users. In contrast, Veldhuizen et al. [20] proposed a transition technique that shifts from opaque to transparent as a hand approaches to grasp an object. Their study argued that such a transition significantly impacts precise object manipulation.

Furthermore, another study by Knierim et al. suggested that invisible virtual hand avatar visualization increases workload during typing in VR, while realistic hand visuals lead to the lowest workload compared to other visualization techniques [7]. These varied findings underscore the importance of carefully considering the choice of hand visualization techniques and their potential impact on different tasks within the VR environment.

2.2 Purdue Pegboard Test

The Purdue Pegboard Test (PPT) was developed by Dr. Joseph Tiffin at Purdue University in 1948 [10]. This test is specifically designed to assess fine motor hand skills by tasking individuals with completing activities involving pegs, washers, and collars. Over the years, it has proven valuable in measuring various neurological diseases, including brain damage, Parkinson's disease, and multiple sclerosis [1, 4, 5, 18].

Neuropsychologists often use the PPT to evaluate hand-eye coordination, manual dexterity, and fine motor skills in the context of patient treatments [9]. Moreover, in the occupational therapy field, the PPT is recognized as a confidential and effective tool for assessing the fine motor skills of the fingers [19]. Its scalability makes PPT a widely used measure in both clinical and therapeutic settings.

In a previous study, PPT was used to investigate the effect of different hand visualizations on user performance during fine and gross movements in VR HMDs [22]. Following a method inspired by Vasylenko et al. [21], Voisard et al. [22] investigated four subtasks of PPT: reaching, grasping, transporting, and inserting. In this paper, we adopt a similar approach.

3 Motivation & Hypothesis

Occlusion of the hand can hinder the user's ability to manipulate virtual objects. This limitation can be particularly detrimental in applications where precise object manipulation is crucial, such as medical simulations or training scenarios. Previous studies experimented with different hand interaction techniques to solve this problem by proposing novel visualization styles, such as invisible hand visualization [16]. However, such methods can also affect the user's spatial awareness and telepresence in mid-air, if there are no visual cues. A hand transparency method that combines the advantages of both visibilities can enhance the user motor performance and the user experience.

In this paper, we hypothesize that **H. The gaze movement of participants varies with each subtask (i.e., reaching, grasping, transporting, and inserting) of the PPT**. Building on previous literature that highlights the correlation between gaze movements and cognitive load [8, 23], our goal is to apply gaze movement analysis to the development of a novel interaction technique aimed at decreasing the cognitive load of users.

4 Pilot User Study

Building upon the previous work of Voisard et al. [22], we conducted a pilot study to investigate the gaze movements of participants while they performed in a PPT.

4.1 Apparatus

The experiment was conducted on a desktop PC equipped with an 11^{th} Gen Intel(R) Core (TM) i7-11700F processor running at 2.5 GHz, 32 GB RAM, and an NVIDIA GeForce RTX 3070 graphics card. As VR HMD, we used an Oculus Quest Pro. The virtual environment was designed and implemented using Unity3D version 2021.3.24 and the Oculus Unity-Integration SDK v51.0. For hand tracking, we did not use external hardware, such as a glove, but we used the built-in hand tracking system of the HMD. We also used the integrated eye-tracking system of the Oculus VR HMD.

4.2 Participants

We recruited 12 participants (11 male and 1 female) from the local university with ages ranging between 21 and 29 (average age 24.75 $\pm$ 2.75). All participants had normal vision or corrected-to-normal vision. Among the 12 participants, 11 of them were right-handed, and 1 was left-handed, and similar was with the dominant eye. When asked how many times they had experienced VR in their lifetime, 4 participants reported none, 3 reported 1-3 times, and 5 reported more than 5 times.

4.3 Procedure

For this paper, we conducted a user study where the participants performed a virtual PPT with three different hand visualizations: 3_HV**: opaque, transparent, and invisible hand**. Based on the previous literature and PPT, participants performed four tasks T_4 **main hand, off-hand, both hands and assembly**, where each activity is specifically tailored to evaluate the participants' manual dexterity in VR HMD.

4.3.1 Dominant Hand Task

Participants retrieved pegs from the dominant hand side's cup using their dominant hand and then inserted them into the column of the hole of that same side running down the board. We instructed them to perform this task as fast and as precisely as possible for no more than 30 seconds.

4.3.2 Non-Dominant Hand Task

Participants performed the same procedure described above, however, they were asked to use their non-dominant hand to pick up the objects and then to place them in their respective placement locations on the non-dominant hand side. The objective remained the same for both tasks.

4.3.3 Both Hands Task

For this task, participants were instructed to perform both the dominant hand task and the non-dominant hand tasks simultaneously within 30 seconds.

4.3.4 Assembly Task

Participants had to (a) pick up a peg from the peg cup on the dominant hand's side, and insert it in the column of a hole on the dominant hand side of the board. (b) Participants then had to pick up a washer in a cup on the non-dominant hand side of the board with their non-dominant hand and insert the washer over the peg placed in step (a). In step (c), with their dominant hand, participants then had to pick up a collar from the middle cup and place it on the peg and over the washer from the previous steps. Finally, in step (d), participants had to repeat step (b) and place it over the collar placed in the previous step. This task is also explained in Fig. 2. Participants were also directed to perform this task as fast and as precisely as possible for 60 seconds.

4.4 Sub-tasks

To systematically assess participants' hand dexterity, we adopted a methodology inspired by Vasylenko et al. [21], breaking down the PPT into four distinct subtasks: *reaching, grasping, transporting, and inserting*. This segmentation allowed us to examine gaze movements in detail.

4.4.1 Reaching

The participants performed the *reaching* subtask as their hands approached the cup of objects for grasping. The movement started when the hand initiated its motion towards the cup and ended when the hand reached close proximity to the cup.

4.4.2 Grasping

The participants performed the *grasping* subtask as they retrieved the desired objects from the cups. The movement started when the hand descended towards a cup and concluded when the hand successfully grabbed an object and moved away from the close proximity of the cup.

4.4.3 Transporting

The participants performed the *transporting* subtask while moving the picked object toward its designated location within the pegboard. This movement started when their hands first started to move toward the designated target and ended when their hand approached close proximity to the designated target.

4.4.4 Inserting

The participant performed the *inserting* subtask while placing the object into the designated hole or onto the already inserted object (peg or washer) into the said hole. This movement started when the hand first moved down towards the designated hole or the object and ended when the object was successfully inserted.

4.5 Eye Tracking

In our study, we used the integrated eye-tracking solution provided by Oculus Quest Pro, which tracks real-time gaze movements mapped to game objects. Using this information, we performed ray-casting from the gaze position of these objects to obtain hit details, including the hit position. Due to variations, i.e., jitter, in eye focus points, we averaged the positions of the two dwell/focus points, assigning priorities among categories. For example, if the left eye focuses on a virtual object and the right eye on a hand, precedence is given to the left eye. (Objectives > Hand > Environment).

4.6 Virtual Hand Avatar Visibility

In this study, we used three different transparency levels for hand visualization (3_V = opaque, transparent, invisible), following a methodology similar to previous studies [22] using a PPT.

For the *opaque* hand visualization, we used the default virtual hand avatar rendering from the Oculus SDK in Unity, with black color.

For the *transparent* hand visualization, we set the alpha value of the virtual hand avatar transparency to 79%. This is also the default alpha value for the transparent virtual hands in the Oculus SDK.

For the *invisible* hand visualization, we did not render the hand in the virtual scene while the user interacted with objects, such as while they were holding a peg. However, in this condition, if the participant did not interact with any objects, such as while exploring the scene, we rendered the virtual avatar as opaque. This provided participants with an understanding of the hand's pose in the virtual environment and spatial information when not engaged with objects.

4.7 Virtual Environment

For all three user conditions, the participants were placed in a virtual room facing the pegboard where they performed the PPT. The virtual environment featured three indicator spheres resembling traffic lights (colored red, yellow, and green), accompanied by sound cues. Participants were asked to start the task when the spheres turned green and a short sound was played. The task continued until the indicator spheres turned red, at which point all interactable objects, i.e. pegs, washers, and collars, were disabled from movement.

4.8 Experimental Design & Evaluation Metrics

In this study, we investigated the participants' focus of attention by monitoring their gaze movements and measuring the duration of their gaze. This allowed us to determine whether participants were looking at task objectives, their hands, or the surrounding environment. Before starting the experiment, each participant tested all hand visibility conditions for all of the PPT tasks.

It is important to highlight that eye-tracking data is recorded independently for each hand, meaning that the metrics are evaluated separately for the dominant hand and non-dominant hand. In tasks requiring only one hand, the eye-tracking data for the unused hand is not taken into account. However, for bi-manual tasks such as assembly, both hands are considered. For instance, when analyzing

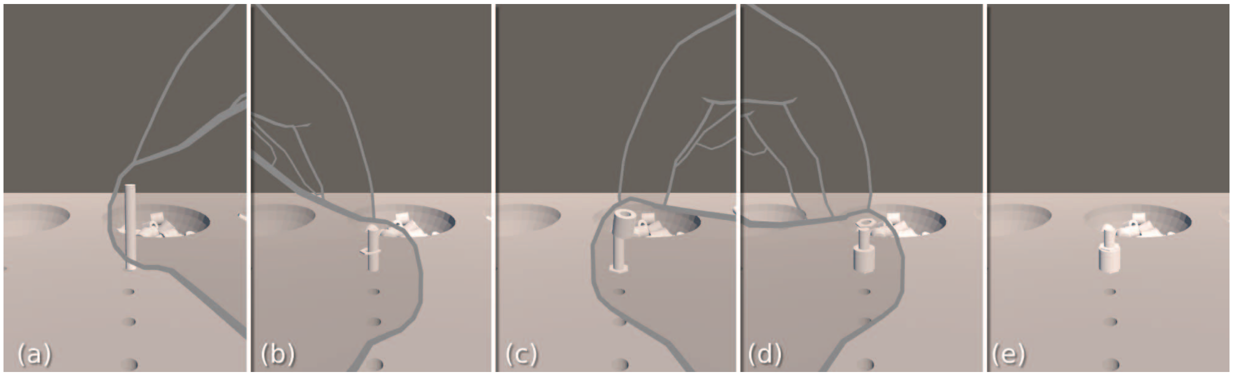


Figure 2: Steps of the assembly task with a right-handed configuration: a) right hand placing a peg in the hole, (b) left hand placing a washer onto the peg, (c) right hand placing a collar onto the peg, (d) left hand placing a washer onto the peg, (e) final result of the assembly task.

the data in the both-hands task, if the gazes are focused on the main hand, the eye-tracking data for the dominant hand is categorized as looking at the dominant hand, the data for the off-hand is categorized as looking at the non-dominant hand, and the data for the table is categorized as looking at the environment.

The following are the different classifications for where participants' eyes can look:

Objective The objective is determined by the location of the next step in the PPT. For instance, during the reaching subtask, if the participant is reaching for a peg with their dominant hand, the objective is the cup of pegs at the top of the board.

Dominant Hand The dominant hand category is defined as participants looking at their dominant hand during the movement.

Non-Dominant Hand The non-dominant hand category is defined as participants looking at their off-dominant hand during the movement.

Environment The participant is looking at the environment if they do not focus on any of the categories mentioned above. This could include looking at the pegboard while the eyes are moving towards the objective or hand.

5 Results

The percentage of time that participants look at their dominant hand, non-dominant hand, objective, and other objects are shown in Fig. 3.

5.1 Reaching

As the initial subtask of the PTT, participants reached for pegs. During the main hand task, participants tended to focus more on their dominant hand. Likewise, during the off-hand task, attention shifted toward their non-dominant hand. In the both-hand task, their gaze was primarily directed at the dominant hand. In contrast, in the assembly task, participants predominantly focused on their non-dominant hand.

5.2 Grasping

Grasping is the act of taking hold of or seizing something with the hand. It involves using the fingers, hand, or sometimes the entire arm to secure and hold onto an object.

In the main hand task, participants mostly directed their gaze toward their dominant hand when using invisible hand visualization for grasping. In contrast, with opaque and transparent hand visualizations, participants focused on the objective, specifically the peg.

During the off-hand task, participants looked more at the peg, regardless of the visualization conditions, although the results for the opaque hand were more pronounced.

In the both-hand task, participants predominantly directed their attention to the overall environment.

In the assembly task, participants focused on their dominant hand when using opaque and transparent hand visualizations, and on their non-dominant hand when viewing invisible hand visualizations.

5.3 Transporting

In the Purdue Pegboard Test, transporting refers to the task of moving small pins or pegs from one location to another on the pegboard.

In the main hand task, participants dedicated more time to looking at their dominant hand, especially while the entire hand was visible.

During the off-hand task, participants focused their gaze on the peg, particularly in the invisible hand condition. However, in both the opaque and transparent hand conditions, their attention shifted to their dominant hand.

In the both-hands task, participants consistently directed their gaze toward the peg, regardless of the visualization conditions.

In the assembly task, participants predominantly looked at their dominant hand in all visualization conditions.

5.4 Inserting

In the inserting task, individuals are required to insert pegs into specified holes on the pegboard.

During the inserting task, participants focused more on the pegs, particularly when using their main hand.

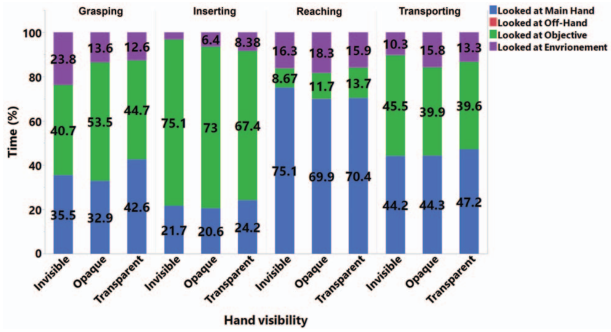
Likewise, in the off-hand and both-hand tasks, participants consistently directed their gaze toward the pegs, regardless of the hand visualization used.

In the assembly task, participants paid more attention to the pegs with invisible and transparent hand visualizations. Meanwhile, with opaque hand visualization, their focus shifted towards looking at their dominant hand.

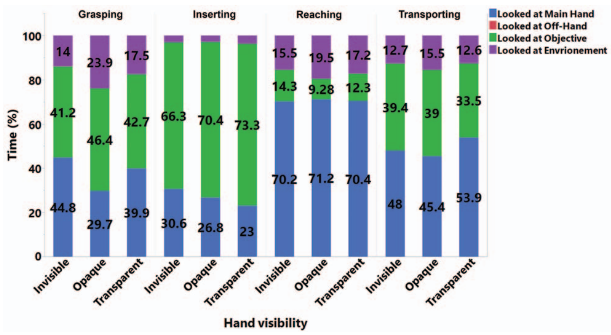
6 Discussion

In our pilot user study, we designed a task that involved 3 different hand visualization techniques (opaque, transparent, and invisible) with four different PPT tasks (main-hand, off-hand, both hands and assembly). While participants performed the PPT, we analyzed the duration of where they looked, e.g., focus, in the virtual environment.

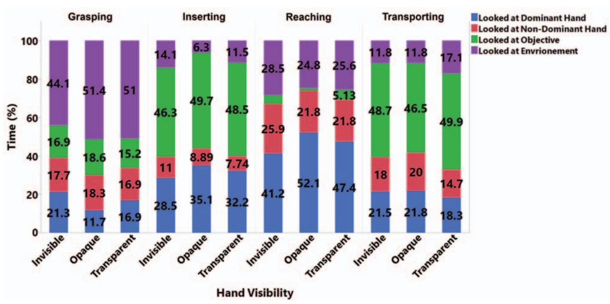
Our findings indicated that participants' gaze movements varied significantly with each subtask, aligning with our initial hypothesis. We attribute this variability to factors such as the pose of the virtual hand, the specific goal in each subtask, and the requisite hand-eye coordination for successful task completion.



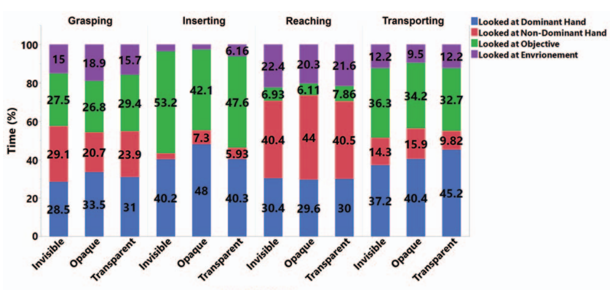
(a)



(b)



(c)



(d)

Figure 3: Results for a) main hand task, b) off-hand task, c) both hands task, and d) assembly task.

Aside from subtasks, the participants' focus also shifted based on different virtual hand avatar visualizations. In essence, how the virtual hand is rendered may impact the cognitive load of the participants in the PPT. While previous studies have explored cognitive load with various hand visualizations [17], we extended this literature to specifically investigate its implications within the context of the PPT.

Visual feedback from the hand is integral to proprioception, our sense of the relative position and movement of body parts. For example, when visual feedback is compromised due to occlusion, users may perceive a disconnect between their physical actions and the virtual environment, influencing their ability to perform tasks accurately. Thus, we also recommend further user experience research on virtual avatar hand rendering.

One limitation of this study is related to the design of the PPT. All tasks were intentionally made ergonomic to minimize user fatigue. For instance, in the dominant hand task, pegs were positioned close to the dominant hand, eliminating the need to cross the center of the experimental setup to reach pegs on the non-dominant side. Therefore, interactions involving such movements were not analyzed in this paper. Given the outcomes concerning different subtasks, we recommend conducting a follow-up experiment tailored to different tasks and environments to further validate and extend our findings.

6.1 Proposed Virtual Hand Visualization Method

Based on the main hand results of the Fig. 3, we propose the following hand visualization methodology to increase the accuracy of the users:

6.1.1 Reaching

In the "reaching" subtasks, we recommend using an opaque virtual hand visualization. When users are reaching for a target or goal, they focus on both the target and their hand. If the hand is fully visible and not transparent, users can keep it in their peripheral vision, allowing them to understand the hand's pose without directly looking at it. Therefore, suggesting an opaque virtual hand during the "reaching" subtask is aimed at helping users stay more focused on their hand movements and the target they are reaching for.

6.1.2 Grasping

In the "grasping" subtask, users require precise movements of the hand and fingers to effectively grasp the object. During these subtasks, the user's gaze is typically shifted between the target and their hand (or fingertips) as they approach it with high accuracy. However, our results showed that the participants predominantly focused on the target. Using a transparent hand visualization in such scenarios might allow users to track both their hand's pose and see the target or goal, e.g., minimize the obstruction caused by the hand. This approach can potentially enhance users' accuracy and speed during the "grasping" subtask.

6.1.3 Transporting

In the "transporting" subtask, users focused on moving the object from one point to another, dividing their attention between the target (in this case, the hole) and their virtual hand. Since the specific points on the virtual hand that the participants focused on during the transportation subtask were not extensively analyzed, we recommend that researchers investigate whether participants predominantly focused on the peg, fingertips, fingers, hand, or other virtual objects during this stage.

Considering that participants were observed shifting their attention between their virtual hand and the target, similar to the "grasping" subtask, we propose the use of a transparent hand visualization. This choice enables users to simultaneously keep track of their virtual hand pose and monitor the transferred object, e.g., the peg. It can also contribute to an accurate approach towards the destination, e.g., the hole.

6.1.4 Inserting

In the "inserting" subtask, users primarily concentrate on the target, e.g., the hole. In this scenario, using the invisible hand condition could help participants focus directly on the target, eliminating potential occlusion issues. We also hypothesize that because users already have spatial information about the peg from the previous subtask, they can focus more on the target, potentially enhancing accuracy. However, it is important to note that this speculation requires further investigation.

Following the "inserting" subtask, the system should reset the algorithm above and resume the virtual hand visualization as in the "reaching" subtask, with the hand being opaque.

It is important to note that the transition between different hand visualizations is a crucial component of this method. To prevent user distraction, we recommend avoiding sudden changes in visualization. A gradual transition between virtual hand visualizations can enhance user experience and engagement. An example virtual hand visibility change is shown in Fig. 1 (c, d, and e).

In this paper, we did not evaluate the proposed subtask-based interaction method in the context of the PPT. Consequently, the efficiency and effectiveness of this method still need to be evaluated and compared with existing solutions.

7 Conclusion & Future Work

In this paper, we analyzed the gaze movements of participants while they performed a Perdue Pegboard Test (PPT) with a Virtual Reality (VR) Head Mounted Display (HMD). The findings revealed that participants directed their attention to different objects during each subtask, as well as virtual hand visualization can affect where the participants focused. Specifically, participants tended to focus on their hand during the "reaching" subtask, the peg during the "grasping" and "transporting" subtasks, and the hole during the "inserting" subtask.

Based on these results, we created a novel virtual hand interaction technique customized for each subtask using virtual hand avatar visualizations. In this approach, the hand is visualized as opaque during the "reaching" subtask, transparent during "grasping" and "transporting," and not rendered during the "inserting" subtask.

In the future, we aim to evaluate the effectiveness of our proposed interaction technique on the PPT and extend its application to various fields such as surgical planning, technician training, and virtual car driving. Additionally, we plan to enhance the interaction technique by switching from a position-based approach to a speed-based one, where each subtask is defined by the speed of the hand. We hope that our proposed technique can be used to increase the usability of virtual reality systems.

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