The Effects of Hand Representation on Experience and Performance for 3D Interactions in Virtual Reality Games

NICHOLAS BALCOMB, University of New Brunswick, Canada
MAX V. BIRK, Eindhoven University of Technology, Netherlands
SCOTT BATEMAN, University of New Brunswick, Canada

Fig. 1. Three Virtual Hand Representations performing various interactions. Showing Left to Right: Sphere in interaction *Grab & Drop*, Controller in interaction *Pull-Down*, and Hand in interaction *Rotate-Around*. Top Row shows the representations when Idle. Bottom Row shows the representations when actively grabbing an object.

In Virtual Reality (VR), natural 3D interactions are performed with hand representations – the visualizations and interactors used for manipulating objects. Hand representations in VR games range from abstract shapes, to graphical versions of input controllers, to realistic human-like hands. Hand representations have been shown to have an important effect on play experience and performance. However, previous work has only considered them for individual 3D interactions or an entire game, giving designers little information about how a representation might perform and be experienced across different 3D interactions (like picking up and rotating objects, or opening a container). In this work, we compare three hand representations across 12 different 3D interactions and in a longer game experience in a study of 45 participants. We find that while

Authors' addresses: Nicholas Balcomb, nbalcomb@unb.ca, University of New Brunswick, Fredericton, Canada; Max V. Birk, m.v.birk@tue.nl, Eindhoven University of Technology, Eindhoven, Netherlands; Scott Bateman, scottb@unb.ca, University of New Brunswick, Fredericton, Canada.

2573-0142/2023/11-ART420 $15.00
https://doi.org/10.1145/3611066

representation did not affect performance, representations were overall experienced differently across 3D interactions. Our work provides a deeper understanding for VR game designers about how hand representations can be used to shape play experiences.

CCS Concepts: • **Human-centered computing** → **Virtual reality**; *Interaction techniques*; *Interaction design*.

Additional Key Words and Phrases: virtual reality, representation, interaction, ownership, agency, performance, usability, games, video games, game tasks

ACM Reference Format:
Nicholas Balcomb, Max V. Birk, and Scott Bateman. 2023. The Effects of Hand Representation on Experience and Performance for 3D Interactions in Virtual Reality Games. *Proc. ACM Hum.-Comput. Interact.* 7, CHI PLAY, Article 420 (November 2023), 28 pages. https://doi.org/10.1145/3611066

1 INTRODUCTION

In Virtual Reality (VR), the primary means of performing 3D interactions is through hand representations – the visualizations and interactors used for manipulating objects. In VR games, a small set of example 3D interactions with virtual objects includes picking up, rotating, throwing, dropping, placing, opening, attaching, separating, and performing object-specific actions (e.g., firing a gun), among others. Virtual hand representations in VR games have taken many different forms. For example, *Moss* [G17] uses a simple abstract shape (a sphere). The hand representations in *Hot Dogs, Horseshoes & Hand Grenades* and *Keep Talking and Nobody Explodes VR* [G19, G21] are 3D models of the VR controller being used. *Beat Saber* and *Pistol Whip* [G1, G6] use a light saber and gun, respectively, as hand representations as these objects are always 'held' in these games. *Boneworks* and *Half-Life: Alyx* [G22, G25] use realistic, human-like, fully-rigged hand models. Some games use combinations of the previously mentioned approaches. For example, *Super Hot VR*, *Gorn* and *Job Simulator* [G8, G16, G23] use realistic hands that are replaced by objects once the objects are picked up. The range of hand representations used and their visibility and importance for 3D interactions in VR games raise questions about their potential impact on players and play.

Embodied interaction describes the possibility of interacting with technology that aligns with how people naturally interact and understand the world (e.g., through tangible interfaces [19]). This can allow people to better understand their interactions and the information being manipulated [9]. Embodied interfaces like those found in VR can promote natural interactions and lead to positive effects on experience and performance in 3D manipulations [4], and VR [14]. Hand representations, like other body part representations [14], affect embodiment, performance and experience in VR games [1, 13, 25, 26, 34]. Previous work has established that embodied representations, such as those representing the point of interaction (i.e., the hands), require careful consideration in designing VR play experiences.

Despite the importance of hand representation for player performance and experience in VR games, there are basic questions that still exist around the design of hand representations. In particular, previous work has only considered hand representations for individual 3D interactions [3, 25] (for performing particular interactions like moving an object to and from a location [3, 25] or moving the hand following a specific path [3]). Recent work did consider hand representations at the level of a game [1, 26]; however, while covering a range of 3D interactions, they were not evaluated individually, limiting our understanding of the use of representations for individual interactions. Overall, the effects observed from previous work on hand representations in VR games has found conflicting information. Some work suggests representation can increase ownership [3, 25, 37] or agency [3, 37], while other work has suggested there is no effect from representation on either [24, 26, 39]. The same is found for performance, where some work suggests representation has an effect [39], and others find no effect [26, 30]. Together, current work gives designers only limited information about how a particular representation might perform and be experienced across different types of 3D interactions in their game. For example, a hand representation that occludes the view of an object might be a problem for a task that requires object inspection, but that same representation might provide improved embodiment and have a desirable effect on player experience. Whether or not such situations might exist for certain interactions and hand representations has not been previously studied.

In this work, we aimed to study hand representations drawn from VR games under a variety of different 3D interaction conditions to better understand how the combination of interaction and representation might affect performance and experience. To do this, we first identified three hand representations drawn from existing VR games: an abstract sphere (Sphere), a controller model (Controller), and a realistic, human-like hand (Hand). Next, we identified a series of 3D interaction properties that we used to help us select and implement 12 different 3D interactions. Forty-five participants completed a study using the three hand representations in all 12 different interactions and in a longer game-like experience called the Alchemist Experience. No previous work has explored this wide of a space of the different factors that might affect play experience and performance with hand representations.

Our results show that while representation did not meaningfully affect performance, participants did experience representations differently across 3D interactions. The more realistic hand led to improved embodiment and provided the best play experience across all 3D interactions, with only a few exceptions where issues such as occlusion arose. Our results also demonstrate a nuanced relationship between hand representation and the interactions they are used in, and the need for more study to help game designers understand how a critical design choice can be made. Our work deepens the understanding of and provides new directions for studying embodied play in VR games.

2 RELATED WORK

In this section, we present related work on the effect of virtual hand representations on experience and performance in 3D interactions and game-like experiences. Previous research has studied the effects of visual representations on user embodiment (e.g., [21, 24–26, 39]), but not across different types of 3D interactions (grasping, pulling, rotating, etc.), using consumer VR controllers, or also in the context of a game. However, we present work that informs our research by examining the factors (interaction and visual representation) independently and their effects in VR contexts.

2.1 Interactions in Virtual Reality

The design of VR interactions varies across VR experiences. In VR games, how a specific interaction is designed relies on many factors, such as the devices used for input, the tracking technology, the interaction to be performed, and the aesthetics and setting of the game. Whether it is through tools with defined purposes [G1, G14], or realistic, freehand interactions [G22], VR interactions benefit from a natural and intuitive design [27].

The input and tracking device can greatly affect the trade-off between the naturalness of manipulations and their precision. For example, a previously designed cutting interaction in VR using a hand-tracking system was accomplished by opening and closing a peace sign (i.e., with the middle and index finger outstretched) [27]. A study of this interaction found users felt it was natural and intuitive but lacked precision. Exact and precise cutting operations were more easily accomplished using physical VR controllers because of the improved capability to track their movement.

Not all 3D interactions require precision to be effective, as the effectiveness of an interaction depends on the task it's applied to [23]. Various tasks, such as Selection or Positioning, are accomplished with different interactions (i.e., grasping, pointing) [23]. Because interactions can be accomplished in many ways and different interactions might be used to accomplish a task, complex relationships exist between task and interaction types. Further, the properties of an input device/method can allow for additional inputs or constrain the design of the task due to the features of the technology [23].

2.2 VR Input Devices

Input devices vary in quality (i.e., precision and reliability) and quantity of inputs. For VR games, devices typically come in three forms: the common gamepad, gesture-based hand tracking, and 6-DOF tracked-controllers designed for VR. Gamepads such as an Xbox controller are not as common in VR; however, some users may prefer them for certain games, and some VR games exclusively support gamepads (e.g., Star Wars: Squadrons [G15]).

The controllers used can have a substantial impact on play experience. In a recent study, a VR controller (the VIVE Wand) used in a VR FPS game resulted in higher presence, engagement, and both perceived and real performance when compared to a gamepad [2]. Despite this, players held a preference for a gamepad. This effect, described as “genre fidelity” [2], explains player expectation of the input device combined with the game’s genre affects preferences [2].

The physical design of a controller and its available inputs also impacts performance and experience for different game genres, whether through their physical form or the naturalness of their input mapping [38]. The latter directly influences the perceived presence and enjoyment of a game [38]. This is a challenge for actions in VR, from basic actions such as pointing [29] to complex grasping actions. Grasping in particular is far more complex due to it inherently requiring highly dexterous and versatile movements [7].

Hand tracking can support natural grasping actions through free-hand interactions. However, the devices used for hand tracking, such as data gloves or controllers, may constrain movements or cause discomfort [7]. You’re often limited to grasping or gestures for interaction, and depending on the number of required actions, these gestures may be arbitrarily designed for recognition and not intuitive [7]. Additionally, unless the user is holding a real-world analogue for each object [11, 28], the risk of the in-game hand representation intersecting a virtual object is high, which breaks the illusion [1, 6]. This can be improved upon by using physics-based interactions [7] or using pre-defined poses [6].

VR controllers may offer a compromise, having both intuitive and natural mappings for interactions while still benefiting from a physical input device. For example, a VR controller tracking finger movement and position allows the virtual hand to animate its fingers. This allows for a more realistic virtual representation through visual feedback and stimuli, leading to an increased sense of embodiment and immersion [13, 16, 37].

2.3 User Embodiment

The feeling of controlling a virtual body, with all of its properties being felt as one’s own is User Embodiment [3, 13, 22, 25, 31]. This is often defined by three dimensions: the sense of ownership, the sense of agency, and the sense of self-location. For the purposes of this study, we focus on the first two dimensions.

The sense of ownership is described as the sense of one’s own virtual body being their own, including all sensations, features, and attributes [3, 20, 25, 31]. While this may be responsible for the effects of physical appearances or stimuli from interactions [3, 16, 26, 33], it is different from being in control of the body. The sense of agency is the feeling of control over your actions in a virtual environment and is best induced when the intended and actual motion of a user is replicated exactly in real-time to the virtual body [3, 20, 31].

Many factors aid in strengthening the sense of ownership and agency in virtual reality, such as providing a realistic environment and body for a user. The appearance of the avatar can be affected by its general structure and visual appearances, such as being more human-like or similar to the user [13, 34]. However, in some cases, even if the appearance differs greatly from the user, ownership might not be reduced much [16, 40]. The realism of the body's motion and interactions relies on accurate tracking and mapping to movements in VR. Representing the hands is a challenge in VR as they are the primary way that users interact with VR games.

2.4 Effects of Virtual Representation

How the virtual body interacts with and is represented in a virtual environment may affect the user experience. This includes how the hands or body appear [26], or during interactions such as snapping pre-defined poses or full physics-based interactions [10, 17]. Another factor is the rendering and animations of the hands or body. A mismatch between user actions and the animation or graphical rendering can affect immersion and ownership [13, 24]. Further, the user's ability to perform actions can be affected when rendering issues such as visual occlusion or object collision/intersection are not adequately handled [6, 10, 15, 40].

It is not currently well understood why a change in representations sometimes affects play experience (including through the senses of embodiment: ownership and agency) and performance, while other times it does not. Several studies have come to varying conclusions about how the hand's representation in VR can affect performance and experience. These studies have compared various hand-like representations, shapes and controller models [3, 25, 37]. Some studies have also explored full arm or body representations [26, 39]. Some research has found that ownership increases with more realistic representations [3, 25, 37] while less realistic models, such as controller models, icon-based models, or abstract representations increase agency [3, 37]. Yet other research has concluded that there is no effect of the specific hand representation on ownership or agency [24, 26, 39]. Additionally, for performance, there is research that representation both does [39] and does not [26, 30] have an effect.

The factors affecting experience and embodiment have a relationship with how the user may perform with certain interactions and manipulations [3, 8, 35], and can cause different behaviours to be exhibited [21]. This relates to the Proteus Effect [43], which suggests how we are represented in a virtual environment matters for how we then act in it. Thus, defining the effects of the virtual representation of the user is multi-faceted, involving how closely the virtual and physical match [24], the input device used including its physical shape and characteristics [2], how inputs are mapped [38], the visual representation, and any feedback from the system and how it is experienced [36].

2.4.1 Virtual Hands. Virtual hand representation varies between VR experiences based on several factors: the design, setting, input devices, interactions, the goal of the system, and more. They also range in complexity: the number of features, level of realism, and level of compatibility with various VR platforms. For example, a sphere-based representation is commonly used [3, 25], as found in *Moss* [G17]. While lacking in realism (compared to fully rigged photo-realistic hand models) [3, 25], sphere-based representations are less complex in terms of implementation. On the other end of the spectrum are more realistic, human-like hands [G25]. Depending on the input data available and implementation, realistic hands can be fully articulated and pose naturally, and can react dynamically when interacting with objects.

Another common approach that may strike a balance between a simple shape and a realistic hand-like representation, is a one-to-one virtual controller representation [25], as found in *Hot Dogs, Horseshoes & Hand Grenades* and *Keep Talking and Nobody Explodes VR* [G19, G21]. In these games, a controller model is used that matches directly with the physical controller being held. The controller may be augmented to include feedback (e.g., highlighting a corresponding button press) or new interaction techniques (e.g., built in laser pointer for selection). Using controller models might have the advantage of helping the player see the orientation and input state of the physical controllers, and they would likely not need to be developed from scratch (high-quality and accurate controller models are readily available). On the other hand, controller models likely do not match the theme or other design elements of many games.

2.5 Summary

In summary, research has established that the virtual representation of a user can affect their experience (e.g., of embodiment), behaviour and ability to perform in 3D interactions and VR games. However, virtual hand representations (i.e., the representation of what we primarily use to interact with in VR) have only been tested in single 3D interaction tasks [25] or in game-like experiences [1, 26]. Since previous work has also found conflicting results in the effect of hand representation, this leads to questions about how different hand representations might be experienced or perform in different types of 3D interactions, and a game-like experience.

3 METHOD

Our research aims to help VR game designers better understand the potential impacts of a fundamental design choice for most VR games. Hand representations vary widely in practice, and it seems like how they are designed could have an important impact on player performance and play experience.

To this end, our study was designed to focus on three broad research questions to help inform VR game designers:

- Does hand representation affect performance?
- Do hand representations perform differently during different interactions?
- Does hand representation affect player experience?

To shed light on these questions, we designed a user study that compared three different representations for a variety of 3D interactions in VR. Our study consisted of two parts. The first part, *3D Interactions*, had participants perform a sample of 12 unique 3D interactions with three hand representations (Sphere, Controller, and Hand). In this part of the study we focused on measuring performance (interaction completion time), parts of play experience through embodiment (via ratings of ownership and agency), and ratings of usability and general play experience.

The second part of our study was a game-like experience called the *Alchemist Experience*, in which participants completed a brief game-like scenario incorporating all the interactions used during the *3D Interactions*. In this part, we focused on assessing how different representations might affect play experience (via the PENS questionnaire [32]).

3.1 Representations and Features

We implemented and tested three different virtual hand representations (called Sphere, Controller, and Hand). Each representation varied in its appearance and behaviour. Each representation's position was matched to the participant's hand and position using positional data of Valve Index controllers (described in Apparatus 3.5, below).

In creating the hand representations used in the study, the authors first discussed representations that we had previously experienced in games and seen in related work. We then sampled a set of popular VR games (see Ludography for the full list of sampled games) and identified the hand representations used. While these representations are clearly different in their abstraction and may exist on a multi-dimensional continuum of abstraction (i.e., Controller may be more true to reality than Hand in some cases), defining just how different they are is out of scope for this study. We simplified the selection with a practical approach based on popular VR games for the purposes of this study.

Below we described each of the three representations, but we first describe important properties that we established while identifying the representations. The properties relate to **Assistance Features**, **Interaction Behaviour**, and **Action Animations**. These properties are described first to make clear similarities and differences in feedback and interactions across the three representations.

Fig. 2. The Assistance Feature *Input Highlighting* implemented with the Controller hand. The grip is highlighted in yellow, indicating that the user is squeezing both controller grips (Interaction: *Attach*).

Fig. 3. The Interaction Behaviour Feature *Hand Tether* implemented with the Sphere hand. When the hand grabs the handle and pulls away, a tether connects it to the hand (Interaction: *Rotate-Fixed*).

Fig. 4. Interactions *Grab & Place* (Left) and *Separate* (Right) with the Sphere hand. The Sphere's size matches its bounds for its area of activation (*Activation Area Visibility*), highlighting an interactable object when it collides.

3.1.1 VR Hand Representation Properties. Through our analysis and implementation, we identified properties that were either common across multiple hand representations or that are most salient in how the representation is realized.

- **Assistance Features**: refers to making visible details about interaction with the physical controller or the virtual environment visible to the user.
  - *Input Highlighting*: Inputs (e.g., button presses or closed hand gripping the controller) from the VR controller would be displayed visually to the user in the hand representation.
  - *Activation Area Visibility:* The bounding box that dictates the area of activation for interacting with virtual objects is visible. See Figure 4.

Fig. 5. Left: A hand approaching an interactable, highlighted handle from the *Rotate-Fixed* interaction. Right: The hand interacting with the handle after the user grips the controller - the hand poses to the handle.

Fig. 6. *Animated Tracking* feature. Left shows the hand in its open state. Right shows it in its closed state, triggered when the user's real fingers close around the controller's grip.

- **Interaction Behaviour**: refers to details about how actions taken by the user are represented with the technique and to convey interaction state.
  - *Hand Tether*: Certain interaction types create a tether to the hand as it moves away from the interaction focus, signalling the object is still interacted with. For example, when rotating a virtual wheel (Figure 3), if the representation's bounding box no longer intersects with the object after interaction started, a virtual tether connects the representation to the wheel, indicating that the wheel can still be turned.
  - *Object as Hand*: When the user grabs an object or performs an interaction, the representation of their hand disappears and the interaction focus then becomes the hand. This can be both an interaction behaviour, or a fully-fledged hand representation. See Figure 1.
- **Action Animations**
  - *Animated Tracking*: Elements of the hand representation are tracked and represented based on the state of the user's real hand, such as finger position, or through inputs such as button presses (Figure 6).
  - *Animated Fixed Poses*: The hand representation animates into a predefined pose during interaction. Animated fixed poses are an alternative to fully dynamic posing (where the virtual hand can pose in any way that the hand might) or non-animated fixed poses (no transitions between pose states). For example, when grasping the controller around an object, the hand animates to fit around the object (Figure 5).

3.1.2 Hand Representations Created for the Study. Below we describe three hand representations we implemented, which range from more abstracted to less abstracted. Each representation shares a set of common features and properties, including location being centred exactly to the real-world position, providing feedback for common inputs such as grasping, having the same size bounding box for interactions, and methods for avoiding occlusion and distraction issues such as unrealistic intersections [6, 40]. The three representations can be seen in Figure 1.

- **Sphere**: Symmetrical, semi-transparent spheres (Figure 1). The Sphere representation is the simplest in terms of its visual representation, and was designed to mimic the hand representations in *Moss* [G17]. Sphere uses 'input highlighting' to denote a grasping state, where a smaller yellow sphere in the centre of the hand denotes the controller is being gripped. For certain interactions involving objects in fixed positions, a visual tether between the object and the hand was displayed as the user pulled away to maintain the visibility of the interaction state. The sphere was sized to match its activation area. Because the sphere is semi-transparent it allows players to have an un-occluded view of objects and the environment. Sphere featured the following properties: *hand-tether*, *activation-area-visibility*, and limited *input-highlighting*.
- **Controller**: Semi-transparent models of the VR controllers used, with their virtual representation exactly matching the physical controllers being used. See Figure 7.

Fig. 7. Left: The virtual Controller hand. Right: The user's hand holding the controller (Valve Index) in the real world.

  The Controller representation visually highlighted buttons pressed on the controller, allowing for instant input feedback. While the Controllers were semi-transparent like Sphere, when a user grasps an interactable object, the controller model disappears and only the virtual object remains. Our implementation for the controller representation and its behaviours are inspired from *Hot Dogs, Horseshoes & Hand Grenades* and *Keep Talking and Nobody Explodes VR* [G19, G21]. Controller featured full *input-highlighting* and *object-as-hand* properties.
- **Hand**: Realistic gloved hands of a fixed size provided by the *SteamVR SDK*. The realistic Hand representation does not use transparency or disappearing behaviour (more closely representing real hands; see Figure 1). However, visual occlusion was reduced through the use of animated, pre-defined poses for object interactions. This ensured the pose was placed optimally, would look natural and not unrealistically intersect with an object.
  The position and angle of the hand closely matched their real-world counterparts. Hand featured *animated-tracking*, *animated-fixed-poses*, and limited *input-highlighting* properties. The hand model was recoloured from the Steam SDK to better fit the medieval theme of our system.

3.2 Action Types and 3D Interactions

The 3D interactions chosen for the study were based on several rounds of brainstorming between the authors and observation of games to establish a sample of interactions and manipulations found in VR games. In this process we first emphasized creating a large set of different *action types* (e.g., pulling, rotating or placing) that covered unique combinations of motions and/or other input. This process was meant to be informative only and act as a guide for designing 3D interactions, not to create a definitive list of action types. Next, we identified a set of 12 3D interactions that contained these action types. For example, interaction *Grab & Drop* contained *Grab* and *Drop* Action Types. See Figure 2 for the complete mapping of interactions to Action Types. These 12 3D interactions were additionally chosen for being distinct yet simple, and they could be cohesively put together for a small game-like experience. Other interactions, such as aiming, throwing, or climbing were observed but not included as due to the already large set of interactions.

We took this approach because we realized that many games contain a wide range of interactions, but that the exact set of interactions was largely distinct based on the goals, setting, and other game specific factors. In this way, we hope to maximize the generalizability of our findings by covering a wide range of different 3D interactions.

3.2.1 Action Types. The list below describes the action types that we first identified (as described above) and that were used to guide the design of the 12 3D interactions used in our study.

- **Grab, Place, Move, Drop**: The user grabs an object and either places it in a specific location, moves it through a location, or drops it into a location in the environment.
- **Rotate**: The user must rotate either a fixed-axis object (such as turning a valve or screwdriver), or hold and rotate an object around a point in the environment (such as grinding a herb using a stirring motion).
- **Push & Pull**: The user pushes and/or pulls an object. This can be done either horizontally or vertically.
- **Bimanual**: The interaction involves the use of both hands at the same time in coordination.
- **Multi-System**: The interaction requires multiple distinct systems, objects or interactions to be used together.
- **Attach, Separate**: The user must attach two interactable objects together, or separate one object into two.
- **Controller Input**: Utilizing the inputs or buttons of a controller to perform a step of or the full interaction.
- **Pouring**: The user must grasp an object such as a bottle and tilt it to pour its contents (creating an interaction that is strongly coupled to the physics of the system).
- **Precision**: The interaction requires fine control or precision in order to execute.
- **Look Around**: The user manipulates an object's position and rotation in their hand to look around it.

3.3 3D Interactions Used in the Study

From the different action types (described above), we designed and implemented 12 different 3D interactions for our study (see Table 1 for the name and description of the interactions). Table 2 shows how the interactions relate to each of the action types.

3.4 Game Theme of the Experimental Environment

Recall that in the first part of our study (3D Interactions) we asked participants to complete each of the 12 interactions (described in Section 3.3). This first part of the study also let participants get familiar with each interaction, as in the second part of the study, the *Alchemist Experience*, we asked participants to complete an extended potion making game-like experience that combined all 12 interactions into one longer task.

Table 1. Descriptions for 3D Interactions 1-12.

Interaction	Name	Description	Figure
Interaction 1	Grab & Drop	Grab an object and drop it into a highlighted location.	Figure 1
Interaction 2	Grab & Place	Grab an object and place it in a specific location.	Figure 4
Interaction 3	Pull-Down	Pull a lever on the wall down.	Figure 1
Interaction 4	Rotate-Fixed	Rotate a valve between values to control temperature.	Figure 5
Interaction 5	Open-Close	Open a chest and drop an object in before closing it.	Figure 8
Interaction 6	Look-Around	Grab a cube and look around it, changing the colour on button press.	Figure 8
Interaction 7	Push-Pull	Pull a tray out and drop an object on it before pushing it back.	Figure 9
Interaction 8	Rotate-Around	Place an object in a stone bowl and rotate a handle to grind it.	Figure 1
Interaction 9	Attach	Attach a cork onto an empty bottle.	Figure 2
Interaction 10	Separate	Pull a cork out of an empty bottle.	Figure 4
Interaction 11	Precision-Pour	Pour a precise amount of liquid from a bottle.	Figure 9
Interaction 12	Scoop	Fill a bottle by scooping it through a larger cauldron.	Figure 8

Fig. 8. Various Interactions using the Controller representation. Interactions shown are *Open-Close*, *Look-Around*, and *Scoop*.

Fig. 9. Example Interactions using the Hand representation. Interactions shown are *Push-Pull* and *Precision-Pour*.

Our interaction implementations in *3D Interactions* were also undertaken in the Alchemist Experience environment, and so took place in a medieval theme, e.g., in a room of a castle. We did this partially to simplify our implementation, but also to identify whether realistic game environments can interact with the representations and interactions in any way. We piloted our experiment extensively to ensure there were no unexpected interactions. We found that we had no reason to believe that our performance results would be affected in a meaningful way by conducting our experiment in the game environment (as opposed to, for example, a generic environment with no background).

Table 2. The relationship between Action Types and 3D Interactions used in the study. Interactions can contain multiple action types.

Actions Type	3D Interactions
Grab Object	All
Place Object	Grab & Place, Rotate-Around, Attach
Move Object	Scoop
Drop Object	Grab & Drop, Open-Close, Push-Pull, Look-Around
Rotate (Fixed)	Rotate-Fixed
Rotate (Around)	Rotate-Around
Pull (Vertical)	Pull-Down
Push/Pull (Horizontal)	Push-Pull
Bimanual	Open-Close, Push-Pull, Attach, Separate
Multi-System	Open-Close, Push-Pull, Rotate-Around
Attach Objects	Attach
Separate Objects	Separate
Controller Input	Look-Around
Pouring	Precision-Pour
Precision	Precision-Pour
Look Around Object	Look-Around

3.5 Participants and Apparatus

Forty-five participants (self identifying: 35 male, 7 female, 2 non-binary, 1 preferred not to say, median age=22) were recruited from a local university. The majority of participants were right-handed (n=41) and had used VR at least once before (n=28), but only 4 participants used VR at least once a month. We accommodated for handedness by assuring that objects in the virtual environment were positioned at a consistent distance to their dominant hand.

The study used a Vive Pro head-mounted display (HMD) and Valve Index controllers. The system was run on a Windows 10 PC with a NVIDIA GTX 970 and ran at 90FPS in the HMD. It was created using Unity 2020 with the OpenXR plugin version 1.2.8, and the system is available at https://github.com/hcilab/HandRep. The available space for room-scale VR was 3m by 3m. At the start of the experiment, signed consent forms were obtained from all participants.

The choice for using the Valve Index controllers was based upon their features. Offering a comfortable grip, with a strap securing the controller to the hand even with an open palm, they also provide individual finger tracking through sensors (https://www.valvesoftware.com/en/index/controller). For each of the hand representations chosen we were able to support open-hand interactions which, while not the same as free-hand interactions, may still feel natural and intuitive and do not suffer from the tracking issues associated with camera-based hand tracking [7, 27]. All grasping interactions therefore made use of opening and closing the hand (rather than through button presses).

3.5.1 Commentary on Development Effort for Different Representations. The development and implementation of each hand representation was different in the system. The Sphere representation was straightforward, requiring only a primitive sphere object to be linked to the virtual location of the user's tracked hands. The Controller representation required finding readily available 3D models of compatible VR controllers, then mapping individual textures to the different buttons for visual feedback on input presses (which was done even if the button was not used). The Hands representation in comparison was difficult to implement – utilizing the hands provided by the *SteamVR SDK* with an altered texture to better match the theme, the hands required manually creating poses by moving individual bones (linked sub-objects of the hand, i.e., individual bones per finger) for each unique object they could interact with, as well idle poses such as open hand and closed hand. Then smooth animations between all poses were created and linked to actions that can identify the objects or state of the hand(s).

3.6 Study Design

The study was separated into two aforementioned parts, the *3D Interactions* and the *Alchemist Experience*. This was to analyze any effects (if applicable) from testing isolated interaction tasks or in a game-like experience. The experiment used a within-subject design, and each participant was assigned one of six orders of Sphere, Controller or Hand representations, following a full Latin-square.

With the hand representation being the independent variable, the dependent variables can be separated into three categories; embodiment, performance and general play experience. Embodiment is primarily measured through ownership and agency scores, while performance is captured through task completion time. Play Experience is captured through various questionnaires during different stages of the study.

3.7 Procedure

Our procedure and experimental plan was approved by our local University Research Ethics Board (on file as REB 2022-074). Participants were recruited via email from the local University population during the Summer of 2022. Participants were given an informed consent form and a demographic survey before the experiment.

Using their assigned order, participants were first familiarized with the VR equipment and each hand representation in a tutorial virtual environment. Participants then completed the first part of the study (3D Interactions) where they used each hand representation for each of the 12 interactions. The participant started each interaction and trial by hitting a bell within the environment, and the trial ended when the interaction goal was detected as completed by the system. The goal of each interaction can be seen in Table 1. Each interaction was performed in five trials per hand representation (the first two trials were treated as training, and not analyzed).

After completing all 12 interactions for the hand representations, participants removed their headset to answer a questionnaire for their general experience with each representation. This questionnaire was completed on a laptop, giving participants an opportunity to take a break until they were ready to continue with the next part of the study.

In the Alchemist Experience (second part of the study), the participant was randomly given a 'potion recipe' for each hand representation. Each recipe required the participant to use each of the 12 previous interactions as quickly and accurately as possible to create the potion. Potions required the same number of actions and physical movement, and the steps could be completed in any order, but the specific details of each were random (e.g., a different colour potion to pour, a different object to grind in the bowl). After completing the potion making game-like experience with a hand representation, participants removed the VR headset and answered questions on their play experience.

After all interactions, the *Alchemist Experience* and questionnaires were completed, participants were given a brief, semi-structured interview to gather their overall perceptions of the experiment. Participants completed the experiment within 45 to 75 minutes and were offered a $10 Amazon gift card as a thank-you for their participation.

Table 3. The set of verbal questions asked between interactions for Ownership, Agency and Usability. Phrased as a rating of agreement from 1-10.

Metric	Question
Ownership	I felt like the Sphere/Controller/Realistic hands were my own in this task
Agency	I felt like I had control of the Sphere/Controller/Realistic hands in this task
Usability	How effective do you feel the Sphere/Controller/Realistic hands were for this task

Table 4. Questions asked about overall experience when using *3D Interactions*, using a 7-point Likert-scale.

Metric	Question
Connection	I felt a strong connection between my hands and the virtual spheres/controllers/hands
Occlusion	Using the virtual spheres/controllers/hands, I had difficulty seeing what was in my hands
Ease of Use	Using the virtual spheres/controllers/hands, interacting with the world and objects was easy
Confusion	The virtual spheres/controllers/hands were confusing to me
Enjoyment	I had enjoyed using the virtual spheres/controllers/hands as hands for the tasks
Completion	I felt that I was good at completing all the tasks with the virtual spheres/controllers/hands

3.8 Data Collected

Demographics information, previous experience with games and VR, and Gamer Motivation Profile [12, 42] were collected pre-experiment and used in secondary exploratory analysis.

Performance data for *3D Interactions* included completion time in milliseconds (where appropriate). The *Look-Around* interaction was omitted as its goal was not dependent on completion time. After all five trials were completed, participants indicated their play experience with the representations' usability and dimensions of embodiment (ownership and agency [3, 8, 22, 25]) by verbally indicating their agreement on a scale from 1 (don't agree at all) to 10 (fully agree), keeping the HMD in place (Table 3). This procedure was repeated 36 times (after each interaction-representation combination). Due to this the decision was made to keep the repetitive questions short and asked verbally as to not take up the participants' time in an already long study. These verbal questions were inspired from other work [26, 31]. Additional questionnaire data was completed for each representation after completing all interactions including usability and experiential questions phrased as 7-point Likert-scale questions (i.e., connection, occlusion, ease of use, confusion, enjoyment, feeling of completion) (Table 4).

During the Alchemist Experience, completion time was captured for each potion created. The final questionnaires were completed after each potion creation, including the PENS questionnaire [32], and questions about 'the awareness of the representation during idle' and '... active use' states, as well as how distracting they found the representation, also phrased as 7-point Likert-scale questions.

3.9 Data Analysis

Data processing and analysis were performed using Python with Pandas and Pingouin (version 0.5.3) for statistical analysis. Questionnaire and performance data were aggregated and analyzed using repeated measure ANOVAs. Alpha levels were corrected using Bonferroni correction.

To identify outliers, we focused solely on completion time. We first calculated modified z-scores [18] for each trial. Modified z-scores rely on the median of a distribution instead of the mean. Using modified z-scores for outlier removal has been shown to be more robust towards extreme outliers [18]. We summed up outliers across trials and removed individuals with more than 15 outliers — indicating that these individuals clearly struggled with the assignment. In total, we removed 4 participants from our dataset, resulting in 41 participants being included in the reported data set.

4 RESULTS

To understand the effect of virtual hand representation on experience, we first investigate the effect the different representations have on play experience overall. We then investigate participants' experience of ownership, agency and usability for each representation-interaction combination in the 3D Interactions part of the study, then the play experience of the game-like portion of the study (the *Alchemist Experience*) with each representation. Lastly, we are interested in the effects of performance on the individual interactions and the final game-like experience.

4.1 The Play Experience of Different Representations

We first investigated participants' play experience using different representations after the 3D Interactions part of the study. This provided the results for play experience after all interactions were tested. We found representations were experienced significantly differently across all dimensions measured (Table 5). Overall, Hand was experienced most positively for connection, ease of interaction, enjoyment, and satisfaction upon completion, as seen in Figure 10.

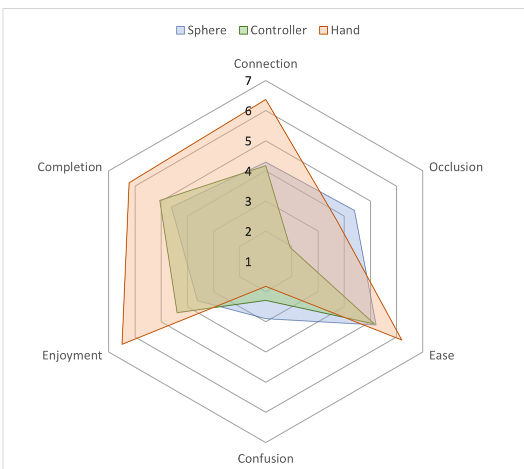

Fig. 10. A radar plot showing the responses from participants for their general experience with each hand representation after completing all 3D interactions. 7-point Likert-type scale, 7 = strongly agree.

Pairwise comparisons show higher ratings of Hand compared to Controller and Sphere for connection, ease, and completion. The more realistic Hand representation was also enjoyed more.

Table 5. Pairwise analysis of responses for general experience with each hand representation. Sphere = S, Controller = C, Hand = H. 7-point Likert-type scale, 7 = strongly agree. Using Bonferroni-corrections, Alpha levels were corrected to 0.05/6 = 0.0083.

	Sphere		**Controller**		**Hand**		**RM-ANOVA**				**pairwise**		
	Mean	SD	Mean	SD	Mean	SD	F	df	p	η_p^2	S vs. C	S vs. H	C vs. H
Connection*	4.29	1.19	4.17	2.03	6.37	0.8	32.03	2,80	.001	0.33	N.S.	S < H	C < H
Occlusion*	4.39	1.31	1.93	1.31	3.71	1.74	24.04	2,80	.001	0.28	S > C	N.S.	C < H
Ease*	5.22	1.06	5.15	1.13	6.2	0.9	13.2	2,80	.001	0.18	N.S.	S < H	C < H
Confusion*	2.9	1.24	2.29	1.35	1.83	1.32	7.95	2,80	.001	0.1	N.S.	S > H	N.S.
Enjoyment*	3.61	1.58	4.39	1.73	6.49	0.93	43.34	2,80	.001	0.42	S < C	S < H	C < H
Completion*	4.61	1.07	5.05	1.26	6.22	0.91	25.46	2,80	.001	0.28	N.S.	S < H	C < H

In addition, enjoyment also differs between Sphere and Controller, with higher levels of enjoyment for the Controller (Table 5).

Occlusion was perceived less of an issue for Controller compared to Sphere and Hand (recall for Controller, the model disappears when interacting). Looking at confusion, we find Hand was perceived as less confusing than Sphere.

Our results show that the realistic Hand representation provides the best experience across most metrics. The only limitation seems to be that hand representations can occlude objects more than Controller.

4.2 Play Experience Across 3D Interactions

Next we look at play experience across different interactions (recall players verbally rated dimensions of embodiment through ownership and agency, and then usability after each interaction-representation combination). Our results show Hand leads to higher experiences of ownership compared to Sphere and Controller across all interactions (Table 6). Controller and Sphere condition show no differences independent of interaction and experience metrics.

Investigating agency, we find agency is perceived higher for Hand than Controller for all interactions except *Rotate-Fixed*, *Look-Around*, and *Rotate-Around*. Hand was significantly higher than Sphere in agency for *Grab & Drop, Push-Pull,* and *Attach*. For *Rotate-Fixed, Look-Around,* and *Rotate-Around*, we find no differences between conditions.

Investigating usability, we find that usability is perceived for Hand higher than both Controller and Sphere for *Grab & Drop, Grab & Place, Push-Pull,* and *Scoop*. For *Pull-Down, Open-Close, Look-Around, Separate,* and *Precision-Pour*, Hand shows only increased usability compared to Controller. For *Rotate-Fixed*, Hand is significantly higher in usability than Sphere. For *Rotate-Around* we find no differences between conditions.

The results provide a more fine-grained understanding of the effect of representation on user experience. The results show how the Hand representation provides an experience of ownership independent of the interaction. The effect sizes (partial eta-squared) for ownership are high throughout interactions (min=0.07, max=0.28) suggesting a meaningful, consistent effect. Agency and usability vary more with lower effect sizes for agency (min=0.05, max=0.08) and usability (min=0.07, max=0.14) — the differences are primarily between the Controller and Hand representations.

Table 6. Pairwise analysis of the three hand representations' perceived Ownership, Agency and Usability across all interactions, answered from 1 (lowest) to 10 (highest) by participants. Sphere = S, Controller = C, Hand = H. Using Bonferroni-corrections, Alpha levels per interaction by metric were corrected to 0.05/36 = 0.00139, and per interaction to 0.05/12 = 0.00417.

		Sphere		**Controller**		**Hand**		**RM-ANOVA**				**pairwise**		
Interaction	Metric	Mean	SD	Mean	SD	Mean	SD	F	df	p	η_p^2	S vs. C	S vs. H	C vs. H
Grab Drop	Ownership	6.27	1.88	6.05	2.06	8.41	1.05	38.77	2,80	0.001	0.28	N.S.	S < H	C < H
	Agency	7.68	1.75	7.63	1.69	8.54	1.31	8.66	2,80	0.00	0.06	N.S.	S < H	C < H
	Usability	7.61	1.63	7.56	1.66	8.78	1.06	16.71	2,80	0.001	0.13	N.S.	S < H	C < H
Grab Place	Ownership	6.95	1.63	6.27	2.01	8.46	1.19	31.08	2,80	0.001	0.24	N.S.	S < H	C < H
	Agency	7.90	1.32	7.63	1.36	8.56	1.27	13.64	2,80	0.00	0.08	N.S.	N.S.	C < H
	Usability	7.76	1.36	7.22	1.44	8.51	1.14	15.59	2,80	0.001	0.14	N.S.	S < H	C < H
Pull-Down	Ownership	7.02	1.71	6.34	2.09	8.51	1.36	30.54	2,80	0.001	0.22	N.S.	S < H	C < H
	Agency	7.95	1.55	7.44	1.57	8.51	1.47	11.38	2,80	0.00	0.08	N.S.	N.S.	C < H
	Usability	7.95	1.61	7.27	1.72	8.56	1.43	12.57	2,80	0.001	0.10	N.S.	N.S.	C < H
Rotate-Fixed	Ownership	6.39	2.00	6.51	1.76	7.76	1.71	13.47	2,80	0.000	0.10	N.S.	S < H	C < H
	Agency	6.78	2.04	7.12	1.66	7.66	1.78	5.16	2,80	0.01	0.04	N.S.	N.S.	N.S.
	Usability	6.51	2.08	6.78	1.75	7.71	1.74	7.37	2,80	0.001	0.07	N.S.	S < H	N.S.
Open-Close	Ownership	7.00	2.06	6.76	1.93	8.32	1.37	16.34	2,80	0.000	0.13	N.S.	S < H	C < H
	Agency	7.90	1.55	7.59	1.47	8.51	1.29	12.17	2,80	0.00	0.07	N.S.	N.S.	C < H
	Usability	7.78	1.78	7.49	1.34	8.49	1.29	9.32	2,80	0.001	0.08	N.S.	N.S.	C < H
Look-Around	Ownership	6.41	2.07	6.85	2.23	8.10	1.74	13.77	2,80	0.001	0.11	N.S.	S < H	C < H
	Agency	7.88	1.58	8.17	1.51	8.22	1.78	1.83	2,80	0.17	0.01	N.S.	N.S.	N.S.
	Usability	7.46	1.76	8.29	1.57	7.15	1.62	8.80	2,80	0.001	0.08	N.S.	N.S.	C < H
Push-Pull	Ownership	7.10	1.87	6.95	2.05	8.71	1.08	26.66	2,80	0.001	0.18	N.S.	S < H	C < H
	Agency	8.00	1.50	7.90	1.55	8.63	1.34	9.18	2,80	0.00	0.05	N.S.	S < H	C < H
	Usability	7.93	1.62	7.73	1.52	8.80	1.29	12.58	2,80	0.001	0.09	N.S.	S < H	C < H
Rotate-Around	Ownership	6.44	2.03	6.54	2.24	7.63	1.77	9.31	2,80	0.000	0.07	N.S.	S < H	C < H
	Agency	6.80	2.15	7.34	1.87	7.37	1.80	2.23	2,80	0.11	0.02	N.S.	N.S.	N.S.
	Usability	6.83	1.95	7.37	1.91	7.73	1.70	5.08	2,80	0.008	0.04	N.S.	N.S.	N.S.
Attach	Ownership	6.32	2.37	6.34	2.12	8.12	1.31	21.76	2,80	0.001	0.16	N.S.	S < H	C < H
	Agency	7.05	2.07	7.10	1.83	8.07	1.40	11.49	2,80	0.00	0.07	N.S.	S < H	C < H
	Usability	6.63	2.23	6.85	1.75	8.07	1.63	11.37	2,80	0.001	0.10	N.S.	S < H	C < H
Separate	Ownership	7.12	1.94	6.73	2.16	8.56	1.12	23.08	2,80	0.001	0.16	N.S.	S < H	C < H
	Agency	8.07	1.62	7.46	1.79	8.63	1.36	13.41	2,80	0.00	0.08	N.S.	N.S.	C < H
	Usability	8.12	1.71	7.63	1.88	8.76	1.41	8.15	2,80	0.001	0.07	N.S.	N.S.	C < H
Precision-Pour	Ownership	6.93	1.88	6.59	2.05	8.41	1.22	29.72	2,80	0.001	0.17	N.S.	S < H	C < H
	Agency	7.73	1.69	7.54	1.61	8.37	1.46	9.45	2,80	0.00	0.05	N.S.	N.S.	C < H
	Usability	7.80	1.55	7.34	1.88	8.41	1.47	14.49	2,80	0.001	0.07	N.S.	N.S.	C < H
Scoop	Ownership	7.00	2.11	7.12	1.99	8.49	1.21	24.49	2,80	0.001	0.12	N.S.	S < H	C < H
	Agency	8.17	1.56	7.98	1.60	8.85	1.13	20.98	2,80	0.001	0.06	N.S.	N.S.	C < H
	Usability	7.93	1.62	7.85	1.56	8.90	1.30	18.78	2,80	0.001	0.09	N.S.	S < H	C < H

4.3 Play Experience for the Alchemist Experience

Next we consider play experience ratings participants provided after completing the *Alchemist Experience* with each representation. This was done to see if a longer game-like experience which involves multiple interactions together with a single goal changes the play experience. We find a significant result for *Intuitive Control* ($F_{2,80} = 5.7$, $p = .005$, $\eta_p^2 = .03$), shown in Table 7. Pairwise

Table 7. Pairwise analysis of results from participants during the *Alchemist Experience* for the PENS questionnaire and hand awareness questions. Sphere = S, Controller = C, Hand = H. 7-point Likert-type scale, 7 = strongly agree. Using Bonferroni-corrections, Alpha levels were corrected to 0.05/7 = 0.00714.

	Sphere		**Controller**		**Hand**		**RM-ANOVA**				**pairwise**		
	Mean	SD	Mean	SD	Mean	SD	F	df	p	η_p^2	S vs. H	S vs. H	C vs. H
Competence	5.8	0.85	5.66	0.91	5.9	0.89	2.19	2,80	0.119	0.013	N.S.	N.S.	N.S.
Autonomy	5.43	1.17	5.45	1.12	5.51	1.07	0.67	2,80	0.52	0.001	N.S.	N.S.	N.S.
Intuitive Control*	6.09	0.91	5.84	0.93	6.2	0.077	5.7	2,80	0.005	0.03	N.S.	N.S.	N.S.
Presence	5.04	0.93	4.93	1.07	5.13	1	3.87	2,80	0.0248	0.007	N.S.	N.S.	N.S.
Aware of Idle	4.44	1.96	4.49	1.9	4.59	2.12	0.184	2,80	0.832	0	N.S.	N.S.	N.S.
Aware of Active	5.27	1.79	4.8	1.98	5.46	1.69	3.027	2,80	0.054	0.022	N.S.	N.S.	N.S.
Distraction*	2.68	1.65	2.39	1.41	1.81	1.12	5.95	2,80	0.004	0.064	N.S.	S > H	N.S.

Table 8. Completion Time data for each hand representation in all 12 3D Interactions and the Alchemist Experience, in milliseconds. Using Bonferroni-corrections, Alpha levels were corrected to 0.05/12 = 0.00417.

	Sphere		**Controller**		**Hand**		**RM-ANOVA**			
	Mean	SD	Mean	SD	Mean	SD	F	df	p	η_p^2
Grab & Drop	1224.1	473.58	1235.41	410.29	1144.18	400.16	2.74	2,80	0.07	0.064
Grab & Place	1108.81	350.8	1114.93	398.43	1108.05	486.66	0.01	2,80	0.99	0
Pull-Down	1021.17	387.2	1013.42	380.27	1009.72	542.65	0.02	2,80	0.98	0
Rotate-Fixed	4821	1801.89	4998.78	2022.83	4800.79	1869.36	0.53	2,80	0.59	0.013
Open-Close	2460.33	1123.85	2478.92	1239.88	2341.06	1013.25	0.3	2,80	0.74	0.008
Push-Pull	2795.03	1040.71	2996.75	1476.39	2696.57	1141.51	1.45	2,80	0.24	0.035
Rotate-Around	6026.96	1609.2	5989.47	1673.94	6103.73	1693.87	0.27	2,80	0.76	0.007
Attach	2158.58	1166.52	2287.32	921.15	2041.61	905.19	1.53	2,80	0.22	0.037
Separate	923.66	635.85	1247.26	2313.44	1179.32	1702.94	0.43	2,80	0.65	0.011
Precision-Pour	7159.14	2403.6	7649.01	3399.07	7423.03	2725.93	0.97	2,80	0.38	0.024
Scoop	1192.73	360.77	1258.73	390.69	1144.31	356.96	5.13	2,80	0.01	0.114
Alchemist Experience	113545	34266.5	112116	38677.6	119495	42862.7	0.94	2,80	0.39	0.007

comparisons show no differences between pairs; combined with the weak effect size, we decided to ignore this effect. All other need satisfaction scales yield non-significant results.

We find a significant effect for *Distraction* ($F_{2,80} = 5.13$, $p = .004$, $\eta_p^2 = .064$), shown in Table 7. Pairwise comparisons suggest that participants found Sphere more distracting than Hand.

4.4 Performance: Completion Time

Investigating the performance of all 3D Interactions and the Alchemist Experience across the different representations, we find no differences in completion time ($p > 0.00417$, using Bonferonni Corrections; see Table 8). Our results suggest completion time within a single interaction is not meaningfully affected by the representation. Our data gives no indication that designers who need to consider completion time in their game-design need to consider hand representation as a factor when planning. The *Look-Around* interaction was not analyzed for completion time as it was not designed to test performance.

Participants used hand representations in a fixed order throughout the study and were grouped in six different orders from a full Latin-square. Investigating effects of order in the individual interactions, we find training effects of representation for Sphere and Hand. In *Group A* and *Group B* where Sphere was used first, we find completion time across all interactions to be slower for

Sphere ($p < 0.00417$). A similar pattern emerges in *Group E* and *Group F*, where Hand was used first and shows a slower completion time compared to the other representations ($p < 0.00417$).

To our surprise, performance in individual interactions is not slower in Groups C and D where Controller was used first. We assume the effect of response time is a result of lacking familiarity and adjustment of time to the activation area the controller, e.g., the area that needs to be aligned with the interactive objects in the different interactions.

We find no effects of hand order on play experience or performance within the Alchemist Experience ($p > 0.05$).

4.5 Other Exploratory Analysis

As part of our preliminary questionnaire data, we had participants complete the *Gamer Motivation Profile* from Quantic Foundry [12, 42]. We attempted to use these results to find patterns between player traits and play experience. We compared the experiential and performance results with the player traits and behaviours resulting from this survey and found no significant correlations and decided not to pursue this further.

4.6 Summary

To summarize our findings, we found the play experience of the Hand representation was the most positively received overall, with its only limitation being occlusion (participants found that Controller occluded the least). The Hand representation was reported with the highest ownership across all interactions, but in terms of agency and usability, the results show minor or no differences across the three representations depending on the interaction.

In the Alchemist Experience, we find no significant effect of hand representation on the concepts presented in the PENS questionnaire. The Sphere representation was viewed as the most distracting during use, while the Hand was the least distracting. This is somewhat at odds with the results from our interaction level analysis, which found that the Controller occluded the least giving the impression it might be less distracting. Overall, we find there is no significant effect of hand representation on performance in either the 3D Interactions or the Alchemist Experience.

5 DISCUSSION

We compared three hand representations (i.e., Sphere, Controller, Hand) across 12 different 3D interactions and the Alchemist Experience. Our findings suggest that while representations did not affect performance, the representations affected experiences across 3D interactions differently. People showed strong preferences and had improved play experiences for a more realistic, human-like hand representation. We find slight differences for different 3D interactions. Our findings suggest these differences in experience are not tied to performance (measured as task completion time).

Our analysis provides eight key insights:

(1) There are no performance differences between representation types.
(2) Sphere and Controller show no differences across 3D Interactions.
(3) Hand representation is perceived as most enjoyable.
(4) Hand representation leads to strongest experiences of embodiment comparing general experience (i.e., connection) and individual 3D interactions (i.e., ownership, not agency)
(5) Hand representation is associated with more positive task experiences considering the general experience (i.e., ease, completion, lower confusion) and the experience of individual 3D Interactions (i.e., usability).

(6) Agency differences are less relevant in rotation tasks (*Rotate-Fixed*, *Rotate-Around*) and when the focus is not on the representation (i.e., *Look-Around*).
(7) Usability differences are not relevant when the focus is not on the representation (i.e., *Look-Around*).
(8) Predictors of motivation (i.e., competence, autonomy, relatedness) are not affected by representation type when 3D Interactions are integrated into a single game-like experience.

In the remainder of the discussion, we explore possible reasons for our results and questions raised by our work.

5.1 Play Experience

We found the realistic hand representation provided the best play experience. While being the most detailed and complex to develop, the realistic hands likely provided participants with the most appropriate embodiment when performing interactions. Given the characterization of virtual embodiment as the ideal alignment between the virtual and physical through the sense of ownership and agency, the idea that the hand representation provided the best embodiment makes sense. The hands were much more highly rated in terms of ownership (Table 6), which is in line with previous work which suggested people using hand-like representations have improved play experiences and prefer them [24, 25]. Reasons provided for the improved experience of realistic hand representations included increased ownership through physical similarities [5, 22], improved immersion due to the realism of body parts [13, 16, 24, 25, 33, 41], or simply familiarity with natural functions as opposed to an unnatural and unfamiliar representation [25, 33, 34].

People also found Hand to be the least confusing to use (Figure 10), followed by Controller and Sphere, and of the three, Hand was also the easiest to use (Figure 10). Additionally, people felt the most connection between Hand (Table 5) and their real hands. This suggests that the mapping of controls and physical similarity of the virtual hand to the real was effective for enabling a sense of ownership [3, 22].

The Controller and Sphere representations were found to have less ownership than Hand, but for agency and usability it depended on the specific interactions (Table 6). For example, *Rotate-Fixed* found that there was no effect of representation on agency, and *Rotate-Around* found no effect of representation on agency and usability. We believe that these examples show that the functionality of the Controller and Sphere representations can be more useful for certain interactions. The Controller and Sphere representations both were semi-transparent and had additional features (e.g., the tether) that provided assistance compared to the realistic hand (which was opaque and had no assistance). The Controller in particular, was the least occluding (Figure 10) because it disappeared when interacting with an object, which can make it more usable when the object is the focal point. The highlighting features of both Controller and Sphere can impact the sense of agency with the VR input, because they can support an awareness of what the player is doing. While Controller and Sphere do not outright overcome the natural qualities of Hand, our results show that given the right circumstances, their features can make up for the lack of embodiment they provide.

5.1.1 Did the testing environment affect play experience and embodiment? Our experiment setting may have an influence on the play experience and embodiment of each representation. A user may expect a realistic, gloved hand to be used in the medieval setting, whereas a transparent floating sphere may seem out of place. A semi-transparent model of a virtual reality controller on the other hand, is thematically out of place, but it may be expected in a VR game given that it is an ideal match for what players held in real life. This user expectation of the representation is reminiscent of the Proteus Effect [43]; i.e., if a user is expecting to be represented in a particular way, and that representation affects their behaviour in the virtual environment, then unexpected representations can alter their experience.

The choice of VR controllers and their capabilities may also have an influence on our results. The Valve Index controllers allow for a more granular tracking of fingers and their positions compared to other types of VR controllers, and some of our representations leveraged these capabilities. Because the buttons of the Valve Index controllers have touch sensors, the Controller models highlighted the input buttons. Hand leveraged additional tracking, and our virtual hand representation was able to move fingers individually according to their real counterpart, and smoothly transition between poses. The more realistic and animated qualities of virtual hands has previously been credited as having beneficial effects on immersion and embodiment [16]. Sphere did not benefit from the additional sensors of the Valve Index controllers, and only needed tracked position of the controller. While the ability to use the controller sensors may have provided additional benefit for Hand, VR development has been progressing with better and more detailed tracking such as this, making our results in line with currently available device capabilities.

5.2 Implications for Game Designers

Our results suggest that independent of representation, play performance remains stable across different types of tasks. This is good news, because it allows Game Designers to adopt representation types that are suitable for their game context and they do not need to draw from generic representation types. Using representations that fit the theme (such as an alchemist's gloved hand in our example) might have usability side-effects (such as occlusion), but is not necessarily detrimental to experience across the different interaction types.

Our results contribute to the on-going discussion about the tension between usability and immersion. Our results suggest that designers can focus more on immersion because the embodied experience of using an actual hand in VR may override (at least some minor) usability limitations that result from issues like occlusion.

Our results are in line with design practices of 2D games, where in games played from the first-person perspective, player hands are often represented as humanoid hands and not abstract representations. It is important to note that the 3D Interactions span a wide array of interaction types used in VR games, which suggest that our findings are generalizable – in all 3D interactions a Hand representation would likely be the preferred choice.

5.2.1 2D vs. VR. In 2D environments, we tend to focus more on usability because we are used to focusing on systems that maximize performance in both work and play. However, VR environments are more captivating, and it matters how close the experience is to our expectations. For example, if our movement in VR is too fast we may quickly feel sick [23], or using hand representations that have fewer than five fingers leads us to feel less present [33].

Our work contributes to our understanding of how to represent human bodies in fully immersive environments, suggesting that we value embodiment over usability. Following this line of thought, designing for improved experience through embodiment in virtual environments might mean moving away from abstract representations even when they increase usability. We believe that when we embrace and understand the effects of our expectations on experience we can design better interactions (e.g., taking into consideration that when we engage in VR games, we have the 'natural' expectation from our real-world experience that our hands will occlude what we touch).

Sometimes we use occlusion also as a tool or feature (e.g., when Einstein occluded the night sky with one finger to give an example of the vastness of the universe – imagine how many stars are covered by just one finger, and how many times your finger could fit into a night sky). Advancing how our representations in VR function (e.g., by being transparent) might be advantageous for usability, but would require further exploration. We believe that our research informs how we might transition from standard screen-based paradigms into immersive paradigms considering our anatomy as we increasingly become embodied in digital spaces.

5.3 Performance

We found no significant effect of representation on performance in terms of completion time across all interactions. This was true for both the individual interactions (*3D Interactions*) and the game-like experience (*Alchemist Experience*) (Table 8), suggesting that *how* hands are represented in VR does not necessarily affect performance. While some previous work has found that the level of embodiment can affect performance [39], others did not [26, 30]. We found that the tested hand representation did not affect performance in our study. While our representations varied in their appearance and the provision of feedback related to hand position (from the Valve Index's sensors), the controllers were all functionally equivalent. The size of the interaction box (i.e., the collider) and the way that objects were interacted with (by closing the hand around the controller) was the same across representations, and this was the most important factor in determining performance. Given that previous work has found that hand representations have a mixed effect on performance [26, 30, 39], our findings suggest that future work should also take care that their representations are functionally equivalent, or to report when they are not. Comparing across studies is difficult, because evaluated tasks and representations varied widely. In our work, we drew examples from actual games and took care to carefully describe our tasks and their rationale. We hope this can improve the replicability of our work and better inform future studies. However, future work should consider creating test beds and evaluation environments, so that VR interactions can be more consistently compared across studies.

A potential explanation is that our participants were more focused on the interaction and less aware of their feedback from the representations. This is supported by our results on awareness of hands – there was no effect found of representation on participant awareness of the representations while they were actively using them or they were idle (Table 7). We did find that representation had a significant effect on how distracting the hand representation was, where Hand was the least distracting, but increased distraction for Controller and Sphere did not affect performance.

Participants mentioned during their post-experiment interviews, there were times when they felt immersed and focused on the interaction and despite being aware of what their hands were doing, they were not aware of what their hands looked like or how they interacted all of the time. They experienced a form of kinesthesia – an awareness of the position and movement of one's body. This means that the level of embodiment and the level of focus and immersion participants experienced was sufficient to allow similar performance for all representations.

Other work found no significant difference in performance for different levels of a VR body's fidelity [26]. This lack of focus on the virtual body is explained through the level of immersion of the system and as a side effect of autotelic activities – where the experience of performing the interaction is the main goal [26]. This work suggested that the user experiences enjoyment and flow performing the interaction, allowing for the representation of their virtual body to not have a significant impact and thus a lack of focus, aligning to our results for the user's awareness of their virtual hands.

5.4 Representations in Different 3D Interactions

Our findings show ownership is largely affected by the representation alone; however, agency and usability had minor differences, favouring some interactions for a given representation. Specifically for interactions that require rotation of the object, to rotate an object in place (*Rotate-Fixed*), around a point (*Rotate-Around*) or to rotate the hand to look around an object (*Look-Around*), agency is unaffected, but for other interaction that did not involve rotation, agency was highest for Hand. Usability has similar results to agency, where non-rotation interactions tend to favour Hand. Some participants mentioned that occlusion was an issue with Hand and Sphere representations during the rotation interactions. This is backed up by the overall perception of 'occlusion' being rated lowest for the Controller representation.

The individual 3D interactions chosen for the study were drawn from interactions found in VR games. We studied the 3D interactions both in isolation and combined in the Alchemist Experience, because previous research has focused on either single types of repetitive interactions or just a game by itself. For the Alchemist Experience, we find no significant differences on any metric. Our lack of observed differences in the game-like experience show that hand representations may be consistent across interactions, whether isolated or in a larger game-like context. This was true for the Alchemist Experience; however, it may change depending on the genre of VR game.

It should also be noted that our experience-related metrics in the Alchemist Experience focused on the PENS questionnaire, and not on the questions asked during first part of the study where the interactions were studied in isolation. We did this to keep the total number of questions to a minimum. However, we believe if we had asked the questions regarding ownership, agency and usability, we would have found similar results during the Alchemist Experience, where Hand was rated highest across all interactions.

5.5 Practical Considerations for Implementing Hand Representations

Recall during the description of creating and running the *Alchemist Experience* (Section 3.5), we discussed the differences in implementation of the three hand representations. The complexity for implementing a realistic hand representation is an important consideration for game designers and developers. We found that the Hand representation was the most complex to implement, due to the work required to create the poses that match and work across a number of different physical objects. With more dynamic behaviour and more potential objects that a representation can interact with, the complexity of a realistic hand representation would increase dramatically. Controller model representations require less work, because it is expected that 3D models for controllers exist and would only need some customization for the game. However, given that there are potentially several VR controllers available, this work would be repeated for each controller. An abstract shape representation, like Sphere, would have a single common implementation across controllers and objects (for the most part), making it the least difficult to implement.

Some games avoid much of the difficulty of implementing realistic hand representations, by having the hand disappear when holding or interacting with an object. Interestingly this is the case for some popular Indie VR games, where implementing poses for different objects may have been a challenge [G8, G16, G23]. In other games, it makes sense to forgo the hand altogether and just use an object as the hand for the entire experience [G1, G6].

However, in this paper we have largely framed the choice of hand representation as a static one that does not change for a game, but this does not necessarily have to be the case. A combination of representations can help on-boarding to a game during a tutorial section, as seen in *Moss* (Figure 11) and *Half-Life: Alyx* (Figure 12) [G17, G25]. In these situations, a controller representation is used initially to introduce the game controls to the player, and then they are taken away to provide the improved embodied experience of the controller. It can also be up to player preference as in *Skyrim VR* [G3], where by default, the hand model is visible and will disappear when holding an object (i.e., object as hands), but it can be optionally set to display a posed hand holding an object (i.e., hand is always visible).

Fig. 11. *Moss* showing a controller to aid the sphere hands during the tutorial.

Fig. 12. *Half-Life: Alyx* using both a controller and hand model in the tutorial.

6 LIMITATIONS & FUTURE WORK

Our research expanded upon prior work by testing three hand representations that were carefully created to reflect implementations in real games, across the largest number (12) of 3D interactions that has yet been tested. While care was taken to identify a set of interactions that would provide a good amount of generalizability, there may be more 3D interactions that could have been tested. As we found, hand representations can be experienced (and potentially perform) differently in different interactions. We believe further evaluation and explorations of 3D interactions are warranted, and for different hand representations.

Concerning different hand representations, in our study the differences between representations was not purely visual. Each had a set of properties applied differently based on examples found in VR games and the affordances the representation could offer (i.e., the Hand had fingers to move, while Controller could show button highlighting). Further work could be done to test the impact of the choice of properties of hand representations. Future work evaluating multiple interactions with representations may also benefit from counterbalancing the order of interactions, as previously discussed in our study it was a fixed order.

Further, we also evaluated our representations in a particular game-like environment, as previously discussed. Exploring representation in different environments (i.e., different genres, settings), in a more controlled environment (i.e., out of the context of a game), and in a fully fledged game (i.e., where there is longer play and goals are motivated within the game) would provide confidence that our results will hold across any VR game setting. Our environment was medieval themed, but we only modified the Hand representation to fit in (e.g., recoloured to look like a leather glove). Our other representations did not thematically match, so future work should consider thematically matching their virtual representation to an appropriate and unified theme.

Our evaluation involved a single participant at a time, but this could be expanded into a social setting. Sharing a virtual environment with others may change how a user experiences their own virtual hand representation (i.e., 'How do others see me?'). In this case, users in social VR spaces may pay more attention or care more about how they are represented, whereas in a game space, one may expect the game to help a user experience a character through their embodiment. A user of a social VR game/space might want more control or to be represented in a particular way.

In our evaluation, we verbally asked modified questions to obtain data on ownership, agency and usability. This was done to reduce the time taken for the study, but the non-standardized questions asked in this way may have impacted our results. Future work could use standardized questions and be completed in a VR questionnaire to ensure consistent results with minimal time requirements.

Given that new and improved VR devices are continually being released, and controller-less VR (using camera-based free-hand interactions) is also improving, future work will soon be able to do a fair comparison between a range of physical controllers (e.g., Valve Index, Vive Wands, Quest controllers) and free-hand VR input (e.g., hand tracking in the Meta Quest Pro, Leap Motion) in a study similar to ours. It seems likely that experience can also be affected by the physical means by which hand representations are controlled.

Our sample of participants was quite homogeneous in our study. We had very few experienced or regular VR users, the majority self-identified as male, and the majority were right-handed. Future work should explore more heterogeneous populations, and how experience in the context of VR games and other facets of life might influence play experience and preference for representations. Additionally, comparing between experience levels of VR users (i.e., new to VR, novice users, experienced users, and VR developers/designers) can be done to evaluate differences between performance and experience as it relates to familiarity and comfort with hand representations.

Finally, our findings highlight that issues like occlusion may harm play experience. For a realistic hand representation, this might be dealt with in a number of ways; for example with occlusion, the transparency in the hand representation might be increased. Exploring approaches to dealing with challenges for hand representations is a potentially important direction of research given the importance hand representations have on overall play experience.

7 CONCLUSION

In this paper, we aimed to deepen the understanding about hand representations and how they can affect performance and play experience in VR games. We conducted a study that not only just examines the player experience and performance of three hand representations in 12 different 3D interactions, but also in a longer game-like experience. Our findings confirm that this investigation was important because we find hand representations are experienced differently dependent on the interaction they are used for, but we found no significant effect on performance. In general we find that the most realistic human-like hand representation provides the best player experience for most interactions, as it best embodies the player's own hands into the virtual environment. However, we find issues like occlusion that arise in some interactions can harm usability, but importantly does not come at the expense of play experience. By connecting our research with work on embodied interaction and other work on hand and body representations in VR experiences and games, we have provided a deeper understanding of play in a rapidly growing area and provided promising new directions for further research into how we can shape our experiences in virtual spaces.

REFERENCES

[1] Alex Adkins, Lorraine Lin, Aline Normoyle, Ryan Canales, Yuting Ye, and Sophie Jörg. 2021. Evaluating Grasping Visualizations and Control Modes in a VR Game. *ACM Transactions on Applied Perception* 18, 4 (Oct. 2021), 19:1–19:14. https://doi.org/10.1145/3486582

[2] Monthir Ali and Rogelio E. Cardona-Rivera. 2020. Comparing Gamepad and Naturally-mapped Controller Effects on Perceived Virtual Reality Experiences. In *ACM Symposium on Applied Perception 2020 (SAP '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3385955.3407923

[3] Ferran Argelaguet, Ludovic Hoyet, Michael Trico, and Anatole Lecuyer. 2016. The role of interaction in virtual embodiment: Effects of the virtual hand representation. In *2016 IEEE Virtual Reality (VR)*. 3–10. https://doi.org/10.1109/VR.2016.7504682 ISSN: 2375-5334.

[4] Lonni Besançon, Paul Issartel, Mehdi Ammi, and Tobias Isenberg. 2017. Mouse, Tactile, and Tangible Input for 3D Manipulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4727–4740. https://doi.org/10.1145/3025453.3025863

[5] Matthew Botvinick and Jonathan Cohen. 1998. Rubber hands 'feel' touch that eyes see. *Nature* 391, 6669 (Feb. 1998), 756–756. https://doi.org/10.1038/35784 Number: 6669 Publisher: Nature Publishing Group.

[6] Ryan Canales, Aline Normoyle, Yu Sun, Yuting Ye, Massimiliano Di Luca, and Sophie Jörg. 2019. Virtual Grasping Feedback and Virtual Hand Ownership. In *ACM Symposium on Applied Perception 2019 (SAP '19)*. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3343036.3343132

[7] Andreea Dalia Blaga, Maite Frutos-Pascual, Chris Creed, and Ian Williams. 2021. Freehand Grasping: An Analysis of Grasping for Docking Tasks in Virtual Reality. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. 749–758. https://doi.org/10.1109/VR50410.2021.00102 ISSN: 2642-5254.

[8] Diane Dewez, Ludovic Hoyet, Anatole Lécuyer, and Ferran Argelaguet Sanz. 2021. Towards Avatar-Friendly 3D Manipulation Techniques: Bridging the Gap Between Sense of Embodiment and Interaction in Virtual Reality. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3411764.3445379

[9] Paul Dourish. 2004. *Where the Action Is: The Foundations of Embodied Interaction* (new ed edition ed.). MIT Press, Cambridge, Mass. London.

[10] Mostafa Elbehery, Florian Weidner, and Wolfgang Broll. 2020. Haptic Space: The Effect of a Rigid Hand Representation on Presence when Interacting with Passive Haptics Controls in VR. In *19th International Conference on Mobile and Ubiquitous Multimedia (MUM 2020)*. Association for Computing Machinery, New York, NY, USA, 245–253. https://doi.org/10.1145/3428361.3428388

[11] Martin Feick, Scott Bateman, Anthony Tang, André Miede, and Nicolai Marquardt. 2020. Tangi: Tangible Proxies For Embodied Object Exploration And Manipulation In Virtual Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 195–206. https://doi.org/10.1109/ISMAR50242.2020.00042 ISSN: 1554-7868.

[12] Quantic Foundry. 2022. Gamer Motivation Profile. https://apps.quanticfoundry.com/surveys/start/gamerprofile/

[13] Rebecca Fribourg, Ferran Argelaguet, Anatole Lécuyer, and Ludovic Hoyet. 2020. Avatar and Sense of Embodiment: Studying the Relative Preference Between Appearance, Control and Point of View. *IEEE Transactions on Visualization and Computer Graphics* 26, 5 (May 2020), 2062–2072. https://doi.org/10.1109/TVCG.2020.2973077 Conference Name: IEEE Transactions on Visualization and Computer Graphics.

[14] Guilherme Gonçalves, Miguel Melo, Luís Barbosa, José Vasconcelos-Raposo, and Maximino Bessa. 2022. Evaluation of the impact of different levels of self-representation and body tracking on the sense of presence and embodiment in immersive VR. *Virtual Reality* 26, 1 (March 2022), 1–14. https://doi.org/10.1007/s10055-021-00530-5

[15] Koichi Hirota and Kazuyoshi Tagawa. 2016. Interaction with virtual object using deformable hand. In *2016 IEEE Virtual Reality (VR)*. 49–56. https://doi.org/10.1109/VR.2016.7504687 ISSN: 2375-5334.

[16] Ludovic Hoyet, Ferran Argelaguet, Corentin Nicole, and Anatole Lécuyer. 2016. "Wow! I Have Six Fingers!": Would You Accept Structural Changes of Your Hand in VR? *Frontiers in Robotics and AI* 3 (2016). https://www.frontiersin.org/article/10.3389/frobt.2016.00027

[17] Markus Höll, Markus Oberweger, Clemens Arth, and Vincent Lepetit. 2018. Efficient Physics-Based Implementation for Realistic Hand-Object Interaction in Virtual Reality. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 175–182. https://doi.org/10.1109/VR.2018.8448284

[18] Boris Iglewicz and David C Hoaglin. 1993. *Volume 16: how to detect and handle outliers*. Quality Press.

[19] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems (CHI '97)*. Association for Computing Machinery, New York, NY, USA, 234–241. https://doi.org/10.1145/258549.258715

[20] Camille Jeunet, Louis Albert, Ferran Argelaguet, and Anatole Lécuyer. 2018. "Do You Feel in Control?": Towards Novel Approaches to Characterise, Manipulate and Measure the Sense of Agency in Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics* 24, 4 (April 2018), 1486–1495. https://doi.org/10.1109/TVCG.2018.2794598 Conference Name: IEEE Transactions on Visualization and Computer Graphics.

[21] Konstantina Kilteni, Ilias Bergstrom, and Mel Slater. 2013. Drumming in Immersive Virtual Reality: The Body Shapes the Way We Play. *IEEE Transactions on Visualization and Computer Graphics* 19, 4 (April 2013), 597–605. https://doi.org/10.1109/TVCG.2013.29 Conference Name: IEEE Transactions on Visualization and Computer Graphics.

[22] Konstantina Kilteni, Raphaela Groten, and Mel Slater. 2012. The Sense of Embodiment in Virtual Reality. *Presence* 21, 4 (Nov. 2012), 373–387. https://doi.org/10.1162/PRES_a_00124 Conference Name: Presence.

[23] Joseph J. LaViola Jr., Ernst Kruijff, Ryan P. McMahan, Doug A. Bowman, and Ivan Poupyrev. 2017. *3D User Interfaces Theory and Practice* (second ed.). Addison-Wesley Professional.

[24] Lorraine Lin and Sophie Jörg. 2016. Need a hand? how appearance affects the virtual hand illusion. In *Proceedings of the ACM Symposium on Applied Perception (SAP '16)*. Association for Computing Machinery, New York, NY, USA, 69–76. https://doi.org/10.1145/2931002.2931006

[25] Christos Lougiakis, Akrivi Katifori, Maria Roussou, and Ioannis-Panagiotis Ioannidis. 2020. Effects of Virtual Hand Representation on Interaction and Embodiment in HMD-based Virtual Environments Using Controllers. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 510–518. https://doi.org/10.1109/VR46266.2020.00072 ISSN: 2642-5254.

[26] Jean-Luc Lugrin, Maximilian Ertl, Philipp Krop, Richard Klüpfel, Sebastian Stierstorfer, Bianka Weisz, Maximilian Rück, Johann Schmitt, Nina Schmidt, and Marc Erich Latoschik. 2018. Any “Body” There? Avatar Visibility Effects in a Virtual Reality Game. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 17–24. https://doi.org/10.1109/VR.2018.8446229

[27] Ayano Miyazaki, Hiroko Ota, Kumiko Iwazaki, Mayu Urata, Mamoru Endo, and Takami Yasuda. 2021. Hand Tracking-based VR Ikebana Manipulation. In *2021 IEEE 10th Global Conference on Consumer Electronics (GCCE)*. 723–726. https://doi.org/10.1109/GCCE53005.2021.9621994 ISSN: 2378-8143.

[28] David Panzoli, Paco Royeres, and Mathéo Fedou. 2019. Hand-based interactions in Virtual Reality: No better feeling than the real thing!. In *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*. 1–2. https://doi.org/10.1109/VS-Games.2019.8864546 ISSN: 2474-0489.

[29] Duc-Minh Pham and Wolfgang Stuerzlinger. 2019. Is the Pen Mightier than the Controller? A Comparison of Input Devices for Selection in Virtual and Augmented Reality. In *25th ACM Symposium on Virtual Reality Software and Technology (VRST ’19)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3359996.3364264

[30] Aylen Ricca, Amine Chellali, and Samir Otrnane. 2021. The influence of hand visualization in tool-based motor-skills training, a longitudinal study. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. 103–112. https://doi.org/10.1109/VR50410.2021.00031 ISSN: 2642-5254.

[31] Daniel Roth and Marc Erich Latoschik. 2020. Construction of the Virtual Embodiment Questionnaire (VEQ). *IEEE Transactions on Visualization and Computer Graphics* 26, 12 (Dec. 2020), 3546–3556. https://doi.org/10.1109/TVCG.2020.3023603 Conference Name: IEEE Transactions on Visualization and Computer Graphics.

[32] Richard M. Ryan, C. Scott Rigby, and Andrew Przybylski. 2006. The Motivational Pull of Video Games: A Self-Determination Theory Approach. *Motivation and Emotion* 30 (2006), 347–365. https://doi.org/10.1007/s11031-006-9051-8

[33] Valentin Schwind, Pascal Knierim, Lewis Chuang, and Niels Henze. 2017. "Where’s Pinky?": The Effects of a Reduced Number of Fingers in Virtual Reality. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play (CHI PLAY ’17)*. Association for Computing Machinery, New York, NY, USA, 507–515. https://doi.org/10.1145/3116595.3116596

[34] Valentin Schwind, Pascal Knierim, Cagri Tasci, Patrick Franczak, Nico Haas, and Niels Henze. 2017. "These are not my hands!": Effect of Gender on the Perception of Avatar Hands in Virtual Reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1577–1582. http://doi.org/10.1145/3025453.3025602

[35] Valentin Schwind, Sven Mayer, Alexandre Comeau-Vermeersch, Robin Schweigert, and Niels Henze. 2018. Up to the Finger Tip: The Effect of Avatars on Mid-Air Pointing Accuracy in Virtual Reality. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY ’18)*. Association for Computing Machinery, New York, NY, USA, 477–488. https://doi.org/10.1145/3242671.3242675

[36] Sofia Seinfeld, Tiare Feuchtner, Antonella Maselli, and Jörg Müller. 2021. User Representations in Human-Computer Interaction. *Human–Computer Interaction* 36, 5-6 (Oct. 2021), 400–438. https://doi.org/10.1080/07370024.2020.1724790 Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/07370024.2020.1724790.

[37] Sofia Seinfeld, Tiare Feuchtner, Johannes Pinzek, and Jörg Müller. 2020. *Impact of Information Placement and User Representations in VR on Performance and Embodiment*. Vol. PP. https://doi.org/10.1109/TVCG.2020.3021342 Journal Abbreviation: IEEE transactions on visualization and computer graphics Publication Title: IEEE transactions on visualization and computer graphics.

[38] Paul Skalski, Ron Tamborini, Ashleigh Shelton, Michael Buncher, and Pete Lindmark. 2011. Mapping the road to fun: Natural video game controllers, presence, and game enjoyment. *New Media & Society* 13, 2 (March 2011), 224–242. https://doi.org/10.1177/1461444810370949 Publisher: SAGE Publications.

[39] Tanh Quang Tran, HyunJu Shin, Wolfgang Stuerzlinger, and JungHyun Han. 2017. Effects of virtual arm representations on interaction in virtual environments. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology (VRST ’17)*. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3139131.3139149

[40] Michiel Van Veldhuizen and Xubo Yang. 2021. The Effect of Semi-Transparent and Interpenetrable Hands on Object Manipulation in Virtual Reality. *IEEE Access* 9 (2021), 17572–17583. https://doi.org/10.1109/ACCESS.2021.3050881 Conference Name: IEEE Access.

[41] Huagen Wan, Yang Luo, Shuming Gao, and Qunsheng Peng. 2004. Realistic virtual hand modeling with applications for virtual grasping. In *Proceedings of the 2004 ACM SIGGRAPH international conference on Virtual Reality continuum and its applications in industry (VRCAI ’04)*. Association for Computing Machinery, New York, NY, USA, 81–87. https://doi.org/10.1145/1044588.1044603

[42] Nick Yee. 2006. Motivations for Play in Online Games. *CyberPsychology and Behavior* 9, 6 (Dec. 2006), 772–775. https://doi.org/10.1089/cpb.2006.9.772

[43] Nick Yee and Jeremy Bailenson. 2007. The Proteus Effect: The Effect of Transformed Self-Representation on Behavior. *Human Communication Research* 33, 3 (2007), 271–290. https://doi.org/10.1111/j.1468-2958.2007.00299.x arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1468-2958.2007.00299.x

LUDOGRAPHY

[G1] Beat Games. 2019. *Beat Saber.* Game [PCVR].
[G2] Bethesda Game Studios. 2017. *Fallout 4: VR.* Game [PCVR].
[G3] Bethesda Game Studios. 2018. *The Elder Scrolls V: Skyrim VR.* Game [PCVR].
[G4] BlackTale Games. 2020. *Tales of Glory.* Game [PCVR].
[G5] Boundless Dynamics, LLC. 2017. *VTOL VR.* Game [PCVR].
[G6] Cloudhead Games. 2019. *Pistol Whip.* Game [PCVR].
[G7] Downpour Interactive. 2016. *Onward.* Game [PCVR].
[G8] Free Lives. 2019. *Gorn.* Game [PCVR].
[G9] id Software. 2017. *Doom VFR.* Game [PCVR].
[G10] JoyWay Ltd. 2021. *STRIDE.* Game [PCVR].
[G11] jrbudda and Techjar. 2016. *Vivecraft: Virtual Reality Minecraft for SteamVR.* Game Mod [PCVR].
[G12] Just Add Water. 2021. *Sniper Elite VR.* Game [PCVR].
[G13] Mighty Coconut. 2021. *Walkabout Mini Golf VR.* Game [PCVR].
[G14] Mojang. 2016. *Minecraft VR for Windows.* Game [Oculus/PCVR].
[G15] Motive Studio. 2020. *STAR WARS: Squadrons.* Game [PCVR].
[G16] Owlchemy Labs. 2016. *Job Simulator.* Game [PCVR].
[G17] Polyarc. 2018. *Moss.* Game [PSVR].
[G18] Ready At Dawn. 2017. *Lone Echo.* Game [Oculus Rift].
[G19] RUST LTD. 2016. *Hot Dogs, Horseshoes & Hand Grenades.* Game [PCVR].
[G20] Skydance Interactive. 2020. *The Walking Dead: Saints & Sinners.* Game [PCVR].
[G21] Steel Crate Games. 2015. *Keep Talking and Nobody Explodes.* Game [PCVR].
[G22] Stress Level Zero. 2019. *Boneworks.* Game [PCVR].
[G23] Superhot Team. 2016. *Superhot VR.* Game [PCVR].
[G24] Urban Wolf Games Inc. 2021. *Legendary Tales.* Game [PCVR].
[G25] Valve. 2020. *Half-Life: Alyx.* Game [PCVR].
[G26] Vertigo Games and Jaywalkers Interactive. 2016. *Arizona Sunshine.* Game [PCVR].
[G27] WarpFrog. 2018. *Blade and Sorcery.* Game [PCVR].

Received 2023-02-21; accepted 2023-07-07