*Mapping Physical Environments to Create A Hybrid Environment Approach for Virtual Reality Experiences*

*Student: Thomas Groves (17006680)*

*Supervisor: Adam Stanton*

*BSc in Computer Science*

*24th March 2021*

SCHOOL OF COMPUTING AND MATHEMATICS
Keele University
Keele
Staffordshire
ST5 5BG

**Word Count (Excluding Figure & Appendices): 9124**


## Abstract:

The VR industry is currently receiving increased attention in previous years and especially since the start of the pandemic. The present report introduces the concept of matching certain components of a physical room to an entirely virtual environment. This has been dubbed the hybrid environment approach. The purpose of this is to see if users experience a positive correlation of their immersion factor when inside a hybrid environment verses an entirely virtual one. This immersion factor was assessed using the Spatial Presence Experience Scale (SPES) (Werner, et al., 2015) model which demonstrates immersion as a two-dimensional construct. I hypothesised that creating a virtual environment that has some objects transforms synchronised with physical world objects will positively increase a user's immersion.

The project was achieved using the Unity Engine in conjunction with the Oculus SDK, OpenVR, OpenXR and SteamVR SDK. The hardware used in the locomotive & interaction segments of this report were conducted on an HTC Vive with Valve index controllers, whilst the rest ran on an Oculus Quest 2 using the touch controllers and Oculus' hand recognition technology.

The following tests carried out within this report presents preliminary findings that support the hypothesis. Users experience an increased immersion level of approximately 19% when carrying out the same test in a hybrid environment verses a purely virtual.



## Acknowledgements:

I first and foremost would like to thank my project supervisor, Adam Stanton, for all the help and support throughout the duration of not just this project but also throughout my time in higher education. Without him I don't believe this project would have had the clear direction it needed.

I would also like to thank my testers for time given and the invaluable data they provided.

Lastly, I would like to thank all my family for the immense support they have shown me. More specifically my parents: Victoria Livesey, Matthew Livesey, Robert Fisher and Victoria Fisher. Always making me strive to do my best and supporting me by any means they can. Through thick and thin I know I can always count on you.


## Specialist Glossary:

**3/6 DOF –** 3/6 degrees of freedom
**IVE –** Immersive Virtual Environment
**SP –** Spatial Presence
**AR –** Augmented Reality
**XR –** Extended Reality
**HMD –** Head Mounted Display
**PQ –** Presence Questionnaire
**VR –** Virtual Reality

# Contents

# Chapter 1: Introduction and background review

## 1.1 Why should we care about VR

VR in recent years has started to regain an interest from the general public. In 2020 the industry shot up more than likely due to the pandemic and people wanting an escape to outside without having to leave the house.

According to (Alsop, 2021) the market is projected to grow from $6.2 billion from 2019 to a whopping $16 billion by 2022. This is a growth of about 2.5 times. This is just in the consumer sector of VR. The commercial sector is even bigger in XR products such as created with Microsoft’s HoloLens and Apples upcoming VR & AR devices.

With the industry growing exponentially as it is, it’s a good idea to get involved and help innovate what could potentially change entertainment and other commercial applications in the years to come.

## 1.2 Problems with current hardware

After performing an in-depth review of the current consumer hardware available (Review available in **APPENDIX B**). It is clearly apparent there are at least two major problems that need addressing in order to propel the platform forward.

The first is how we traverse large scale environments that are larger than the players defined play space. Currently this partial solution to this are Locomotion Techniques. This is discussed in **CHAPTER 3.**

Another major problem is how we interact with virtual environments and also how we then provide feedback to the users. A key issue is this is force feedback i.e. how do we restrict the players physical motion when their body or hands collide with a virtual object. This is discussed in **CHAPTER 4.**

## 1.3 The Virtual Dream

The platform virtual reality provides aims to give immersive experiences due to the new way it allows for people to interact with the environment. Industry leaders such as Oculus refer to this as “presence” meaning you have the feeling of really being in that virtual environment.

By allowing an individual to truly feel like they are in an environment, we open up such a vast world of opportunities for use cases. You can do an extreme sport without the risk of injury; you can train astronauts to use equipment available on the International Space Station or you can have a full on shoot out in a WWII setting. The possibilities are endless.

This true bodily transportation has been shown many times throughout the years. I think a great example of this is a movie such as the matrix where people are living in a virtual world without the realisation of it because that is their reality. In the example the movie gives reality matches the simulation however this is not always the ideal case as can be seen in **SECTION 4.4**

The argument is though is what makes a user feel like they are there? Well we define this an immersion meaning the user has “deep mental involvement in something” as defined by the oxford dictionary. Now we know true immersion to be the end goal, but the question is how do we get there? And how do we measure it? **More on this in CHAPTER 2.**

There are however a lot of key barriers that need addressing before we can reach the “VR Utopia” as addressed in **SECTION 1.3**.

**1.4 Hypothesis**

We know that in order for a positive VR experience the user must experience a high/comfortable level of immersion. This can be achieved by attempting to give at least a partial solution to the afform mentioned problems earlier. I believe a way to improve our traversal/locomotive and object interaction problems would be to have certain physical world objects mapped and synched with ones within the virtual world. This would ensure that when a player collides with a virtual object they will also collide with the physical because their transforms are synched overlayed on one another. And since their transforms are synchronised and the room is mapped the user essentially has a large roomscale experience with little-to no need for other locomotion techniques.

*I hypothesise that creating a virtual environment that has some objects transforms synchronised with physical world objects will positively increase a user’s immersion.*

**1.5 Aims & Objectives**

In order to successfully proceed with the project, it is important to lay out the aims and objectives so that I can direct my efforts towards a defined end goal.

**Aim:** To identify the appropriate hardware for the project

**Objectives:**

- Select XR devices to research
- Review the features and capabilities of each device
- Select devices to carry out development

**Aim:** To review and compare existing techniques for interaction and locomotion

**Objectives:**

- Research Traversal Problems
- Research Interaction Problems
- Review Current Locomotion Techniques
- Review VR Interaction Guidelines
- Gather Data on Users Preferred Locomotion Technique

**Aim:** To Create a physically mapped immersive virtual environment

**Objectives:**

- Create a 1:1 scale model of a room
- Implement interaction methods
- Implement traversal methods
- Devise a task
- Collect Data from users
- Review data against hypothesis

### 1.6 Methodology

As with all projects it would be sensible to determine a form of methodology to allow me to break down the project.

First, we need to define what immersion is, how we can measure it? and more importantly what affects it? To do this we need to research current problems with the platform and look at previous papers that have already made great strides in understanding immersion.

Second, we need to investigate what solutions we currently have that address the problems laid out in the previous step. We can achieve this using Unity as it has extensive documentation for XR development which makes it ideal to implement the proposed solutions.

Third, we need to implement my proposed solution from my hypothesis. To do this I can create a 1:1 virtual-physical environment from my house and then devise a test to carry out in order to measure the immersion within the physical play space and also in an entirely virtual one.

Finally, I can review the results from my previous steps and evaluate the success of the project as well as what future work could be done to improve.

The structure of the development will follow an AGILE methodology as it allows me to create iterations of a feature and revisit and adjust it as and when needed.

## Chapter 2: What about immersion then?

### 2.1 What is immersion?

With the identified limits and capabilities identified in **SECTION 1.2 & Appendix B (Current Hardware Problems and limitations)** we can start to think about why we want VR as a platform. The idea of being transported to another world, that you feel like you're in, makes the word **immersion** come to mind. It's a word thrown about by the giants in the industry but is never given a formal definition and why their next big tittle is "the most immersive VR game yet". Oculus like to use the word **presence** a lot when referring to immersion.

Immersion as defined in the oxford dictionary as "deep mental involvement in something" now again we are tasked with well What is immersive? And how do we measure it?

### 2.2 How do we measure immersion?

The big question we need to address in order to support this reports hypothesis is how we measure immersion. It would have been ideal to have access to more equipment in order to get a better understanding of how a user is "feeling". This could have been in the form of EEG sensors to measure a user's cognition/concentration, as to be immersed is to be deeply mentally involved. However due to the scope of this project in the environment it takes place in a survey/questionnaire would be more suited to the needs and inventory of the project.

After scouring the web for any form of information on this matter it is apparently clear we are not the first to attempt this type of task. Out of all the papers available there were two that specifically appeared on the surface to fit our needs. The first being the Spatial Presence Experience Scale (SPES) and the second being A questionnaire to measure the User Experience in Immersive Virtual Environments which used a similar model and approach as SPES. Discussion of both scales with their justifications is attached in **APPENDIX B.**

### 2.3 The Spatial Presence Experience Scale

One scale reviewed in this paper is the Spatial Presence Experience Scale (SPES). This scale was developed due to the increased attention in media psychology and communication research. The model used was derived from a process model of spatial presence (Werner, 2007). The scale assesses spatial presence as a two-dimensional construct that comprises first a user's self-location; Second, a user's perceived possible actions within a media environment. A previous conference proceeding referenced within this article states spatial presence as "Spatial Presence can be briefly defined as the user's subjective feeling of 'being there' in the space defined by a medium" (Riva, et al., 2003)

One of the earlier models the SPES is derived from is the Presence Questionnaire (PQ). This was developed to measure spatial presence in immersive virtual environments that allows users to navigate through sceneries conveyed by HMD's. It aims to assess the intensity of spatial presence as a state but also attempts to assess contributing factors. Thanks to work done by (Witmer & Singer, 1998) they reported there is a large negative correlation between the PQ score and simulator sickness questionnaire developed by (Kennedy, et al., 1993)**.** Due to this correlation we can deduce the validity of the PQ. However, it is not that simple as subsequent reports of the PQ yield mixed results according to (Johns, et al., 2000) (Nystad & Sebok, 2004) (Youngblut & Perrin, 2002).

Work performed by (Witmet, et al., 2005) devised a third iteration of the PQ with several additional items. Data collected from 325 unique-users of immersive virtual environments resulted in a 4-factor solution.

These 4-factors are labelled **involvement** (i.e., ‘‘focusing one's mental energy and attention on the stimulus’’; (Witmet, et al., 2005) p.308) **sensory fidelity** (i.e., the accuracy of sensory stimulation), **adaptation/immersion** (i.e., ‘‘perceiving oneself to be enveloped by, included in, and interacting with an environment’’; (Witmer & Singer, 1998) p. 308), and **interface quality** (i.e., the degree to which ‘‘display devices interfere/distract from task performance’’; (Witmet, et al., 2005) p. 299).

The SPES report states that although the PQ is well suited to assess users' experiences in interactive VR systems, particularly if performing a task. There are potential problems with the PQ as it has a narrow scope. There a lot of mixed findings about the PQ so although it has aspects that are perfectly suited to the needs of this study, it is clear that more work needed to be done in order to get something more suited to our needs.

Another questionnaire the SPES report reviewed is the **IGroup PQ (IPQ).** Like others before it, the aim is to measure **spatial presence (SP)** as a sense of "being there". This scale was derived based on both explorative and confirmative factor analysis conducted through the medium of two survey studies with a sample size of N = 246 and N = 296. It measured two potential subcomponents of SP . Involvement (Focusing on the environment instead of the real world) and realness (How real the virtual environment is judged to be). This scale like the above-mentioned PQ seems like it may be a good contributor to our project however the final aspect of realness appears to be closely related however is not a actual subdimension of spatial presence.

The paper then goes on to summarise the existing scales they reviewed. The two scales they identified as being the most reputable were the **Independent Television Commission-Sense of presence inventory (ITC-SOPI)** and the IPQ. The reason for this being both studies of the scale included extensive testing of psychometric qualities. It is very apparent that it is difficult to evaluate the quality of these existing measurements. Most of the scales relied on a derivative approach.

The SPES proposes as an alternative short measure of spatial presence experiences. Unlike the scales before it this scale aims for an inductive approach. SPES is particularly designed and tested as a measure of spatial presence across diverse media settings. This reason alone makes it a viable option for our project.

Before determining our questionnaire, it is important to understand the determinants of spatial presence. The (Werner, 2007) model suggests that there are two critical steps that show the emergence of spatial presence. First being users developing a mental model of the space depicted by a media offering. This is regarded as a necessary pre-condition however it is not sufficient alone to be a precondition of spatial presence. Second, Users may accept the spatial model they visualised as their own egocentric viewpoint. If they accept this model spatial presence is assumed to emerge. According to Wirth et al. (2007) model the acceptance process is said to be unconscious and automatic. This paper suggests that spatial presence occurs if users accept the virtual spatial model  from the media environment as their own and drop the model bound to the real environment. I.e. in the case of my project this would be forgetting they are in a kitchen and accepting the virtual environment created as their spatial model rather than the kitchens physical model. The Wirth Model assumes that "spatial presence increases  the more concise (consistent, error-free, evident) the spatial mental model that users develop." If a user is spatially present, they feel as if they are physically located within that media environment  and the resulting perception of possible actions within the media environment rather than the physical. According to the (Werner, 2007) model the more the user's attention to the media stimulus is the more likely the user will develop a convincing spatial mental model based on the media input.

Finally, we can talk about the actual SPES. The initial item pool for this questionnaire focusses on two-subdimensions of SP: Self location and possible actions. The goal of SPES was to make a short and convenient scale of two equally sized questions categories aimed at identifying subscale performance in the previously mentioned factors. The self-location questions should be items relating to the user's feeling of "being there" or "physically present" in the virtual environment. Self-Location may also insinuate that a user feels like they have left the physical environment and feel like they have entered another place. Moving onto the possible actions questions we are aiming to understand the way users perceived action possibilities attached to objects in the environment. Examples of this would be the items that captured the user's attention, the amount of items the user intuitively thinks they can interact with and most importantly relating to our study the extent that users could move themselves and objects around an environment.

## 2.4 The Selected Measurement

This report uses the Spatial Presence Experience Scale (SPES). The review, background, and justification of the use of this scale is attached in **APPENDIX B**.

The questionnaire itself will be defined in **CHAPTER 6** and then inserted into **APPENDIX B** in order to relate some of the sub-dimensional immersion measurements to the hypothesis of this report and tailored to the IVE the test shall take place.

## Chapter 3: The traversal problem

### 3.1 What is locomotion?

A big problem that is a hot topic of debate within the industry is how do we traverse virtual environments. Traditional 3DOF VR HMD's tended to use more common methods that we see in flat screen entertainment i.e. using WASD/Analog stick to move in a specified direction smoothly. However, it quickly became apparent that Simulator/Motion sickness was a big problem with stereoscopic HMD's.

The introduction of positional tracking (6 DOF) and motion controllers brought in an entirely new possibility. This is the concept of "Roomscale" experiences. This is where the environment in which the user is placed is no bigger than the tracking space defined by the user. The problem with this roomscale experience is although it significantly reduces the risk of people experiencing motion sickness, it also heavily limits the size of a IVE and therefore the possibilities with the technology. This meaning that we need a solution for IVE traversal.

### 3.2 What methods of locomotion?

In order to get a good idea of existing techniques employed by the industry to assist this problem I sourced a review paper of current techniques. The paper used in this review was (Cherni, et al., 2020).

This study analysed and compared 22 locomotion methods identified from 26 separate papers. The objective was to better understand locomotion techniques and their impact on user experiences. The paper successfully identified that from the entirety of all techniques that were researched that they could be categorized into 3 categories: User-body centred; Mixed and external peripheral centred. A break-down of these categorized **locomotion techniques (LT)** is represented by a diagram sourced from this paper in **FIGURE 3.2.1**

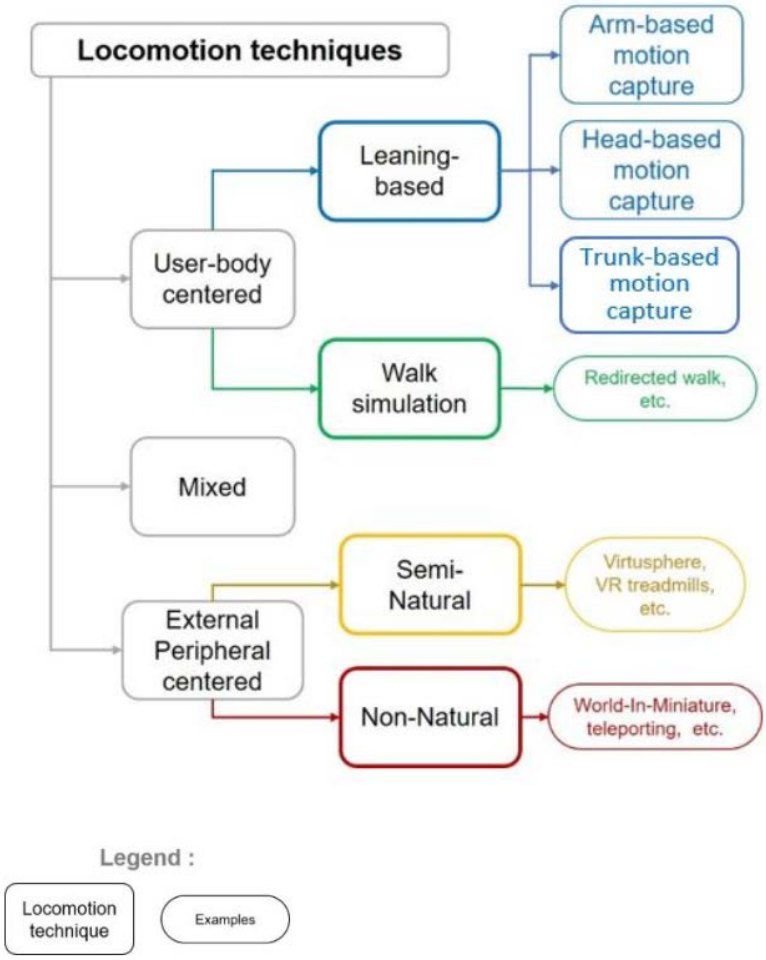



**FIGURE 3.2.1**
**Locomotion techniques** (Cherni, et al., 2020)

Although each locomotive technique brings its advantages and disadvantages, I shall not be discussing all within this paper as it is not within the scope of this project. One is that will be discarded is with the use of semi-natural external peripheral centred techniques as this would involve extra equipment and does not relate to my hypothesis.

Starting with the leaning based techniques, this is where walking is achieved by the user leaning their whole and/or part of it into the desired direction of travel. The leaning itself can be detected using modern HMD's due to their 6 DOF. Another leaning based method is the **head-based motion capture**. This is where the user's HMD's tracked position and/or rotation is used to direct the direction of travel. It is normally a form of **smooth based locomotion** where the user will also control the speed and direction in unity with another device such as a thumb stick on a controller. Another common leaning based technique used with head-based motion capture is the "**walking in place**". This method imitates walking and encourages users to engage their whole body in order to move. This LT aims to simulate a realistic walking motion without actually moving forwards. Other such similar simulation LT's are **Arm Swinging** which again encourages the users to swing their arms in an over the top walking fashion and is normally activated with a button press in order to help filter out unintended input. One of the more common user body centred LT employed by the industry is the **“Point and teleport”** this usually involves the user pressing a button with a motion controller and then pointing to the desired location in which to travel to. The reason this is one of the most common techniques is due to simulator sickness as this instantly transports the user without the need of performing any smooth transitions.

Mentioned frequently in the above paragraph relating to leaning based LT’s is the statement of using in conjunction with another form of input. This leads nicely into the mixed approach. The use of additional peripherals such as motion controllers are very commonly used. This is done in the form of using an external peripheral device as the driving direction for locomotion. A great example for this in the form of a smooth LT as using the head-based motion capture above the user is restricted in where they can look whilst using the artificial LT, however by using the controllers transform for direction of the movement the user can freely look about and “steer” the direction based on the rotation of the controller. The same applies with the swinging arm technique as it is common for developers to use the vector of motion as the direction of movement.

### 3.3 Implementation of the techniques

Based on the reviewed LT’s (Cherni, et al., 2020) as a preface to my project I created an implementation of a selection of common LT’s. The LT’s selected are as follows: Smooth Head-based motion capture (Linear Joystick); Smooth Hand-based motion capture (Linear Joystick); Swinging Arm Hand-based motion capture (Button Activated); and point and click teleport (Button Activated).

In order to create an environment in which to conduct a test the project settled on the following. **Hardware:** the HMD I used the HTC Vive as it’s the easily accessible in my workspace, for the controllers I used the index controllers as they are compatible with the same SDK the Vive functions with. **Software:** Unity with C# and the SteamVR SDK.

Learning the SDK was certainly a challenge at first with all the different subsystems that aren’t part of your typical “game” development process. Once I had understood the SDK, I started reading on design practices in the VR industry so I could best approach the traversal system.

The first traversal system I began work upon was natural locomotion for room scale experiences. One of the main considerations I first considered was the idea of a physics-based body in order to stop players walking into and then through objects. Using Unity’s character controller with a capsule collider I created script in **FIGURE 3.3.1** the purpose of this script it to attach the capsule collider to the player within local space and then have it resize depending on the players height with a minimum size to the collider if they duck too far it clamps. By having it resize it allows players to duck under objects laid within their path and forces them into a physical motion to force them to physically react to the traversal course.

```
// Update is called once per frame
Unity Message | 0 references
void Update() {
    if (!headSet || !rigSet) {
        cameraRig = AssetManager.GetPlayerRig().transform;
        head = AssetManager.GetHead().transform;

        if (cameraRig != null) rigSet = true;
        if (head != null) headSet = true;
    } else {
        HandleHead();
        HandleHeight();
        //Handle movement
        movementScript.GetComponent<LocomotionManager>().HandleMovement();//TODO Move to a proper handle system
        characterController.Move(new Vector3(0.0f, (-gravity * Time.deltaTime), 0.0f));//Applies gravity to the player
    }
}

1 reference
private void HandleHead() {
    //store current
    Vector3 oldPosition = cameraRig.position;
    Quaternion oldRotation = cameraRig.rotation;

    //rotation
    transform.eulerAngles = new Vector3(0.0f, head.rotation.eulerAngles.y, 0.0f);

    //restore
    cameraRig.position = oldPosition;
    cameraRig.rotation = oldRotation;
}

1 reference
private void HandleHeight() {
    //Get head in local space
    float headHeight = Mathf.Clamp(head.localPosition.y, 1, 2);
    characterController.height = headHeight;

    //cut in half
    Vector3 newCenter = Vector3.zero;
    newCenter.y = characterController.height / 2;
    newCenter.y += characterController.skinWidth;

    //Move capsule in local space
    newCenter.x = head.localPosition.x;
    newCenter.z = head.localPosition.z;

    //rotate
    newCenter = Quaternion.Euler(0, -transform.eulerAngles.y, 0) * newCenter;

    //apply
    characterController.center = newCenter;
}
```

**FIGURE 3.3.1 Code for handling capsule collider on player to dynamically scale based on user height & position**

Once the user's physical body was implemented, I could start implementing the LT techniques. I started by creating a locomotion handler class that called a HandleMovement() function in each of the types of implemented LT's. Detailed bellow is the HandleMovement() function in each of the LT's respective classes.

```
public void HandleMovement() {

    //TODO stop string comparison as this is very inefficent todo every frame!
    if (handBased) {
        directionObj = AssetManager.GetLeftController();
    }else if (headBased) {
        directionObj = AssetManager.GetHead();
    }

    float thumbX = inputManager.GetLeftThumbAnalogX(), thumbY = inputManager.GetLeftThumbAnalogY(); ;
    Vector3 moveDirection = Quaternion.AngleAxis(Angle(new Vector2(thumbX, thumbY)) + directionObj.transform.rotation.eulerAngles.y, Vector3.up) * Vector3.forward;


    if(Mathf.Abs(thumbX) > 0.3 || Mathf.Abs(thumbY) > 0.3) {
        //Apply VR comfort
        if (!onTrigger) {
            player.GetComponent<VignetteApplier>().FadeIn();
            onTrigger = true;
        }
        player.GetComponent<CharacterController>().Move(moveDirection * speed * Time.deltaTime);
    }

    //Apply VR comfort for stop
    if (Mathf.Abs(thumbX) < 0.2 && Mathf.Abs(thumbY) < 0.2) {
        if (onTrigger) {
            player.GetComponent<VignetteApplier>().FadeOut();
            onTrigger = false;
        }
    }


}

/**
 * Calculates angle of vector of which to move the player
 */
1 reference
public static float Angle(Vector2 p_vector2) {
    if (p_vector2.x < 0) {
        return 360 - (Mathf.Atan2(p_vector2.x, p_vector2.y) * Mathf.Rad2Deg * -1);
    } else {
        return Mathf.Atan2(p_vector2.x, p_vector2.y) * Mathf.Rad2Deg;
    }
}
```

**FIGURE 3.3.2 Code for handling smooth locomotion**

The code for allowing teleportation was a bit simpler and only involved checking if the thumb stick was within the threshold value and then performing a raycast of the controller to see where the user wanted to teleport. This was a basic implementation; some more modern solutions also allow the angle the user will face on teleporting to be changed on release.

```
private bool teleportDown = false;
private Vector3 pos = Vector3.zero;
1 reference
public void HandleMovement() {
    AssignVariables();

    //Set telport pressed
    if (!teleportDown) {
        if(GetComponent<LocomotionManager>().GetInputManager().GetLeftThumbAnalogY() > 0.5) {
            teleportDown = true;
        }
    }

    if (teleportDown) {
        //Cast location
        Ray ray = new Ray(leftHand.transform.position, leftHand.transform.forward);
        RaycastHit hit;
        if(Physics.Raycast(ray, out hit)) {
            Debug.DrawRay(transform.position, transform.TransformDirection(Vector3.forward) * hit.distance, Color.yellow)
            pos = hit.point;
            pointer.transform.position = pos;
        }
    }

    //Teleport released
    if(teleportDown && GetComponent<LocomotionManager>().GetInputManager().GetLeftThumbAnalogY() <= 0.5) {
        teleportDown = false;
        //teleport
        player.GetComponent<CharacterController>().enabled = false;
        StartCoroutine(Teleport(player.transform.position, pos));
        player.GetComponent<CharacterController>().enabled = true;
    }
}
```

**FIGURE 3.3.3 Code for handling teleportation**

The swinging arm technique was also mundane to implement as it only involved storing the position when triggered and then moving the player along the vector created as long as the button is held down.

```
//Comfort Vignette
private bool firstClick = false;
1 reference
public void HandleMovement() {
    AssignVariables();
    if(firstClick) timer += Time.deltaTime;
    //Obtain Controller exclusivitey to ensure not getting input from multiple controllers
    if (!triggerTransform) {
        if (inputManager.GetLeftADown()) {
            transformObj = leftHand;
            leftHandTrack = true;
            inputDown = true;
        } else if (inputManager.GetRightADown()) {
            transformObj = rightHand;
            leftHandTrack = false;
            inputDown = true;
        }
    }

    if (inputDown && !triggerTransform) {
        originClk = transformObj.transform.position;
        triggerTransform = true;
        if(!firstClick)player.GetComponent<VignetteApplier>().FadeIn();
        firstClick = true;
        timer = 0.0f;
    }else if (triggerTransform && inputDown) {//drag and apply movement
        Vector3 movement = new Vector3(originClk.x - transformObj.transform.position.x, 0, originClk.z - transformObj.transform.position.z);
        player.GetComponent<CharacterController>().Move(movement * speed * Time.deltaTime);
        originClk = transformObj.transform.position;
    }
    if(triggerTransform) {
        if (leftHandTrack) {
            if (!inputManager.GetLeftADown()) {
                triggerTransform = false;
                inputDown = false;
            }
        } else {
            if (!inputManager.GetRightADown()) {
                triggerTransform = false;
                inputDown = false;
            }
        }
    } else {
        if (timer > 0.75f) {
            firstClick = false;
            player.GetComponent<VignetteApplier>().FadeOut();
        }
    }
}
```

**FIGURE 3.3.4 Code for handling swinging arm**

Finally, the most complex method I implemented was the walk-on-spot LT. This is due to trying to account for different user sizes and more importantly filtering out unintended input from the user. For example, we don’t want to propel the player forward if they are crouching so it is important to try and recognise what input is and isn’t intended to move the player.

```
public void HandleMovement() {
    AssignVariables();

    //DEBUG HEIGHT SET REMOVE!!!!
    if (AssetManager.GetInputManager().GetLeftTriggerDown()) {
        playerHeight = AssetManager.GetHead().transform.localPosition.y;
    }

    //calc height average
    heightCalcTimer += Time.deltaTime;
    averageHeight += AssetManager.GetHead().transform.localPosition.y;
    samples++;
    if(heightCalcTimer >= 3) {
        calcAverage = false;
        heightCalcTimer = 0.0f;
        playerHeight = averageHeight / samples;
        averageHeight = 0.0f;
        samples = 0;
    }

    if (move) {
        timeElapsedSinceTrigger += Time.deltaTime;//since last trigger increment
        returnTimer += Time.deltaTime;
    }
    //if barrier is triggered
    if (Mathf.Abs(playerHeight - AssetManager.GetHead().transform.localPosition.y) >= sensitivity){
        if(!triggered) player.GetComponent<VignetteApplier>().FadeIn();//comfort enable
        move = true;
        triggered = true;
        timeElapsedSinceTrigger = 0.0f; //trigger happend reset
    } else {
        returnTimer = 0.0f;
    }

    Vector3 moveDirection = Quaternion.AngleAxis(AssetManager.GetHead().transform.rotation.eulerAngles.y, Vector3.up) * Vector3.forward;//get the angle user is facing
    if (move && returnTimer < 0.25f) {//must have returned within 0.25 Secs
        player.GetComponent<CharacterController>().Move(moveDirection * speed * Time.deltaTime);
        if(timeElapsedSinceTrigger >= 0.75f) {//frequency for trigger to activate
            move = false;
            triggered = false;
            player.GetComponent<VignetteApplier>().FadeOut();//comfort disable
        }
    }
```

**FIGURE 3.3.5 Code for walk on spot locomotion**

Final on the list was to create the course for the users to traverse as well as implement some data collection code i.e. time to complete course & position sampling.

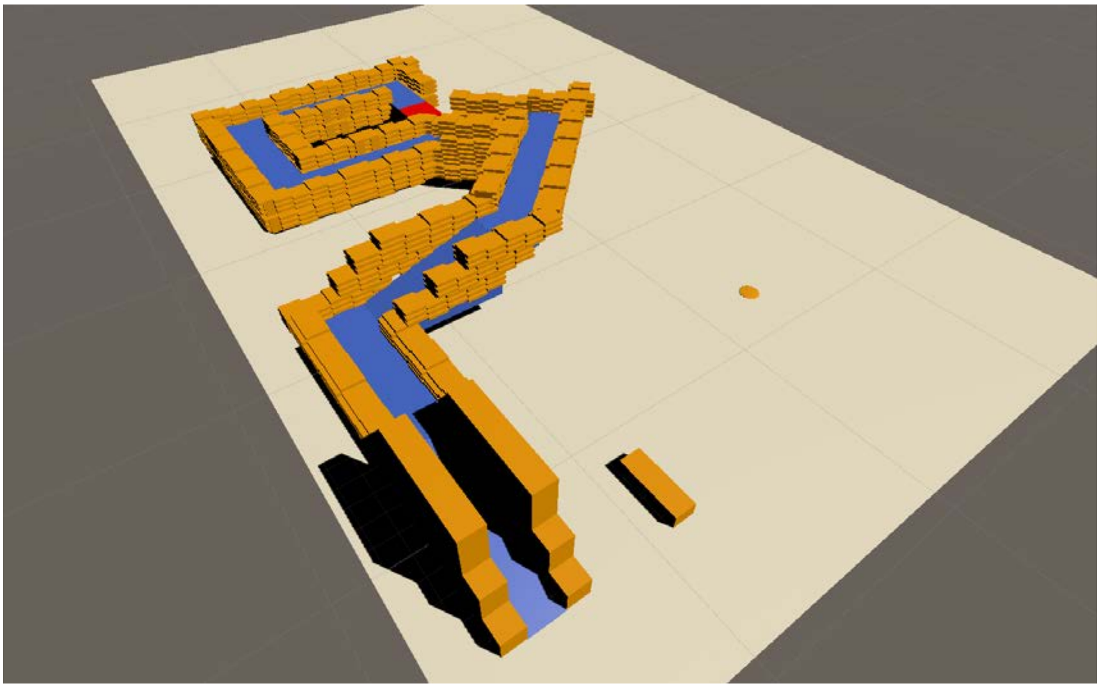


**FIGURE 3.3.6 The locomotion course**

### 3.4 The Hybrid Approach

Although the LT’s are used in order for users to scale larger environments it is important to also keep the 6DOF as it allows users to move and get involved in the IVE still physically. It also helps reduce motion sickness as the translation of position is 1:1 with the users’ actions.

### 3.5 The Test

The test I got users to carry out was to traverse the locomotion course I built using each of the LT’s I had implemented. Once they completed the course from end to end using each LT, I then asked them to rank them in order of preference as well as some thoughts on each technique. The results of which are discussed in **CHAPTER 6**.

## Chapter 4: The interaction problem

### 4.1 What do we mean by interaction?

One of the other problems within the industry as discussed earlier is the issue of how to interact with an IVE. Interaction is an insanely broad scope and would be beyond the scope of this project to discuss it in whole. This project focuses on simpler/general interactions within an IVE. Some examples of these interactions discussed are: Picking Up Dynamic Objects, Touching Static Objects, Interacting with buttons/switches.

Traditional flatscreen games this is “no problem” as the only form of input comes from an external device where we can use raycasts to interact with objects. The problem with 6 DOF input is we need to make more “natural” interactions that are intuitive to the user.

### 4.2 Current Solutions

To start with examine a simple interaction for picking up objects. There have been many implementations over the years which have been based around the types of controllers. With the Vive wands a simple binary button press using either the trigger or grip to interact, whereas modern controllers such as the index support individual finger tracking which are in the form of float values. As stated earlier I am using the index controller, and a way to detect a “grip” with the index is if the sum of values of a “press/grip” passes a threshold value then we detect the user to grip. The addition of capacitive finger tracking is fantastic as it is a more natural interaction for a user as rather than a button press, they can reach out and grab like they would in real life.

### 4.3 Problems with current solutions

One of the big issues with object interaction is simulating the sense of touch whilst also attempting to provide the functions to attend to locomotion i.e. using an analogue stick to traverse large scale IVE’s. The way current systems attempt to address this is in the form of multiple motors providing haptic feedback on the controller whilst showing a virtual pseudo representation of their hands in the game. A great example of this is the holding of objects in **Half Life: Alyx,** a game developed by Valve Software,  as can be seen in **FIGURE 4.3.1**

**FIGURE 4.3.1 hand skeletal maps morphed to object**

Another issue with feedback is restricting the user's motion when colliding with objects. For example, if the user places their hand on a virtual table their real hand can continue to pass through it. Some attempts at addressing this issue are: to only show the virtual representation of the hand stopped on the table; To only display the virtual hand at the physical location (Hand appearing/phasing in the object); The hybrid model of showing two representations of the hand on collision both on and in the table. An example of this hybrid model taken from Half Life: Alyx can be seen in **FIGURE 4.3.2**

**FIGURE 4.3.2 Half Life: Alyx hand limits with actual oculus controller location overlayed**

Today Oculus has also implemented a form of hand tracking. It demonstrates the possibilities of hand tracking interactions with its tech demo “Elixir” made by (Facebook Reality Labs, 2020). Some of the included features demonstrated here is gesture recognition in the form of a two handed “point and pinch” to teleport around a play space **FIGURE 4.3.3** . The issue as mentioned earlier is pinching to teleport in larger scale environments, i.e. open world, is less than ideal. It also means that with hand tracking you get zero haptic feedback because of no external hardware attached to your hands.

**FIGURE 4.3.3 Elixir Gesture Detection** (Facebook Reality Labs, 2020)

**4.4 What are we trying to simulate**

In September of 2019 an employee from valve, Kerry Davis, performed a talk on the challenges of developing for VR (Davis, 2019). Whilst the talk touched on various topics relating to VR already mentioned within this report such as "Motion Sickness", Collisions, the really interesting topic of the talk was on the difficulty of interaction abstractions. When in the VR world should we treat it as if we are in the physical world. Thus, the hypothesis "Simulating Reality Leads to Simulating An Experience" (Davis, 2019)

One of the ideologies mentioned was "In VR everyday common interactions shouldn't be complex they should be intuitive to the user which creates a user experience." (Davis, 2019). This is the idea that actions such as opening a door should be an intuitive experience and should not need a manual for the user to open. During the testing of this (Davis, 2019) went through various iterations of types of doors, one of which was a physically accurate door with a latch that is operated by the handle. You might assume that this would be a good implementation to have, however it was quickly discovered through user testing that people did not know how to open the door presented in the IVE. A user was quoted "I have to pull the handle?" which sounds like a very strange statement.

As a result of user testing, the interaction was then abstracted to allow for user error and also temporarily relinquished control of the user's virtual hand to attach the hand to the door handle. In testing they found that users actually thought they did move the handle when the fact was the handle moved their hand. This also teaches the player how to open the door as it demonstrates the motion without them realising it as a sub-conscious teaching.

Another issue identified by this investigation was the atomicity of interactable objects in games. For example, in this study a door is no longer atomic i.e. no defined states (open, closed) because the user can open the door slightly as a transitional value. The atomic problem raises more issues such as with sound where you can't play an open or closing sound once on the interaction, you need to account for how fast a user opens it, how long they take, do they open it all the way? Do they open it and start shutting it again before its  fully open?

Users also struggled with kinaesthetic sense with their virtual and real bodies. You don't want the user to accidently knock the door around with their virtual bodies unintentionally because this can be quite jarring and result in motion sickness. So even though this would be physically accurate to have the door collide with user bodies, it's an unintended input from the user and would result in "a disconnect for the player" (Davis, 2019).

The conclusion made during this investigation was "Are you trying to simulate reality or the perception of reality? The choice you make should be intentional" - (Davis, 2019). As can be defined from Davis' findings that a physically accurate world does not necessarily have a positive effect on the user experience. My own take on this agrees as we don't want Virtual Reality to be an identical simulation of the real world, we want it to be better!

Some testing was performed as part of this report to gather user preference on how their virtual hands are displayed versus their physical pose using standard motion controllers (in this case the valve index) this is attached in **APPENDIX B**.

## Chapter 5: The hybrid space approach

### 5.1 What is the hybrid space approach?

The hybrid space approach, as I have so called it, is when we take a real-world location/physical model such as a room in a house and then build a 1:1 scale IVE from that physical model.

This report is not the first to attempt such a feat as it has been done various times coming in a few forms. Some of the more basic implementations I have seen available are in the form of YouTube videos from (Valem, 2020) and also (Madison, 2020). Another implementation is from a company called Void who have their own implementation of this hybrid approach called “Hyper Reality” where they have parented with entertainment giants such as ILMxLAB to create immersive entertainment experiences such as Star Wars: Secrets of the Empire (Void, n.d.)

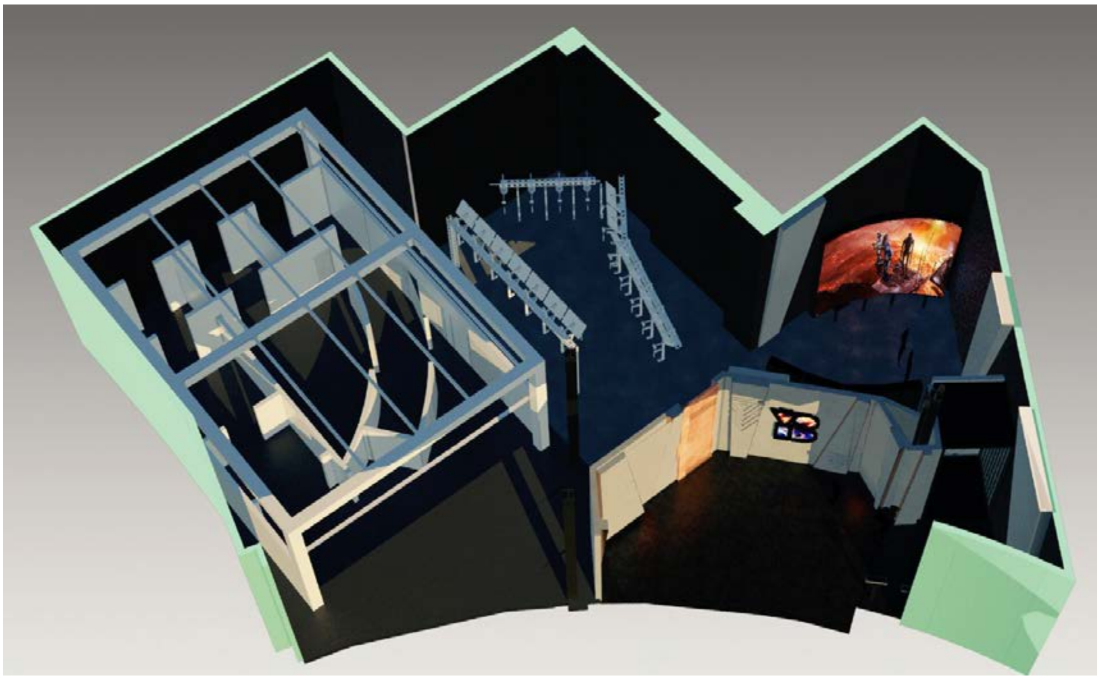


**FIGURE 5.1.1 Virtual render of physical environment setup by the void for secrets of the empire hyper reality experience**

### 5.2 How does this address the interaction & locomotion problems?

By using this hybrid approach, we can address some of the interaction and locomotion problems in VR.

One of the current preferred methods of locomotion in the industry with minimal risk of motion sickness is to use room scale experiences as discussed in **CHAPTER 4** of this report. By using making a 1:1 model of an environment we eliminate the need for any controller based locomotion techniques as when the user walks 1M in the physical model they will also move 1M in the virtual model allowing for a seamless traversal of the environment. If my predictions are correct, if the spatial tracking is able to keep within an acceptable deviation (Not yet defined) from the physical model then the user should be able to comfortably walk around an environment with obstacles i.e. a table, without the worry of potentially walking into an object. The one detriment to this technique is that we are limited by the maximum definable play space for an HMD. Using Valves base station tracking method would more than likely cause problems with occlusion for tracking controllers and the HMD in a place space with larger/many objects. For this reason, I believe the Insight/Inside-out tracking technique would be more appropriate here.

We can address the interaction problem by taking advantage of the 1:1 IVE to allow for hand tracking. By doing this when the user sees the virtual representation of their hands touching the virtual table, they should in turn also feel the physical feedback from the physical table due to this 1:1 mapping. i.e. touching the virtual table results in the touching the real table. However, as with the issues for locomotion, this is not without its caveats. Even with the added addition perfect hand tracking from occlusion, **which currently isn't solved for real-time applications**, we may still encounter problems with dynamic physics objects. For example, if we have an interactable cube in the 1:1 IVE that the user picks up. If the user then dropped this cube the virtual representation and physical object would then become desynchronised as physics engines in games are not a perfect simulation. For this reason, in the project I made the decision to make cubes kinematic and not be effected by gravity, this allows the cube to remain in its released position so long as the users follows the rules, ideally sub-consciously, of the programme. However, it is important to note that when creating an interactable object it should have tailor made decisions. For example in this project I want users to drop some paper balls into a container, based on this requirement I believe it is safe to apply gravity to the virtual paper balls because the intention is to be dropped straight down into the container and should not deviate in the X, Z axis because of this if the previously addressed issues are tackled correctly.

## 5.3 The hardware used

Based on how the problems are addressed in **SECTION 5.2** it is important that the hardware selection is in accordance to the needs.

I have decided to use the Oculus Quest 2 as it is a piece of equipment I already have access to, and it provides all the necessary features required to attempt to build the project. It uses inside-out tracking which helps with the occlusion problem for play spaces with large/many objects in them. It also has an impressive implementation of hand-tracking that is made easy to develop for thanks to the Unity Oculus SDK, however it's worth noting that it still has a large barrier to overcome for occlusion hand tracking. Also, thanks to the headset being a standalone device with wireless capability it makes it even more ideal to walk around a play space with objects as it avoids the wires getting tangled.

## 5.4 The Design of the Experiment

Coming back to the hypothesis, we want to have an IVE of a physical modelled environment that supports the specified features of the hardware in **SECTION 5.3**. I have selected to use a room in my house, the kitchen, to create a 1:1 scale model. In the kitchen there will be specific interactable objects that will have specified tasks the user has to complete. The reason for the tasks is as mentioned in **SPES Review in**

**Appendix B,** where we want the user to forget about the physical model and accept our virtual model as their reality. **SECTION 2.2** talks about immersion being defined by a user's concentration, by having tasks we give the user something to focus on without having to think about the experiment. We want to keep our users busy for the best implementation of the experiment.

When thinking about the kitchen and objects in the house I thought of three physical objects that I could implement. These objects were cupboards, Small cubes and scrunched up paper. The reason for selecting these objects are due to the occlusion problem I would encounter with hand tracking, by using smaller objects, like cupboard handles, we ensure that as long as the user interacts with big motion gestures that their hands are always visible to the tracking cameras on the HMD.

Using the kitchen as an IVE and the objects I selected I devised the following tasks.
**Task 1:** Walk around the kitchen for 60 seconds

**Task 2:** Sit on every chair within the kitchen

**Task 3:** Find all the cubes (4) in the kitchen and build a tower (4 high)

**Task 4:** Press the button (physical object is cello tape) and hit 20 moles.

**Task 5:** Find all the paper in the kitchen (5) and deposit it in the pink container

The tasks devised should give the user enough time to become familiar with the IVE for the purpose of this study. However, running the test only in the hybrid environment is not enough for me to create a link to my hypotheses. To counter this, I proposed that the users perform the test twice. Once in a purely virtual IVE i.e. no physical objects,  this would take place in my garden. Then once more in the hybrid environment which would take place in the synchronised kitchen. At the end of each run the user will answer the questionnaire devised based on **SECTION 3.3** SPES as well as a few added questions to help better understand the data generated by the user. The questionnaire used is devised in **SECTION 5.6.**

## 5.5 How it was made?

### 5.5.1 The Software

Given the hardware discussed above I have decided to use Unity with C# thanks to the extensive documentation on XR development and the integration with the Oculus SDK. I have previous experience with Unity so this will also aid the speed and success of development and it also allows me to carry forward what I learned from XR development in **CHAPTER 3 & 4** of this report.

### 5.5.2 Mapping the room

To create the kitchen, I started by taking measurements of the room. I drew a rough sketched outline of the room and began to measure the objects I knew would remain static throughout the experiment i.e. the counters, chairs, and walls.

With this information I could then go about modelling the room in Unity and used one of the prefabs included with the oculus plugin to allow me to test how accurate my measurements were. I tested this by recentring the headsets tracking origin to the identical location defined in Unity to the physical model. I then went round the room running my hand along surfaces to see if when my virtual hand was touching the IVE objects that I was also touching the physical models' walls.

Once the static objects in the environment had been implemented, I started work on creating and positioning the models of the dynamic objects such as the cubes, scrunched-up paper and cupboards. The cupboards were the most challenging here as I had to ensure that not only the dimensions of the cupboard doors were the same but that they were also exactly positioned where they should be so that when reaching for the virtual cupboard handle my hand was also touching the physical handle.

**FIGURE 5.5.2.1 Real Picture Vs IVE**

### 5.5.3 Gesture Recognition

Now that the room had been accurately mapped, we needed to come up with a method of interacting with objects using our virtual hands. For the approach to this I decided on a gesture recognition approach. Thanks to the prefab included with the oculus SDK it provides a skeletal model with dynamic transforms that move to match your real hands. Using this data, we can see the positions of each part of the hand i.e. knuckles, fingertips, palm, finger knuckles. We can “recognise” certain hand poses by recording the transforms of the hand’s components. We can then compare the users sum of transforms to our recorded gestures and if the current sum lies within the threshold distance to another recorded pose then we can assume the gesture the user is currently displaying.

We check the current hand pose at the beginning of every frame in order to see if it is in our currently registered data set. In order to recognise if the user is interacting with one of the interactable objects I recorded the hand pose by pressing the space bar with the opposite hand to signal the record function, whilst holding the object I want to interact with in the other hand. By doing this the program stores the hand pose in a list. This then allows the program to recognise the hand pose in future i.e. when grabbing the cube, our hand assumes approximately the same pose we used when recording it. We then check to see if the pose is within the allowable threshold and if it is then we can change the appropriate variables to signify the hand is “grabbing”.

There are two gameobjects that contain the GestureDetector script (one linked to each hand). On the user’s hands are sphere colliders that act as triggers when they overlap with an interactable object’s collider.

```
1 reference
Gesture Recognize() {
    try {
        Gesture currentGesture = new Gesture();

        //closest distance
        float currentMin = Mathf.Infinity;

        //Cycle through gestures
        for (int g = 0; g < gestures.Count; g++) {
            float sumDistance = 0;

            bool isDiscarded = false;

            //Get skellington transofrms
            for (int i = 0; i < fingerbones.Count; i++) {
                //Position of current finger bone
                Vector3 currentData = skeleton.transform.InverseTransformPoint(fingerbones[i].Transform.position);

                //compare finger bone to finger bone in gesture being checked
                float distance = Vector3.Distance(currentData, gestures[g].fingerDatas[i]);

                //if our distnace is greater then discard
                if (distance > threshold) {
                    isDiscarded = true;
                    break;
                }

                //increase sum of distnace if not discarded
                sumDistance += distance;
            }

            //if the gesture checked is not discarded and closer than the current closest pose then we set this to be the new closer pose
            if (!isDiscarded && sumDistance < currentMin) {
                currentMin = sumDistance;
                currentGesture = gestures[g];
            }
        }

        return currentGesture;
    }catch(ArgumentOutOfRangeException e) {
        return gestures[gestures.Count-1];
    }
}
```

```
Unity Message | 0 references
void Update() {
    //Debug Mode allows saving with spacebar
    if (debugMode && Input.GetKeyDown(KeyCode.Space)) {
        Save();
    }


    //if the initialization was successful
    if (hasStarted.Equals(true)) {
        // start to Recognize every gesture we make
        Gesture currentGesture = Recognize();

        hasRecognize = !currentGesture.Equals(new Gesture());

        // and if the gesture is recognized
        if (hasRecognize) {
            //already recognised avoids loop
            done = true;
            if (!currentGesture.Equals(previousGesture)) {
                // after that i will invoke what put in the Event if is present
                currentGesture.onRecognized?.Invoke();
            }
        }else {
            //signal finished
            if (done) {
                Debug.Log("Not Recognized");
                done = false;
                //Invoke unrecognised event
                notRecognize?.Invoke();
            }
        }
        previousGesture = currentGesture;
    }
}

1 reference
void Save() {
    Gesture g = new Gesture();
    g.name = "New Gesture";

    List<Vector3> data = new List<Vector3>();

   //Gather postion of finger bones
    foreach (var bone in fingerbones) {
        data.Add(skeleton.transform.InverseTransformPoint(bone.Transform.position));
    }

    g.fingerDatas = data;

    gestures.Add(g);//Add/Save Gesture
}
```

**FIGURE 5.5.3.1 Code for recognising gestures**

In order to allow for interaction between objects our interactable's contain a script derived from "OVRGrabable". Each script such as "GrabbableCube" contains functions relative to that object, such as having the transform centered to the users palm, a stacking function to allow the cubes to snap to each other on release and some task tracking variables.

### 5.5.4 Creation of tasks

The cubes are made up of 3 key components: A Box Collider; GrabableCube script; AttachPoint transform. The cube was the first implementation of an interactable object. In the Oculus SDK a gameobject that contains OVRGrabable script is attached to an object if #1 the collider is overlapping with a hand collider and #2 the hand colliding beings gripping after the overlap. Since out GrabableCube script derives from OVRGrablable the object is parented to the hand when we grab the cube because the hand will have assumed the approximate pose that we recorded for grabbing the cube which then triggers the appropriate grab and attach events.

The rest of the interactable objects are created very similarly just with the added addition of their task specific tracking variables. The cupboard is a bit of an outlier in the sense of rather than transforming the objects position we actually created a script to apply forces to the rigidbody. The main body of the cupboard is restricted via a hinge component so when the rigidbody has force applied it roates around the hinge point. The handle for the cupboard is a little more unique. We have the physical handle with the "Handle" script. Childed to the rendered handle is the "GrabableHandle" this object is invisible and is the object we actually interact with, just as with the other OVRGrabables' it contains a box collider but also the "DoorGrabable" script and a kinematic rigid body. The "DoorGrablable" script is linked to the parent handles rigid body and when grabbed attempts to match that rigidbody transform to the grabable handles rigidbody.

```
Unity Script | 0 references
public class DoorGrabbable : OVRGrabbable
{
    public Transform handler;

    5 references
    public override void GrabEnd(Vector3 linearVelocity, Vector3 angularVelocity) {
        base.GrabEnd(Vector3.zero, Vector3.zero);
        transform.position = handler.transform.position;
        transform.rotation = handler.transform.rotation;

        Rigidbody rbHandler = handler.GetComponent<Rigidbody>();
        rbHandler.velocity = Vector3.zero;
        rbHandler.angularVelocity = Vector3.zero;
    }

    Unity Message | 0 references
    private void Update() {
        if(Vector3.Distance(handler.position, transform.position) > 0.4f) {
            grabbedBy.ForceRelease(this);
        }
    }
}
```

```
Unity Script | 0 references
public class Handle : MonoBehaviour
{
    public Transform target;
    Rigidbody rb;
    // Start is called before the first frame update
    Unity Message | 0 references
    void Start()
    {
        rb = GetComponent<Rigidbody>();
    }

    // Update is called once per frame
    Unity Message | 0 references
    void FixedUpdate()
    {
        rb.MovePosition(target.transform.position);
    }
}
```

**FIGURE 5.5.3.2**

## 5.6 The Questionnaire

The questionnaire for this test was devised from the SPES discussed in **CHAPTER 3**. I took the base questions devised here and then added another set of questions related to the two subdimensions of presence: self-location; possible actions. This second set of questions made it more related to the environment (The kitchen) and actions possible that the testing took place in. The scale used as described by SPES (Werner, et al., 2015) and is rated as agreement statements of 0-5 I decided to allow for .1 increments for rating to help get a clear picture of how much the increase/decrease differs.

The questionnaire used is attached in **APPENDIX B**

The testers were asked the questionnaire at the end of each run of the experiment so that we could see the deviation their answers upon completion of both runs.

### 5.7 Issues in development

There were many challenges I faced during development. The main issues I encountered related to gestures occasionally not being recognised, in order to counteract this, I moved the recognise call to the start of each frame and also increased the threshold in which they would be recognised. I also recorded extra gestures to account for the different ways someone may interact with an object and also used someone with much smaller hands than me to also record the gestures to account for different user hand sizes.

Another common issue was the deviation of the IVE mapped to the physical model the further away from the centred origin the user got. This was due to if the position of the headset was out on the synchronisation or the angle was out by a degree then the further away from that point you get the bigger the difference in deviation due to the skewed angle. To counter this, I used a rudimentary solution of drawing on the HMD and the physical synchronisation point so that it was perfectly matched when re-centring.

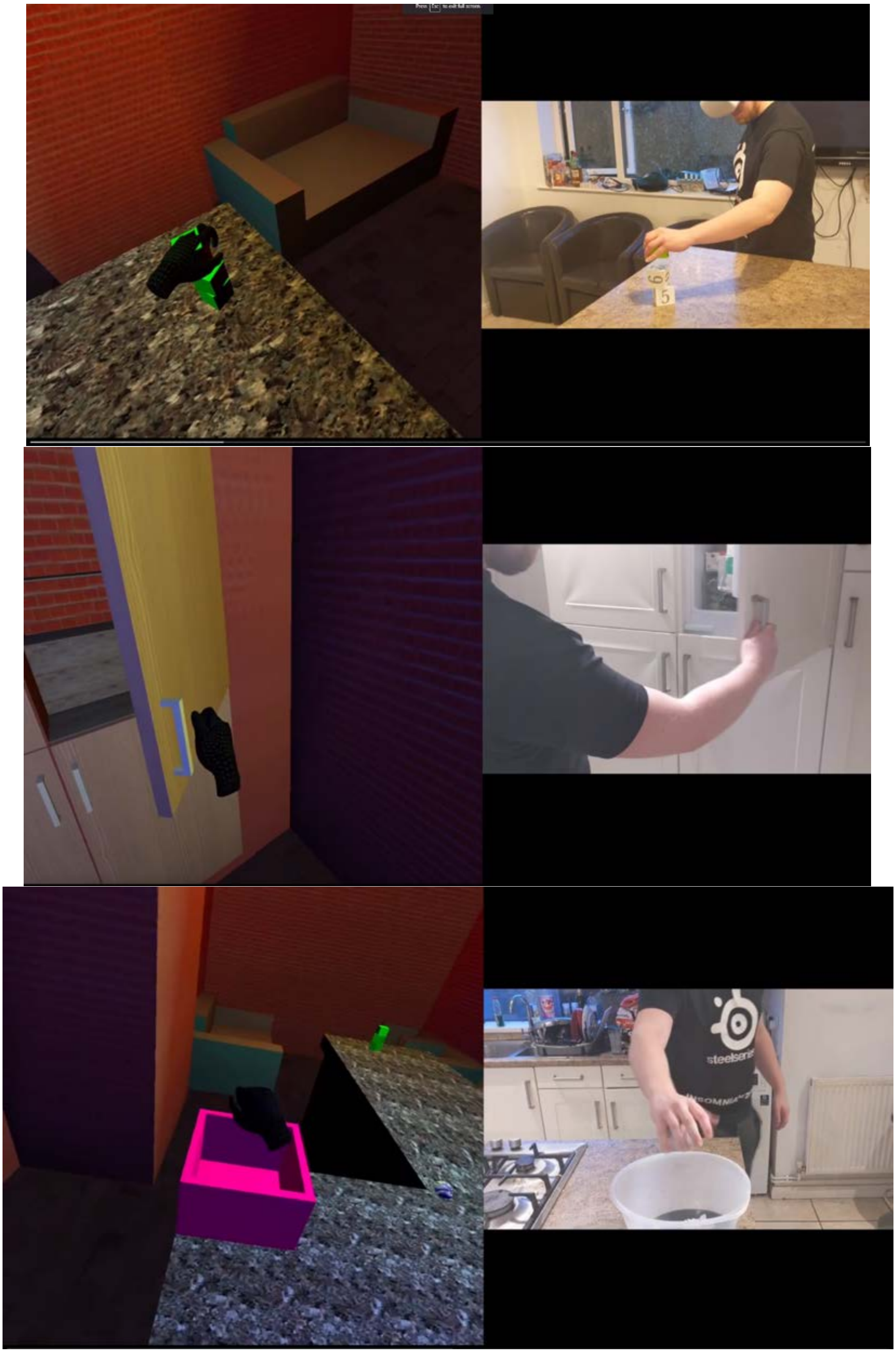


**FIGURE 5.7.1 Images from Final Test**

## Chapter 6: Results & Conclusion:

### 6.1 COVID-19

Sadly, due to the ongoing pandemic the results demonstrated bellow are from a very small sample size of just 5 individuals. I would have preferred to have tested on a much larger sample size; however, I consider the sample size and yielded results to be a good demonstration of preliminary results giving good reason to pursue this further once the pandemic is under control.

### 6.2 Locomotion Results

As described in **SECTION 3.4** the users traversed the course using the various locomotion techniques and were then asked to state their preferred technique and why.

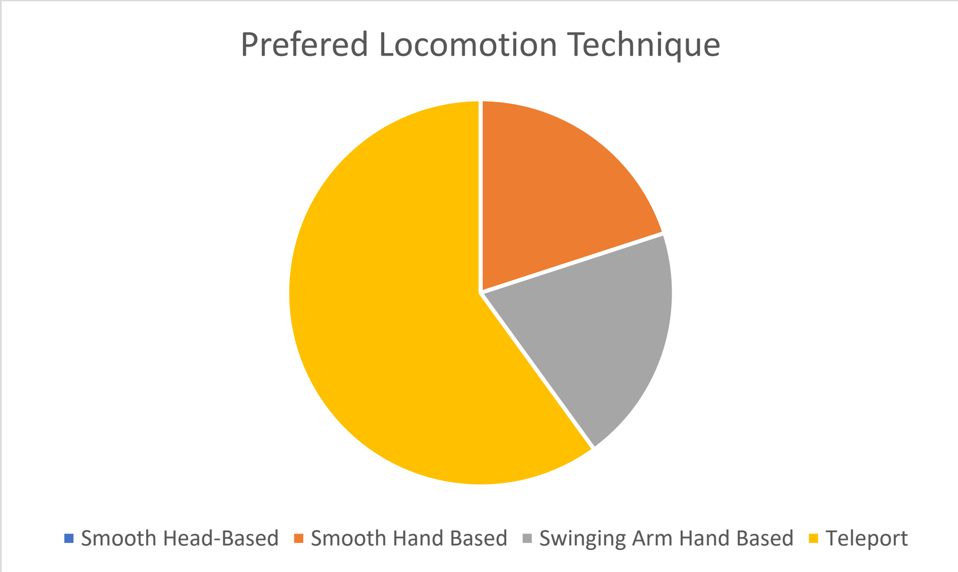



**FIGURE 7.2.1**

| | Preferred Locomotion Technique | VR experience |
|---|---|---|
| User 1 | Swinging Arm Hand-Based | 2 |
| User 2 | Teleportation | 1 |
| User 3 | Teleportation | 1 |
| User 4 | Teleportation | 1 |
| User 5 | Smooth Hand-Based | 3 |

**FIGURE 6.2.2 Users Preferred LT and VR experience**

**User Quotes:**

**User 1: "**I preferred swinging arm locomotion because it didn't make me feel too sick and I still had control of how much I moved just by using my arms"

**User 2: "**I preferred teleportation because it didn't make me feel ill and I could still choose the exact point I wanted to move to. The other methods made me feel way to dizzy"

**User 3: "**I preferred teleportation because the rest of the methods made me feel funny"

**User 4: "**I preferred teleportation because it didn't make me feel sick but I really wanted to like the smother methods as they just felt more genuine"

**User 5: "**I preferred smooth hand-based because I could still move my head around and move in the same direction whereas the head-based meant my desired path changed. It did make me feel a little ill after a bit but is likely because I haven't used VR much lately"

### 6.3 Locomotion Findings

From the chart displayed in **FIGURE 6.2.1** we deduce that the majority of users in this study preferred the teleportation locomotion technique over other techniques. However, it's worth noting the distribution of these preferences based on previous experience with VR devices.

Out of our sample the 3 users that preferred teleportation had only used VR a handful of times. The user that preferred swinging arm hand-based LT had a bit more experience with VR. Finally, the user who preferred smooth hand-based LT had the most experience with VR.

Smooth Hand based is considered to be one of the more intense LT and teleportation being the least intense next to room-scale. Because of those reasons it is no surprise to see the distribution of preferences.

As we can see from my user quotes the reason for these preferred LT's are due to experience and some people suffering from motion sickness. Even when suffering from motion sickness one user even went as far as to state, they preferred another smoother method but couldn't select it as it made them feel ill.

From these results we conclude that it is very much down to the user preference and there is not a "One size fits all" approach because people suffer with motion sickness to different levels.

**Side Note:** There is a term in industry called "VLEGS" which are like sea legs for VR. It can just take some regular use to before the sickness becomes negligible to the user

### 6.4 Hybrid Space Results

As discussed in **chapter 5** my testers will perform the run-through of the IVE tasks twice. First outside in the purely virtual environment and again inside in the hybrid environment.

| | User 1 | User 2 | User 3 | User 4 | User 5 |
|---|---|---|---|---|---|
| T1 | 3.9175 | 3.43 | 3.1375 | 3.1075 | 3.0275 |
| T2 | 4.9075 | 4.1925 | 3.975 | 4.025 | 4.2425 |
| Increase | 0.99 | 0.7625 | 0.8375 | 0.9175 | 1.215 |
| % | 20% | 15% | 17% | 18% | 24% |

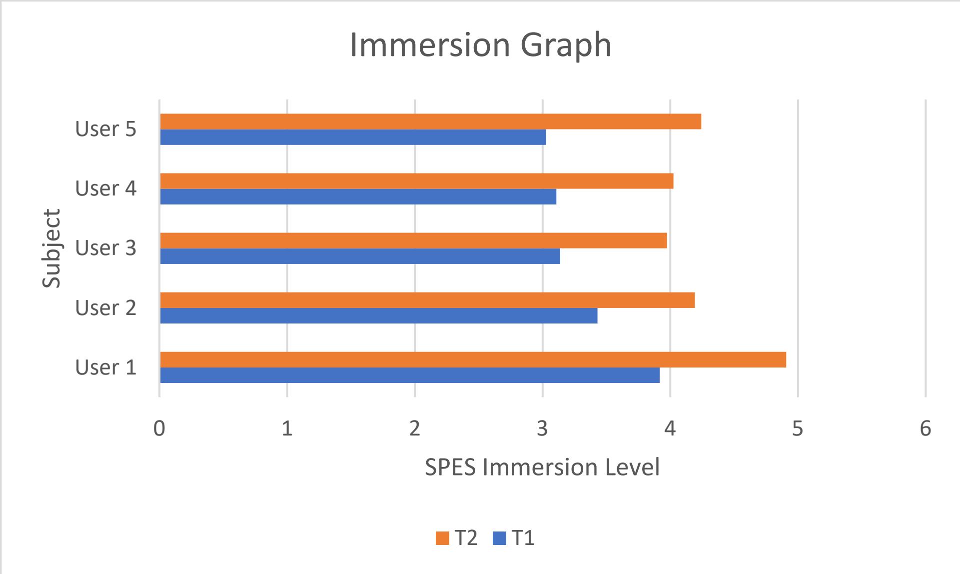



**FIGURE 6.4.1 Immersion Level Graph**
**Legend: T1: Task 1 (purely virtual), T2: Task 2 (hybrid)**

Users were also asked how much previous experience they had with VR devices and IVE's on a scale of 0-5. 0: No experience, 5: Use every day. This produced the following table.

| | User 1 | User 2 | User 3 | User 4 | User 5 |
|---|---|---|---|---|---|
| % Increase | 20% | 15% | 17% | 18% | 24% |
| VR Experience | 2 | 1 | 1 | 1 | 3 |

**FIGURE 6.4.2 VR Device Experience**

### 6.5 Hybrid Space Findings

The users were quoted:

"When working correctly the inside version was a lot more impressive and really allowed me to get involved"

"The experience in the second environment (physical) felt more genuine"

"Interaction felt better in the physical"

"I felt more encapsulated in the physical environment"

They were the notable quotes when talking about the experiment but every user each said that they preferred the hybrid environment over the purely virtual. Now that preference alone is not enough to draw the conclusion that my hypothesis was correct as those statements are not a measure of immersion but rather a preference such as was discussed in **SECTION 6.3**.

As can be seen from the results in **SECTION 6.4** we can see that on average users experienced a 18.89% increase on the SPES when performing the experiment in the hybrid environment.

The interesting thing about these results is how the users responded based on their previous experience with VR. I asked users to also note on a 0-5 scale how much experience they had with VR devices. **FIGURE 6.4.2** shows the people who saw the largest increase in immersion on the SPES were people with more experience with VR. This is likely because people with little experience were very impressed with the first test already as the novelty is still very new to them. As a result of this excitement they ranked the first test much higher than the users who had already used a headset before. However, this could also be due to the fact people with more experience with these devices are better at making the sub-conscious switch of self-location (the sub-dimension of immersion) from the physical world to the IVE.

### 6.6 Conclusion

Based on the results discussed in this chapter we identify many attributes that contribute to the purpose of supporting the hypothesis.

From the results in the simple locomotion test we carried out we identified that "the best Locomotion Technique" is not so black and white. It depends on numerous factors i.e. the environment, how motion sick a user gets, how much experience the user has with VR. But the most important identifier here is preference! If a LT is the preference for the user then they are more likely to accept that method of traversal and be comfortable within the IVE and therefore may be more likely to make the sub-conscious switch and increase, their factor of immersion.

Back to the main purpose of the study relating back to my hypothesis. I said, "I hypothesise that creating a virtual environment that has some objects transforms synchronised with physical world objects will positively increase a user's immersion". The results from the hybrid environment test concours with this statement as on average users saw a 18.89% increase on the SPES and with a spread between lowest and highest increase of just 14%. This increase factored in with the small spread shows that not only does the hybrid environment increase a user's immersion level, but it does so consistently across the board no matter the type of user using the programme.

Was this project enough to prove my hypothesis? No, due to the small sample size. However, it is enough supporting evidence as a preliminary study to justify users experiencing increased immersion levels in hybrid environments. As such justifies future projects to experiment further.

**NOTE:** during the duration of the project, Facebook/Oculus, released an update allowing you to map your physical couch to the virtual world. This only further solidifies the argument to pursue this area further of hybrid environments.

## Chapter 7: Evaluation

### 7.1 How successful was my approach?

My project was a success according to the aims & objectives laid out at the beginning of this project. The programme and tests devised were able to demonstrate as a preliminary study that there is a positive correlation between the use of hybrid environments and the user's level of immersion.

Throughout the project I used an agile methodology in order to rapidly develop features and then test them. This was a good approach as in the final stages of development when time was short it proved an invaluable method of development when cycling through the tasks that still needed to be completed.

### 7.2 What would I do differently?

If I was to perform this project again, I would like to select a different method or perhaps additional method of measuring a user's immersion level. Equipment like EEG sensors would be a great fit here as discussed in **CHAPTER 2** as this is raw data unlike the SPES used where users may have inaccurately ranked the statements in the questionnaire. By deprecating the questionnaire, we eliminate the bias towards the purely virtual test for users with little experience and also the bias towards the second test for users with more experience.

### 7.3 Time Management

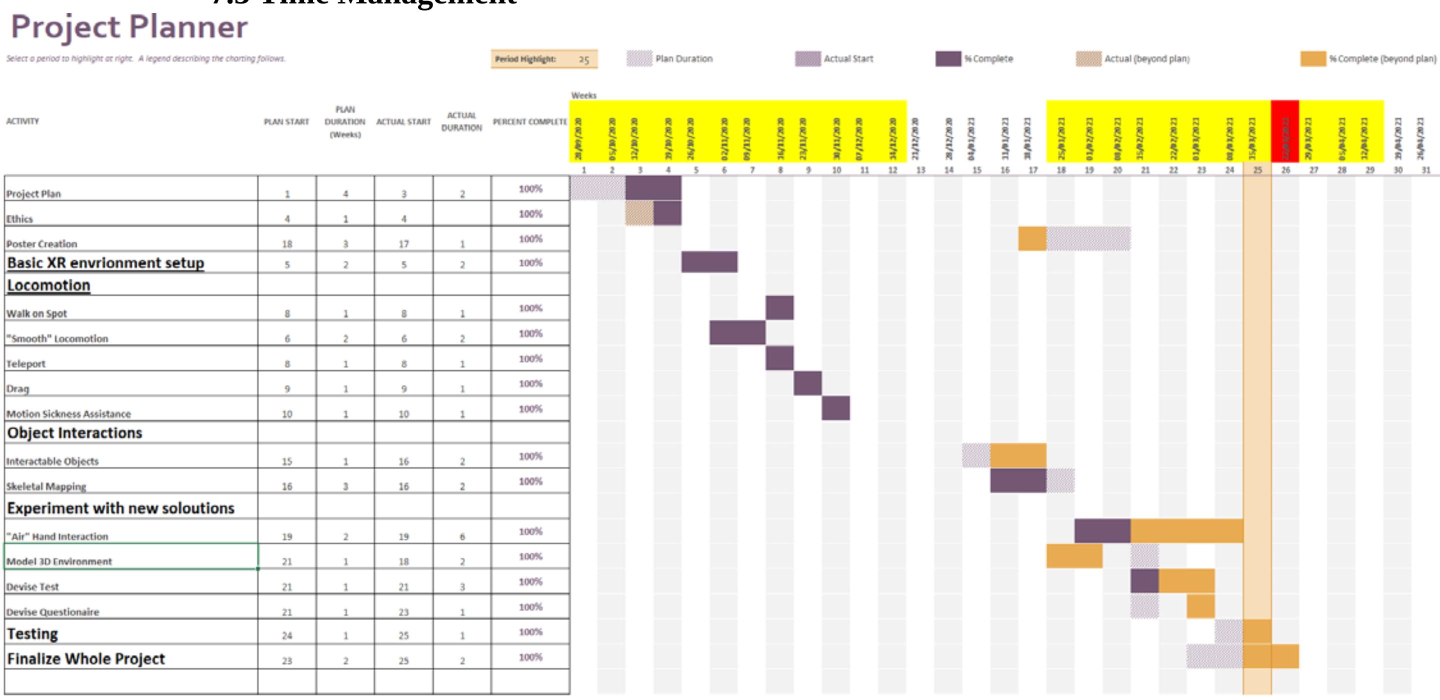



**FIGURE 7.3.1 Project Gannt Chart**

As can be seen by **FIGURE 7.3.1** I more or less kept to my project timeline, however I grossly underestimated how long and difficult the "air" hand interaction would be but thanks to keeping to AGILE development I was able to get it to an acceptable state for testing.

## 7.4 What future work could be done?

### 7.4.1 Hand Tracking

One of the very apparent issues with the programme was how correctly it was able to detect the user's hands. The reason for the issues was more than likely down to occlusion either from the users own hands covering each other or the more likely scenario of when interacting with objects occluding the cameras.

The way this could be improved is through research with neural networks for hand tracking occlusion. Work done by Facebook Reality Labs researchers (Smith, et al., n.d.) has already begun work in this area. However, it does not run in real time yet, so more work needs to be done in either optimisation or in improving the processing hardware.

### 7.4.2 Spatial Tracking

As mentioned in this report we ran into issues with deviation in the IVE and physical model the further away from the centre the user travelled if it was not synched correctly. Even when synched near perfectly we still had issues with deviation.

Using the cameras on the front of the headset we could use them to identify key area points such as a QR code that then resynchs IVE transform to rematch the physical environment based on the player's position. This could be achieved using image recognition neural networks to find the angle, distance, and position of the player relative to the QR code to then resynch the environment.

The neural networks involved in making inside-out tracking possible work from a similar concept so I believe with some work it could be reapplied to this area.

### 7.4.3 BCI's

Brain Computer Interfacing is the future when it comes to the way we interact with digital data. There is a wide variety of applications with BCI's that could be used to add an additional level of control to the user.

In the case of this project the BCI could be used to manipulate virtual objects such as allowing "telekinetic" type abilities to the user. We could even use this BCI to measure the users cognition levels to attempt to get some idea of how "immersed" a user is in the IVE.

On a more science fiction scale we could even simulate touch sensations or perhaps even interpret all users motor neurone signals combined with a HMD to allow the user to really feel like they are walking in an environment when in reality they are sat still.

Some of the industry leaders in this area are "Neurallink" and more in relation to this project "Valve Software" who are working with OpenBCI. An interview with Gabe Newell from Valve Software quoted "We're way closer to the matrix than people realize" – (Newel, 2020).

### 7.5 Future of the project

Given the results concluded from this project and the current industry trend, I have the full intention of continuing this work in future and perhaps even performing a larger scale test on the project when COIVD-19 restrictions allow me to do so.

There has never been a more exciting time to be involved in XR devices as the work currently happening will potentially redefine how we interact with computers and enjoy entertainment in the years to come.

If you like to access the project's source code it is available bellow:

Locomotion Test: https://github.com/TGrovesy/VR-Disseration

Hybrid Environment: https://github.com/TGrovesy/Hybrid-Environment-Test

# Bibliography


Alsop, T., 2021. *Virtual Reality (VR) - statistics & facts.* [Online]
Available at: https://www.statista.com/topics/2532/virtual-reality-vr/

Al, W. e., 2007. In: *Media Psychology.* s.l.:s.n., pp. 493-525.

Anon., n.d. *Research Gate.* [Online]
Available at: https://www.researchgate.net/

Cherni, H., Metayer, N. & Nicolas, S., 2020. *Literature review of locomotion techniques in virtual reality.* [Online]
Available at: https://ijvr.eu/article/view/3183
[Accessed 30 October 2020].

Davis, K., 2019. *Developing for VR.* s.l.:s.n.

Facebook Reality Labs, 2020. *Elixir.* s.l.:s.n.

Johns, C. L. et al., 2000. *The interaction between individuals' immersive tendencies and the sensation of presence in a virtual environment.* Vienna, Austria, s.n.

Kennedy, R. S., Lane, N. E., Berbaum, K. S. & Kilienthal, M. G., 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology,* Issue 3, pp. 203-220.

Kreylos, O., 2016. *Lighhouse Tracking Examined.* [Online]
Available at: http://doc-ok.org/?p=1478

List, J., n.d. *How did the nintendo virtual boy work.* [Online]
Available at: https://hackaday.com/2021/02/20/how-did-the-nintendo-virtual-boy-work/

Madison, G., 2020. *Oculus Quest - Gameified Real Estate.* s.l.:s.n.

Newel, G., 2020. *Valve's CEO opens up about Half-Life: Alyx, Valve, and the future of entertainment as a whole* [Interview] (18 March 2020).

Nystad, E. & Sebok, A., 2004. *A comparison of two presence measures based on experimental results.* s.l., s.n., pp. 266-273.

P, D., 2020. *How much should I ask for on Kickstarter.* [Online]
Available at: https://fundraise.net/how-much-to-ask-for-kickstarter-goals/#:~:text=That%20said%2C%20a%20usual%20Kickstarter,how%20to%20market%20their%20Kickstarter.

Riva, G., Davide, F. & IJsseltsteijn, W. A., 2003. *Being There: Concepts, effects and measurements of user presence in synthetic envrionments.* Amsterdam, s.n.

Smith, B. et al., n.d. *Constraining Dense Hand Surface Tracking with Elasticity,* s.l.: s.n.

Valem, 2020. *I turned my house into a VR game.* s.l.:s.n.

Valve Software, 2021. *Steam Hardware & Software Survey.* [Online]
Available at: https://store.steampowered.com/hwsurvey/Steam-Hardware-Software-Survey-Welcome-to-Steam
[Accessed 1 February 2021].

Void, T., n.d. [Online]
Available at: https://thevoid.com/

Werner, W., 2007. *A process model of the formation of spatial prescense experiences,* pp. 493-525.

Werner, W. et al., 2015. The Spatial Presence Experience Scale. *Media Psychology Theories Methods and Applications.*

Witmer, B. G. & Singer, M. J., 1998. Presence: Teleoperators and Virtual Environments. In: *Measiong Presence in virtual envrionments: A presence questionnaire.* s.l.:s.n., pp. 225-240.

Witmet, B. G., Jerome, C. J. & Singer, M. J., 2005. The factor structure of the presence questionnaire. *Presence: Teleopertors and Virtual Environments,,* Issue 14, pp. 298-312.

Youngblut, C. & Perrin, B. M., 2002. *Investigating the relationship between presence and perfromance in virtual environments,* s.l.: s.n.

**APPENDIX A:**

# UG Project Plan

# CSC-30014

## Project Overview and Description

**Student Name:** Thomas Groves

**Student Username:** w8t09

**Student Number:** 17006680

**Degree Title:** Bsc Computer Science (With year abroad)

**Supervisor Name:** Adam Stanton

**Project Title:** Mapping physical environments to create a hybrid environment approach to virtual reality experiences

**Please provide a brief Project Description:**

| |
|---|
| To review previous and current techniques in creating an immersive virtual reality experience. Using the knowledge gained from the previous attempts at solving key issues within virtual reality, we can then attempt to provide a partial solution to the problem with hybrid environments. To test this we will devise a task for users to undertake twice. Once in a purely virtual environment, and then again in the hybrid environment. At the end of each run we will use a questionnaire to get a measure of the users immersion level. |

**What are the aims and objectives of the Project?**

**Aim:** To identify the appropriate hardware for the project

**Objectives:**

- Select XR devices to research
- Review the features and capabilities of each device
- Select devices to carry out development

**Aim:** To review and compare existing techniques for interaction and locomotion

**Objectives:**

- Research Traversal Problems
- Research Interaction Problems
- Review Current Locomotion Techniques
- Review VR Interaction Guidelines
- Gather Data on Users Preferred Locomotion Technique

**Aim:** To Create a physically mapped immersive virtual environment

**Objectives:**

- Create a 1:1 scale model of a room
- Implement interaction methods
- Implement traversal methods
- Devise a task
- Collect Data from users
- Review data against hypothesis

**Aim:** To propose what future work needs to be done to help improve the hybrid approach

**Please provide a brief overview of the key literature related to the Project:**

List of research:
Valve doors: https://www.youtube.com/watch?v=9kzu2Y33yKM
This seminar talks about the issues developing for virtual reality and the solutions to creating
Immersive experiences

Review of locomotion techniques: https://ijvr.eu/article/view/3183
This covers the different types of existing solutions to locomotion and there effectiveness

Valve Performance Centric Rendering Techniques:
http://media.steampowered.com/apps/valve/2016/Alex_Vlachos_Advanced_VR_Rendering_Performance_GDC2016.pdf
This is a review of the current rendering techniques to produce high enough performance in
A VR environment

Tracking a stylus oculus: https://scontent-lhr8-1.xx.fbcdn.net/v/t39.2365-6/10000000_133279490640739_7053679997730422784_n.pdf?_nc_cat=107&ccb=2&_nc_sid=ad8a9d&_nc_ohc=b6sH8aGtsTMAX94FLDf&_nc_ht=scontent-lhr8-1.xx&oh=8cbcb45ac1b8a9ae2b2d774f849536e0&oe=5FB8818B
This covers having extra 6DOF tracked objects other than just the current standard motion controllers

Social VR experiences oculus: https://scontent-lht6-1.xx.fbcdn.net/v/t39.2365-6/27699338_216733292218561_8182170323903315968_n.pdf?_nc_cat=105&ccb=2&_nc_sid=ad8a9d&_nc_ohc=s_REsZx9oSkAX9pQmwB&_nc_ht=scontent-lht6-1.xx&oh=9e37cb13ab86c451b24ee5087ce99c23&oe=5FB7F93B
This talks about how social interaction in VR add to a users enjoyment and/or immersion

Future Predictions Oculus Connect Keynote:
https://www.youtube.com/watch?v=AtyE5qOB4gw
This covers what is predicted in future from the industry.

Interesting papers: https://ieeevr.org/2020/program/papers.html
This is a collection of papers related to VR so I will check this regularly to look for new material to read

## Project Process and Method

**Please provide a brief overview of the Methodology to be used in the Project (inc. an overview of best practice within the Methodology):**

1) Identify and plan an achievable investigation into the history of virtual reality and then research the current happenings in the industry
2) Read relevant background literature into current problems in the industry and justify the need for more research into solving the issues. Also make key notes on each literature to easily refer to
3) Perform a report on the current solutions to these problems and justify the best methods currently out there by creating demo environments demonstrating the strengths and weaknesses of each solution. Each demo needs to plan out its aim and follow the development lifecycle.
4) Using the research gained from current solutions experiment by creating new solutions to the current posed problems and gain feedback by using each solution in the same demo environments and create new environments to demonstrate the advantages.
5) Using the approaches developed in #4 then compile them together to create a final hybrid environment
6) Compile a report of what to expect next from the industry
7) Demonstrate what needs to happen before better solutions can be created for wider adoption of the tech

**Which Data Collection Methods will be employed (e.g  card sorts, questionnaires, simulations, …)?**

Throughout the project I will run simulations using my test subjects. These simulations will be on different ways to solve key issues in VR. At the end of each test the subject will be asked to fill out a questionnaire related to the test to rate their experience; Each of these end questionnaires will be tailored to the demo done so that we can try and gauge their "immersion". The internal VR view of the player will also be recorded so we can analyse how they interacted with the environment. As well as some standard data collection in game such as a heat map of how long they spent in each area of the environment and perhaps the amount of times interacted with an object. The data collected from each test will change depending on the investigation for each technique.

**Briefly describe how you will ensure your project is in line with BCS Project Guidelines (BSc Computer Science Single Honours Students only)?**

In order to ensure that my project is indeed valid for a BCS accredited degree bellow I have listed why this is in fact a computer science project.

- I will be creating software using an engine such as unity and having to write lots of code to create a final product to run on various virtual reality platforms. This code will perform various functions as needed such a application mechanics, user interaction and analytic gathering.
- The project has been planned out using a Gannt chart which clearly shows the flow of work that leads up to my big final program. I will plan out each development stage and ensure that it is well documented in my final report
- At the end of each stage I need to test the program and gain feedback from the users. This will mainly be black box testing and getting feedback from the users at each stage to help identify what about the experience they did/didn't like and whether they noticed any unexpected outcomes whilst using the program and hardware

## Time and Resource Planning

**Will Standard Departmental Hardware be used?** YES/NO

**If NO please outline the Hardware/Materials to be used:**

Standard department hardware will be used however I will be using my own equipment. All equipment I will be using the school already has access to.

**Will Software which is already available in department be used?** YES/NO

**If NO please outline the Software to be used including how any necessary licences will be obtained:**

**Will the project require any Programming?** YES/NO

**If YES please list the (potential) Programming Languages to be used (including any IDEs and Libraries you may make use of):**

Languages:

- C#
- C++
- Blueprint

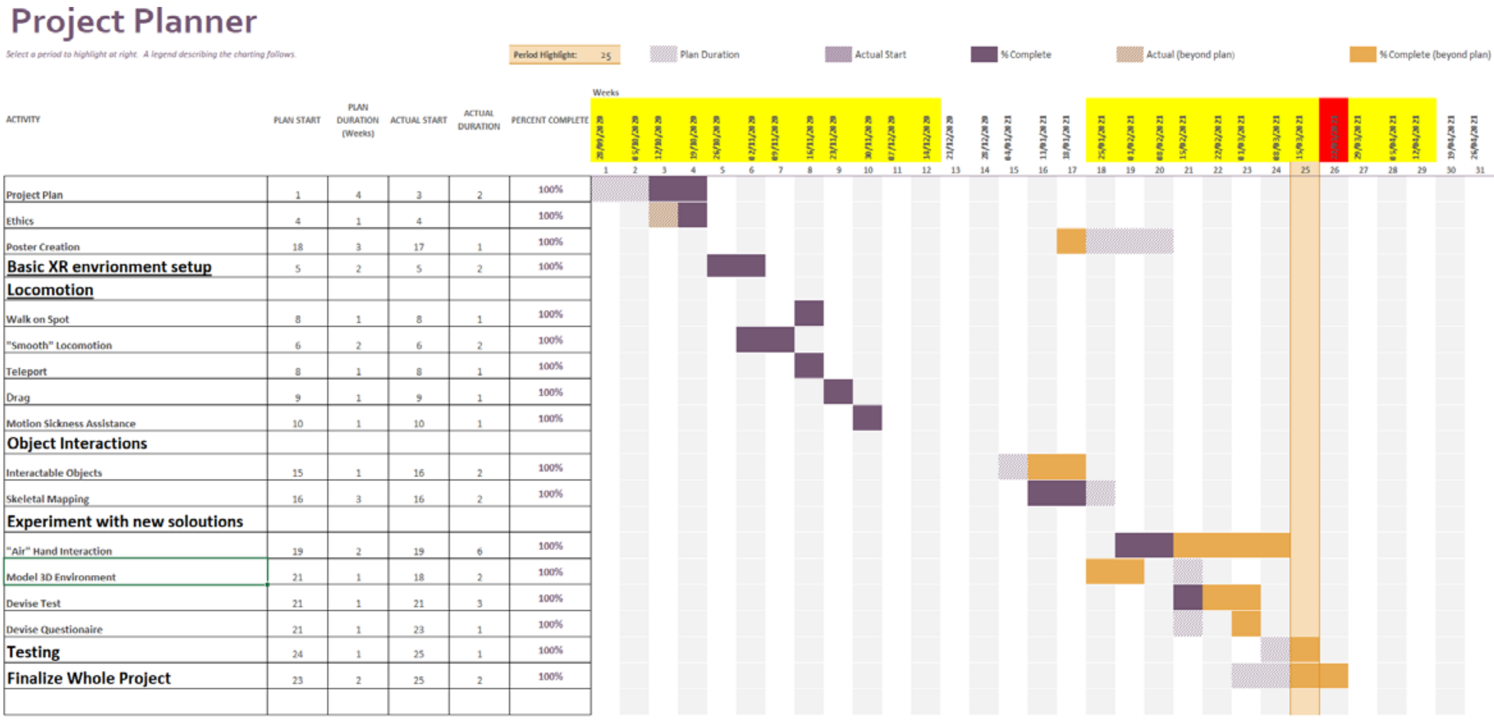
IDE:

- Visual Studio 2019

**Table of Risks (*if non Standard Hardware and/or Software to be used please include backup options/ contingency plans here*):**

| Risk | Level Of Risk | Precautions Taken | Remedial Action |
|---|---|---|---|
| Data Loss | Low | Regular backups made onto external drive. The main project base is uploaded to GitHub regular | Download the backup |
| Headset Hardware failure | Low | Ensuring hardware is correctly stored and when in use that only authorised people use it. | Develop on one less headset for time being and try obtain a replacement to continue. |
| Trip Hazards | Medium | Ensuring that the area is clear before they use the equipment and supervising whilst in use to ensure they don't get tangled in the cables | Assess the injury sustained and take medical action if necessary. In extreme cases seek a medical professional. |
| Colliding with real world walls | High | Ensure that all guardian systems are working before using headset and also supervising the participants when using the equipment | Assess the injury sustained and take medical action if necessary. In extreme cases seek a medical professional. Also Assess the state of the equipment |
| Safeguarding | Low | To ensure that all study participants feel safe whilst using the headset they may choose another party member to also attend and watch them whilst they are essentially blindfolded | |
| Claustrophobia | Low | If a user feels uncomfortable or claustrophobic from any of the experiences, they may take the headset off at any time | Give the participant space and water. Let their party member comfort them |
| Motion Sickness | Very High | If a user experiences discomfort due to the headset they may take it off at any time in the study and water will be on hand to help settle their stomach | Maybe give them a teaspoon of soda bicarbonate in water. |

**Gantt Chart/ Pert Chart (must include milestones and deliverables):**




| ACTIVITY | PLAN START | PLAN DURATION (Weeks) | ACTUAL START | ACTUAL DURATION | PERCENT COMPLETE |
|---|---|---|---|---|---|
| Project Plan | 1 | 4 | 3 | 2 | 100% |
| Ethics | 4 | 1 | 4 | | 100% |
| Poster Creation | 18 | 3 | 17 | 1 | 100% |
| **Basic XR envrionment setup** | 5 | 2 | 5 | 2 | 100% |
| **Locomotion** | | | | | |
| Walk on Spot | 8 | 1 | 8 | 1 | 100% |
| "Smooth" Locomotion | 6 | 2 | 6 | 2 | 100% |
| Teleport | 8 | 1 | 8 | 1 | 100% |
| Drag | 9 | 1 | 9 | 1 | 100% |
| Motion Sickness Assistance | 10 | 1 | 10 | 1 | 100% |
| **Object Interactions** | | | | | |
| Interactable Objects | 15 | 1 | 16 | 2 | 100% |
| Skeletal Mapping | 16 | 3 | 16 | 2 | 100% |
| **Experiment with new soloutions** | | | | | |
| "Air" Hand Interaction | 19 | 2 | 19 | 6 | 100% |
| Model 3D Envlronment | 21 | 1 | 18 | 2 | 100% |
| Devise Test | 21 | 1 | 21 | 3 | 100% |
| Devise Questionaire | 21 | 1 | 23 | 1 | 100% |
| **Testing** | 24 | 1 | 25 | 1 | 100% |
| **Finalize Whole Project** | 23 | 2 | 25 | 2 | 100% |

## References and Administration

**Please include a list of References used in this Plan:**


Abrash, M. (2016). *Oculus Connect 3 Opening Keynote: Michael Abrash - YouTube*. [online] www.youtube.com. Available at: https://www.youtube.com/watch?v=AtyE5qOB4gw [Accessed 4 Nov. 2020].

Cherni, H., Métayer, N. and Souliman, N. (2020). Literature review of locomotion techniques in virtual reality. *International Journal of Virtual Reality*, 20(1), pp.1–20.

Davis, K. (2019). *HLVR Door Talk*. [online] www.youtube.com. Available at: https://www.youtube.com/watch?v=9kzu2Y33yKM [Accessed 4 Nov. 2020].

ieeevr.org. (n.d.). *Papers*. [online] Available at: https://ieeevr.org/2020/program/papers.html [Accessed 4 Nov. 2020].

Smith, H.J. and Neff, M. (2018). Communication Behavior in Embodied Virtual Reality. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*.

Wu, P.-C., Wang, R., Kin, K., Twigg, C., Han, S., Yang, M.-H. and Chien, S.-Y. (2017). DodecaPen: Accurate 6DoF Tracking of a Passive Stylus. *DodecaPen: Accurate 6DoF Tracking of a Passive Stylus*. [online] Available at: https://scontent-lhr8-1.xx.fbcdn.net/v/t39.2365-6/10000000_133279490640739_7053679997730422784_n.pdf?_nc_cat=107&ccb=2&_nc_sid=ad8a9d&_nc_ohc=b6sH8aGtsTMAX94FLDf&_nc_ht=scontent-lhr8-1.xx&oh=8cbcb45ac1b8a9ae2b2d774f849536e0&oe=5FB8818B [Accessed 4 Nov. 2020].

**Submission Date: 06/11/2020**

**PLEASE NOTE THAT SHOULD YOUR PROJECT UNDERGO ANY MAJOR CHANGES FOLLOWING THE SUBMISSION OF THIS PLAN YOU ARE EXPECTED TO SUBMIT AN UPDATED PLAN WHICH ACCURATLEY REFLECTS YOUR PROJECT.**

# Computer Science Final-Year Project
# Ethics Application Form 2020-21

## Applicant details

| | |
|---|---|
| **Project title** | Mapping physical environments to create a hybrid environment approach to virtual reality experiences |
| **Name of final-year project student** | Thomas Groves |
| **Keele e-mail address of student** | w8t09@student.keele.ac.uk |
| **Name of project supervisor** | Adam Stanton |

## Project Summary

Provide a short summary of your project **(max 250 words).**

The aim of the project is to determine the current best solutions for "problems" with VR development and then continue that into experimenting with non-widely adopted solutions and experiment with these newer solutions. Also getting feedback on details that do and don't add to a player's immersion. Then using the knowledge gained from the experimentation create an example demo to demonstrate what creates an "immersive VR" experience.

The work will involve:

1. asking people their opinions on the current solutions to problems in VR and their preferences of these solutions based on different scenarios.
2. creating an immersive VR experience using the newly researched methods and around people's preferences
3. testing the "immersive quality" of the final experience and comparing it to how people found the previous solutions.

In simple terms, provide a *short* description of your planned experimental method that involves participants (e.g., focus groups, questionnaires, interviews, experimental observations).

**Intended sessions:**

- Testing the current solutions in VR
- Testing what details do and don't add to a player's immersion in VR
- Testing the newly researched solutions in VR
- Testing the final made experience demo and asking them to rate their experience

Each one of the tests above will ideally be conducted in 1 session for each point (this will depend on the participant). From each of these sessions I may do the following collection methods:

- Questionnaire
- Interview
- Video & Audio recording of the session
- Heatmap of the participants location in the virtual world
- General analytics for interaction with objects in game

Describe the characteristics of your participants, and any inclusion or exclusion criteria. Estimate the approximate number of participants.

All participants will be students or staff of the Keele University.

Approximately,10-18 participants will be recruited as

- participants for each test stage described above (participants need to do every session)

## Recruitment and Consent

Indicate how potential participants will be identified, approached and recruited and outline any relationship between the researcher and potential participants.

Participants are likely to be friends and family.

Students and staff will be invited in person or via email with the following invitation:
Dear Sir/Madam

I would like to invite you to a study involving the use of virtual reality equipment. The study will involve about one hour of your time wearing a Virtual Reality Headset for 3 short sessions and answering a short questionnaire after each session.

Some of the data recorded may/will include:
-Audio of the test
-Written Quotes from your feedback
-Video of the test

The data is all completely anomalous. If this research opportunity interests, you please reply directly to this invitation.

Kind Regards,
Thomas Groves

Describe the process that will be used to seek and obtain informed consent.

If individuals express an interest in participating, they will be provided with an Information Sheet (printed or electronic). If they are happy to proceed, they will be asked to sign the Consent Form before participating.

Will consent be sought to use the data for other research? Yes ☐ No ☒

Will consent be sought to contact the individual to participate in future research? Yes ☐ No ☒

Can participants withdraw from the research? Yes ☒ No ☐

**If yes**, state up to what point participants are able to withdraw from the research

Participants can withdraw their data up to one week after participating.

**If yes**, outline how participants will be informed of their right to withdraw, how they can do this and what will happen to their data if they withdraw.

Contact information for withdrawal is provided on the Participant Information Sheet.

**If no**, explain why they cannot withdraw (e.g., anonymous survey).

## Confidentiality and anonymity

Outline the procedures that will be used to protect, as far as possible, the anonymity of participants and/or confidentiality of data during the conduct of the research and in the release of its findings.

All participant names will be replaced by codes, for example, User 1, User 2, User 3, etc. No names (or other information that might reveal participant identity) will be included in the project dissertation or in any other presentation.

## Storage, access to, management of, and disposal of data

Describe how participant data will be stored; where it will be stored and for how long; and how/when it will be disposed of.

All participant data will be securely stored until the end of the project. All electronic records will be stored on university drives. Only the applicant (student investigator) and supervisor will have access to participant data. At the end of the project the participant data will be deleted.

## Other ethical issues raised by the research

Are there any other ethical issues that may be raised by the research? Yes ☐ No ☒

If yes, please give details.

## Declarations

**Declaration by student**

I confirm that:

- The form is accurate to the best of my knowledge.
- I will inform my supervisor and resubmit an ethical application if there are any changes to the project.
- I am aware of my responsibility to comply with the requirements of the law and any relevant professional guidelines.

Student name Thomas Groves

Student signature

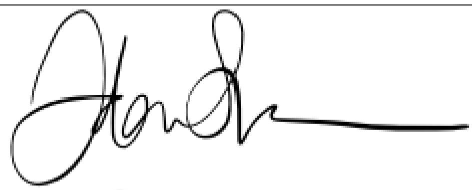
Date 02/11/2020

**Declaration by supervisor**

I confirm that:

- I have read the **application** and am happy for it to proceed for ethical review.
- The application is accurate to the best of my knowledge.
- I am aware of my responsibility to ensure that the applicant is familiar with and complies with the requirements of the law and any relevant professional guidelines.

Supervisor name Adam Stanton



Supervisor signature

Date 02/11/2020

# CONSENT FORM

# (for use of quotes)

## Title of Project:

**Name and contact details of student investigator and supervisor:**

Thomas Groves w8t09@students.keele.ac.uk & Dr Adam Stanton, a.stanton@keele.ac.uk

Please initial box if you agree with the statement

1. I agree for my quotes to be used

☐

2. I do not agree for my quotes to be used

☐

# Participant Information Sheet

**Study Title: Mapping Physical Environments to Create a Hybrid Environment Approach for Virtual Reality Experiences**

**Aims of the Study**

**To see if there is a positive correlation between mapping a virtual environment onto a physical environment and a user's level of immersion**

**Invitation**

You are being invited to consider taking part in the study: "**Mapping Physical Environments to Create a Hybrid Environment Approach for Virtual Reality Experiences**". This project is being undertaken by Thomas Groves (w8t09@students.keele.ac.uk) under supervision of Dr Adam Stanton (a.stanton@keele.ac.uk)

Before you decide whether you wish to take part, it is important for you to understand why this study is being done and what it will involve. Please take time to read this information carefully to make sure you understand the study and what you are being asked to do. If you have questions or concerns about taking part in the study, please feel free to email Thomas Groves or the supervisor of this project Dr Adam Stanton

**Why have I been invited?**

All people who have various levels of computer skills and knowledge are welcome to take part

**Do I have to take part?**

You are free to decide whether you wish to take part or not. If you do decide to participate you will be free to stop participating at any time and you can remove your data, any time after participating without giving reasons.

**What will happen if I take part?**

You will attend 1 session to perform 3 experiences in VR. At the end of each ~15-minute session you will answer a short questionnaire and have a short discussion about what just took place.

**What are the benefits (if any) of taking part?**

no benefits have been identified for this participation

**What are the risks (if any) of taking part?**

No risks have been identified for this participation.

**How will information about me be used?**

**Who will have access to information about me?**

Your data will be stored securely until the end of the project. All electronic records will be stored on my personal hard drive. Only I (student) and supervisor will have access to your data.

At the end of the project your data will be deleted.

**What if there is a problem?**

If you have a concern about any aspect of this study, please speak to myself or my supervisor. We will do our best to answer your questions. Our contact details are:

Thomas Groves, w8t09@students.keele.ac.uk & Dr Adam Stanton, a.stanton@keele.ac.uk

**Contact for further information and withdrawal**

If you would like to withdraw your data from the study, please contact:

Thomas Groves, w9t09@students.keele.ac.uk

# CONSENT FORM

**Title of Project: Mapping Physical Environments to Create a Hybrid Environment Approach for Virtual Reality Experiences**

**Name and contact details of student investigator and supervisor:**

Thomas Groves, w8t09@student.keele.ac.uk & Dr Adam Stanton, a.stanton@keele.ac.uk

Please tick box if you agree with the statement

1. ☐ I confirm that I have read and understood the Participant Information Sheet and have had the opportunity to ask questions.

2. ☐ I understand that my participation is voluntary and that I can stop participating at any time and can withdraw my data up to one week after participation without giving a reason.

3. ☐ I agree to take part in this study.

4. ☐ I understand that data collected about me during this study will be anonymised before it is reported in any reported results.

5. ☐ I give permission for my voice to be recorded

| ______________________ | ______________________ | ______________________ |
|---|---|---|
| Name of participant | Date | Signature |

| Student investigator | Date | Signature |
|---|---|---|

**CONSENT FORM**

**(for use of quotes)**

**Title of Project: Mapping Physical Environments to Create a Hybrid Environment Approach for Virtual Reality Experiences**

**Name and contact details of student investigator and supervisor:**

Thomas Groves w8t09@students.keele.ac.uk & Dr Adam Stanton, a.stanton@keele.ac.uk

Please initial box if you agree with the statement

☐

1. I agree for my quotes to be used

☐

2. I do not agree for my quotes to be used

Signed: ______________

Date: ________________

## Appendix B:

### History and Background of VR (Formally Section 2.2)

The VR industry has come and gone over the past few decades. Every time it has returned it's dubbed as the next big thing however as we have seen it quickly fizzles out.

I think one of the key examples of VR coming to market and fizzling out would be Nintendo's "Virtual Boy" in the mid 1990's as it was dubbed by many as a consumer flop. According to reports about the device it was "Sickness and headache inducing" (List, n.d.) which was probably down to the graphical rendering capability at the time. Now that's not to say it wasn't ahead of its time with the stereoscopic, although monochromatic red, images for each eye. However, that is all it had going for it and as you can imagine although fun for perhaps the first five minutes it was nothing more than a gimmick that soon became unused. It was missing many features which in today's age we consider to be essential to the success of VR. But what are these features and why do we dub them as necessary?


**FIGURE 1.2.1 Nintendo Virtual Boy**

Fast forward to 2012 and a man by them name of Palmer Lucky co-founded oculus and started a Kickstarter campaign for their first headset the "Oculus Rift". The campaign was a hit from the very start as it had an ambitious goal of $250,000 which is already much higher than the stated average raised of "$10,000-$23,000" (P, 2020). They successfully managed to raise a whopping ~10 times that amount coming in at $2,473,429. To say the interest in the industry was there would be an understatement with big names like Gabe Newel (President and owner, Valve), John Carmack (id Software), David Helgason (CEO, Unity) and Cliff Bleszinski (Design Director, Epic Games) just to name a few. With these big names in the industry backing the project the confidence in the platform really grew. This headset brought in low latency rotational 3DOF, higher resolutions (640*800 per eye), Higher FOV's of 90$^{o}$ and a 60 Hz refresh rate. This was game changing of showing the capabilities of the platform (**More on why this is important later**), However it was still missing key features of what we determine as imperative to a good experience.

**FIGURE 1.2.2 Oculus DK1**

The next **publicly** available iteration of oculus' headset the rift DK2 quickly followed in mid-2014 bringing a few smaller improvements such as using a modified Samsung galaxy display to improve the resolution to 960*1080 per eye with a 75hz refresh rate. The most notable and important change was the addition of positional tracking, albeit rudimentary this is the first consumer grade example of a 6DOF headset device. Again, though there is still a piece of the puzzle missing that's included in modern devices.


**FIGURE 1.2.3 Oculus DK2**

Introducing the HTC Vive! This was the first direct competitor to the devices offered by oculus and came out around the same time as the rift CV1 (consumer version 1) in early 2016. This boasted a lot that we came to love with the rift such as high resolutions than previously seen, a high refresh rate of 90Hz and improved 6DOF tracking thanks to the base station tracking system they employed. The headset was created in partnership with Valve as they were the ones who had done the R&D on the base station/lighthouse tracking technology. The game changing addition with this headset was the included 6DOF motion controls dubbed the Vive wands. The addition of these controllers allows for richer interactions within virtual environments to attempt to replicate our hands. The release of the HTC Vive and Oculus rift CV1 with their touch controllers are what I consider to be the beginning of the take-off for consumer VR.


**FIGURE 1.2.4 HTC Vive and Vive wands**

## Current Hardware Problems and limitations (Formally Chapter 2)

### 2.1 What are the three most used/notable headsets

So, what current hardware is available to the mass consumer market? For this information I shall be looking at information provided via Steam (Valve Software, 2021) as it has accurate statistics on current hardware for users on the steam platform thanks to their hardware survey. According to figures from February 2021 the top 3 most used headsets on the platform are the Oculus Quest 2, Oculus rift S and the Valve index. Due to two headsets from oculus taking the top three I shall also be including 4$^{th}$ place which is the HTC Vive. The reason for taking this extra headset is explained in **2.2**.

### 2.2 Oculus

As can be seen from the hardware survey, Oculus takes the top 2 spots. With the Quest 2 and rift S taking 22.91% and 21.58% of the market share respectively. This means oculus currently holds 44.49% of the share on steam. This is especially interesting to see the Quest 2 taking the top spot as the headset has only been available since October 2020 less than 6 months but yet has the top spot on Steam. Even more interesting is the fact the Quest 2 is a standalone headset meaning that this figure doesn't even consider the users who aren't using a PC with steam.

Oculus have slowly been removing support for the Rift S by even going as far as to not allow newer games to support it. There is also nothing the Rift S can do that the Quest 2 can't. For this reason, I am going to only be examining the Quest 2 as it is essentially the next iteration of the rift. The only exception to that statement being the Quest 2 is linked via USB C to a PC which causes some bandwidth problems with compression, however oculus does a fantastic job with their software making the compression basically unnoticeable.

| **Headset** | Quest 2 |
|---|---|
| **Resolution** | 1832 x 1920 Per Eye |
| **Refresh Rate** | **Launch:** 72Hz, **now:** 90Hz, **coming:** 120Hz |
| **FOV** | |
| **Wireless** | Yes |
| **Weight** | 503g |
| **Tracking** | Inside-Out |

As can be seen from the above specs it's a very impressive piece of equipment especially considering the 64GB storage variant comes in at a low cost of £299 which is a lot cheaper than its competitors. As a result, this headset has been snapped up by the mass market.

The only area this headset compromises is through the use of inside-out tracking. Using the 4 cameras on the headset it uses a spatial tracking algorithm to figure out where in space a user is. Through many iterations the performance of Oculus' algorithm has become phenomenal to the point where jitter of the players head transforms almost completely eliminated. The reason Oculus opted for this “compromise” is due to the ease of setup verses the base station technique meaning that the headset can quite literally be used anywhere without the need to setup external equipment from the HMD.

The headset also has an app available that takes advantage of its WiFi6 support to allow for low latency wireless PCVR. The headset takes care of tracking whilst the PC takes runs the software.

### 2.3 HTC Vive

The HTC Vive as of February 2021 takes up 13.05% of the share of the Steam platform. This is impressive as this is what people consider to be one of the first of generation one hardware. Released in April 2016 this headset truly demonstrated what room scale VR was a capable of with early demos of motion controllers in games like “The Lab” from valve.

This use of positional data is possible due to base station tracking which was developed by valve. The idea is you have at least 2 “base stations” in opposite corners of the room. The base stations then communicate with each other and the head mounted display (**HMD**) via Bluetooth using positional data gathered by transmitting lasers that are on a spinning motor refreshing at 60Hz in the base stations and are received by the headset. This allowed for super accurate within ~1mm positional data to be gathered by the headset and its “wands” (motion controllers).

Post launch third party addons allowed for wireless use of the headset with a PC using Intel Wi-Gig technology. Although impressive it wasn’t adopted by the mass market. Likely due to its price and “bulkiness”.

| **Headset** | HTC Vive |
|---|---|
| **Resolution** | 1080 x 1200 Per Eye |
| **Refresh Rate** | 90Hz |
| **FOV** | 110 |
| **Wireless** | Supported with Addon |
| **Weight** | 555g |
| **Tracking** | Base Station |

### 2.4 Valve Index

The Valve Index holds a 16% share of the current steam VR userbase. This headset comes with impressive specs but at a premium price of £919. It was released in June 2019.

The headset boasts a rather unique feature of an expansion slot for an addon at the front of the headset along with 2 cameras which currently serve no use other than a passthrough function. Useful features in the consumer market are yet to be seen from these capabilities.

The really unique selling point of this headset though was the index controllers. **Section 2.6** goes into more detail on this however the controllers were very popular with people who already owned a base station supported devise, such as the HTC Vive, as they can be used out of the box with any base station headset.

| Headset | Valve Index |
|---|---|
| **Resolution** | 1440 x 1600 Per Eye |
| **Refresh Rate** | 144Hz |
| **FOV** | 130 |
| **Wireless** | No |
| **Weight** | 555g |
| **Tracking** | Base Station |

**2.5 Tracking**

Tracking methods have iterated over the years. Some early 3DOF hardware only used gyroscopes and accelerometers for tracking. Later down the line with headsets like the Oculus DK2 also used IR LED's for positional tracking. However, today the main two tracking techniques employed by manufacturers currently are Base Station/Lighthouse and Inside-Out/Insight.

The need of those names are merely the names given by manufactures. For the sake of argument in this report. I shall be dubbing tracking done via cameras on a HMD Inside-Out. External tracking done via base-station shall remain being referred to as normal.

Starting with base-station tracking. This technology was developed inhouse by valve to be used in the collaborative Vive headset produced by HTC. The technology works by using 1-4 base stations, ideally 2, in opposite corners of a space. Inside each base station is a laser that sits on a vertical Axis spinning motor. The laser "sweeps" the play space horizontally. Another laser sits on a motor that spins on a horizontal axis to "sweep" the room vertically. The lasers rotate at 60Hz. This means any trackable object that is within sight of a laser is able to send positional data. It allows for 360-degree tracking meaning that as long as its within sight of a laser it's tracked. By having 2+ base stations it solves the occlusion problem of a user's body if a controller was to go behind there back. According to a study done by Oliver Kreylos determined the jitter of the headset to be "residual noise with two base stations is isotropic, and has a range of about 0.3mm" - (Kreylos, 2016) which is pretty much negligible to users when donning the headset.

The inside-out tracking method is employed by various headsets and uses cameras located on the HMD to map the environment the user is in. Using this mapping the headset can detect where in 3D space it currently is. In the early days the jitter of the headsets was quite significant which discouraged a lot of users taking the jump, however after many iterations most headset manufactures have gone to sub-MM levels of jitter so just like with the base station method it is indistinguishable to the user. The main drawback of inside out tracking has to be the lack of cameras on the back of the headset meaning if you were to move your motion controllers outside of a cameras viable field the controllers positional tracking would stop working.

**2.6 Controllers**

The first consumer available motion controllers existed were the Vive wands as seen in **FIGURE 1.2.4** and as you can see were not very ergonomic, but they demonstrated the capabilities of this medium for interaction. The touch controllers by Oculus soon followed and remain virtually unchanged to this day as they are very ergonomic and there's a lot of capacitive touch and also the addition of the grip being analogue instead of digital, like the Vive wands, allowing for richer visualisation of the users hands.

**FIGURE 2.6.1 Oculus Quest 2 Touch Controllers**

Now I could write a lot about the different types of controllers and their various iterations, however the last notable set of controllers used in this project come from Valve software dubbed "The index controllers (Formally: Knuckles)". This controller has capacitive touch everywhere, allows for individual finger tracking as well as a grip pressure sensor allowing the user to slowly "squeeze" things by gripping progressively harder. There is also a strap that wraps around the users knuckles allowing the user to release the controller, but it remains attached to their hand. All of these features combined can lead to richer, and more importantly, more natural interactions in IVE's under the correct conditions.

**FIGURE 2.6.2 Valve Index Controllers**

**2.7 Common Problems**

Given the hardware available, albeit impressive, it poses lots of problems that need addressing before the industry can reach an even bigger market.

Some issues include: Visual Clarity with resolution, lens, refresh rate etc..; Positional and rich Audio. The issues this study focuses on are the traversal locomotive problem for scaling larger environments; Interaction problems relating to the lack of force feedback.

## UX in Virtual Reality Environments (Formally Section 2.4)

The next paper I reviewed was "A Questionnaire to measure the user experience in immersive virtual environments". Like with the SPES this paper pulls data from previous work presented by the PQ and Simulator Sickness, among others. The approach they took was similar as the methodology of the paper starts by reviewing existing work. However, this paper differs to the SPES as they use a holistic UX in IVE model in order to best construct their work.

They use the definition of user experience (UX) as given by the norm ISO 9241-210 which is "The user's perceptions and responses resulting from the use of a system or a service". The paper references the term virtual environment as an **immersive virtual environment (IVE).** The model presented **FIGURE 3.4.1** is how the questionnaire is intended to be structured. Each existing questionnaire reviewed within this work aims to find questions relating to each of the 10 components listed within this model. Once reviewed, rather than asking 9 different questionnaires the product of this work aims to condense it down into a single questionnaire that is a mixed but synthetic approach for creation of the final questionnaire.

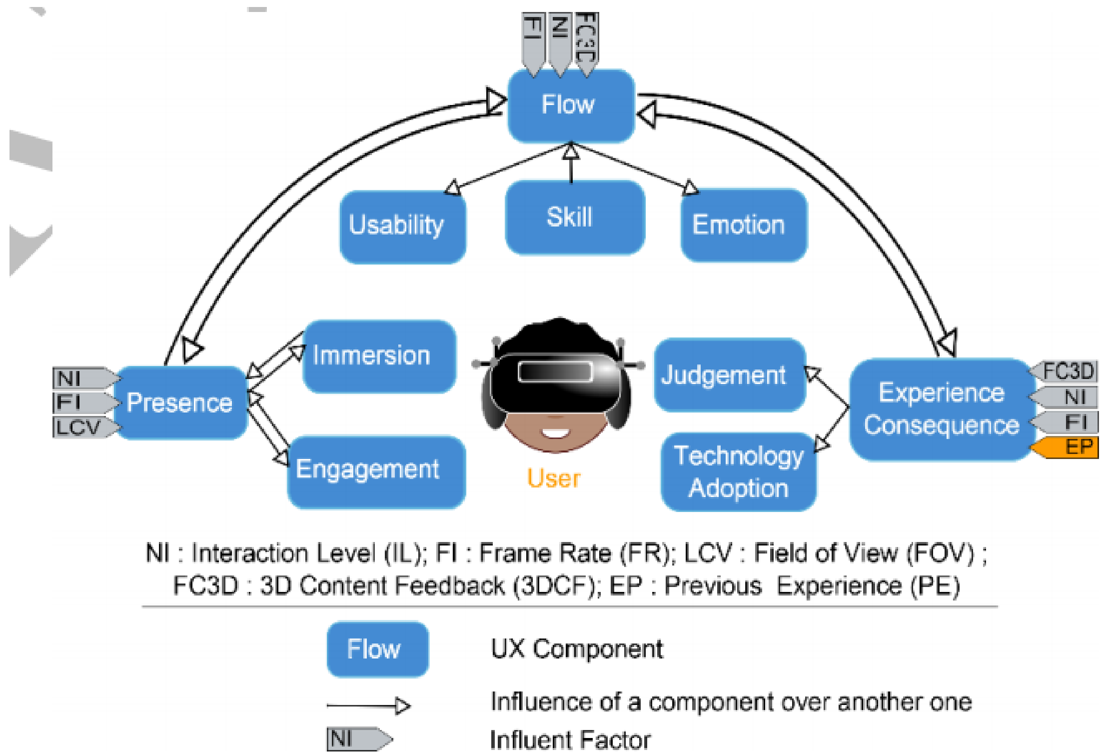



**FIGURE 3.4.1 Holistic UX in IVE model**

The selection criteria for the existing questionnaires is as follows: Accessibility; Frequent use of the questionnaire; existence of several translations (if unavailable the translation process must at least keep the real original meaning of the question). From the selected questionnaires they will then select items that best fit the goal of the mixed questionnaire

**<u>Experimentation with virtual hand representation when interacting with objects (Formally Section 4.5):</u>**

I decided to experiment with basic object interaction inside of the locomotion scene to help me visualise this problem and get feedback from my own testers. In order to create this, I decided to user the SteamVR SDK with the index controllers to allow for individual finger tracking. I implemented 3 interactable objects: A large Cube; Small ball; Large ball.

Each of the objects had the SteamVRInteractable script attached in order to allow for the object to be parented to the hands of the user when "gripped". The testers/users the interacted with each of the objects under the following conditions: With no finger tracking; With Finger Tracking; With Skeletal Mapping Morphing. For clarification no finger tracking resorts to binary values (grip or no grip), finger tracking allows the fingers to move freely when gripping the object and finally the Skeletal Mapping Morphing forces the users hand to map to the object they are gripping, see **FIGURE 4.5.1 & FIGURE 4.5.2**

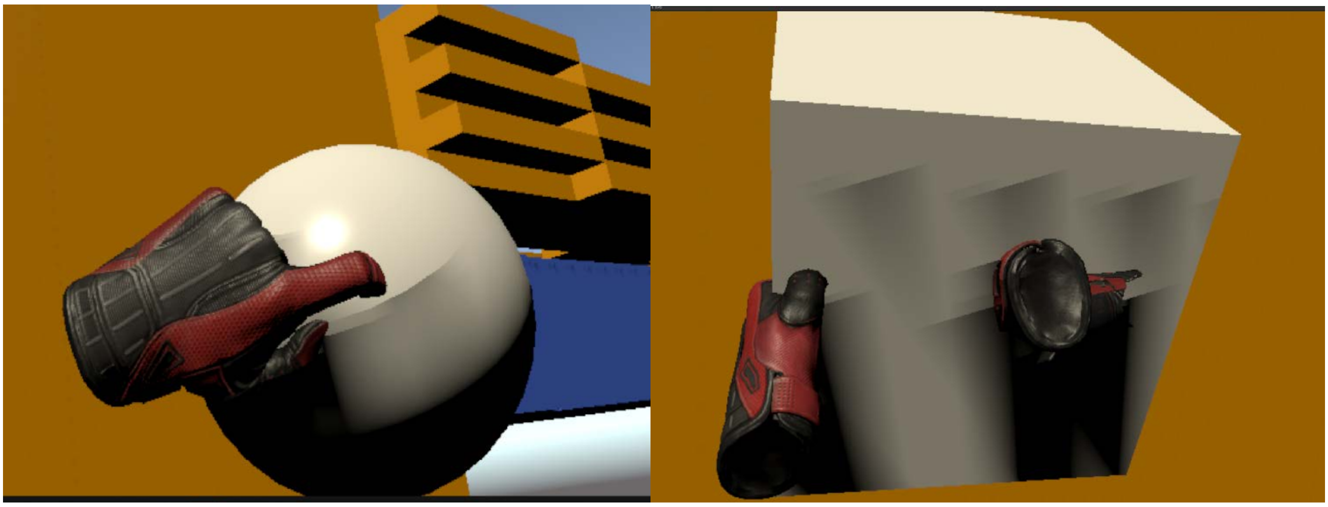


**FIGURE 4.5.1 No skeletal mapping**

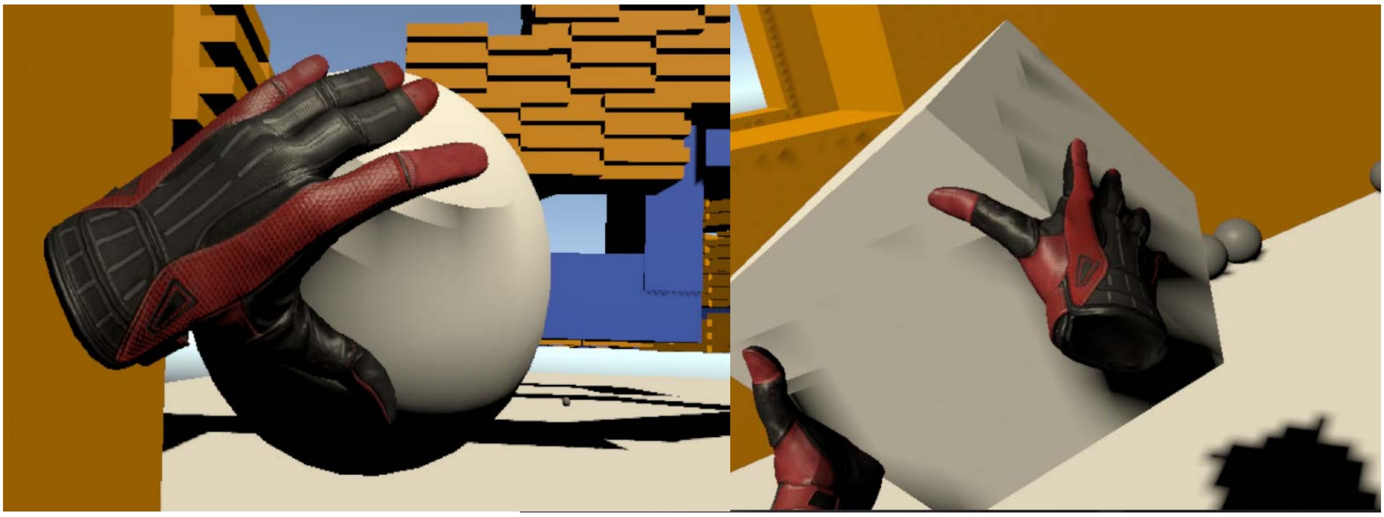


**FIGURE 4.5.2 Skeletal Mapping**

There was no official testing here, however I did ask the testers of the final deliverable to rank their preferences for how their hand is represented. All 5 responses resorted in the hand morphing to the object regardless of their real finger position as the preference.

From these preferences on first look with the small data set it appears as though it agrees with **Section 4.4** on (Davis, 2019) evaluation of relinquishing control from the player slightly and them not only preferring it but also not easily noticing there hand is not in the represented pose. The fact users prefer seeing their hand morph to the object further justifies the hybrid space approach discussed in **CHAPTER 5** as the hand tracking implementation combined with physical objects means their displayed pose will be more-or-less identical if they were actually interacting with that object.

## Appendix C:

## User 1 Results

Purely Virtual

| Self Location | Value | Possible Actions | Value | Test Specific Self Location | Value | Test Specific Possible Actions | Value | |
|---|---|---|---|---|---|---|---|---|
| Q1 | 4 | Q1 | 4.1 | Q1 | 5 | Q1 | 4 | |
| Q2 | 3.5 | Q2 | 4.1 | Q2 | 4 | Q2 | 4 | |
| Q3 | 3.5 | Q3 | 4 | Q3 | 3.8 | Q3 | 2.5 | |
| Q4 | 4 | Q4 | 4.2 | Q4 | 4 | Q4 | 4 | |
| Q5 | 3.7 | Q5 | 4.2 | Q5 | 3.8 | Q5 | 4.2 | |
| Q6 | 4.2 | Q6 | 4.3 | Q6 | 4 | Q6 | 3 | |
| Q7 | 5 | Q7 | 4.5 | Q7 | 4 | Q7 | 3.5 | |
| Q8 | 4 | Q8 | 4.4 | Q8 | 3.9 | Q8 | 3.8 | |
| Q9 | 4.1 | Q9 | 3.6 | Q9 | 3.4 | Q9 | 3.5 | |
| Q10 | 4 | Q10 | 3.9 | Q10 | 3.5 | Q10 | 3.5 | |
| | 4 | | 4.13 | | 3.94 | | 3.6 | 3.9175 |

Hybrid Model

| Self Location | Value | Possible Actions | Value | Test Specific Self Location | Value | Test Specific Possible Actions | Value | |
|---|---|---|---|---|---|---|---|---|
| Q1 | 5 | Q1 | 5 | Q1 | 5 | Q1 | 5 | |
| Q2 | 5 | Q2 | 5 | Q2 | 5 | Q2 | 5 | |
| Q3 | 4.8 | Q3 | 5 | Q3 | 5 | Q3 | 5 | |
| Q4 | 5 | Q4 | 5 | Q4 | 5 | Q4 | 5 | |
| Q5 | 5 | Q5 | 5 | Q5 | 4.8 | Q5 | 5 | |
| Q6 | 5 | Q6 | 5 | Q6 | 4.8 | Q6 | 4.5 | |
| Q7 | 4.9 | Q7 | 4.8 | Q7 | 5 | Q7 | 4.6 | |
| Q8 | 5 | Q8 | 4.8 | Q8 | 5 | Q8 | 5 | |
| Q9 | 5 | Q9 | 5 | Q9 | 5 | Q9 | 4.5 | |
| Q10 | 5 | Q10 | 5 | Q10 | 4.8 | Q10 | 4 | |
| | 4.97 | | 4.96 | | 4.94 | | 4.76 | 4.9075 |
| | | | | | | | | |
| | 0.97 | | 0.83 | | 1 | | 1.16 | 0.99 |
| | 19% | | 17% | | 20% | | 23% | 20% |

## User 2 Results

Purely Virtual

| Self Locati | Value | Possible Actions | Value | Test Specific Self Location | Value | Test Speci | Value | |
|---|---|---|---|---|---|---|---|---|
| Q1 | 3.5 | Q1 | 4 | Q1 | 2 | Q1 | 4 | |
| Q2 | 3.5 | Q2 | 4 | Q2 | 3 | Q2 | 3 | |
| Q3 | 4 | Q3 | 4 | Q3 | 2 | Q3 | 2 | |
| Q4 | 3.5 | Q4 | 3.5 | Q4 | 4 | Q4 | 4.5 | |
| Q5 | 3.5 | Q5 | 3 | Q5 | 4.5 | Q5 | 4 | |
| Q6 | 4 | Q6 | 3.2 | Q6 | 3 | Q6 | 4 | |
| Q7 | 3.5 | Q7 | 4 | Q7 | 3 | Q7 | 2 | |
| Q8 | 3 | Q8 | 3.5 | Q8 | 3 | Q8 | 4 | |
| Q9 | 3.5 | Q9 | 3 | Q9 | 4 | Q9 | 4 | |
| Q10 | 3.5 | Q10 | 3.5 | Q10 | 3 | Q10 | 3 | |
| | 3.55 | | 3.57 | | 3.15 | | 3.45 | 3.43 |

Hybrid Model

| Self Locati | Value | Possible Actions | Value | Test Specific Self Location | Value | Test Speci | Value | |
|---|---|---|---|---|---|---|---|---|
| Q1 | 4 | Q1 | 4.5 | Q1 | 4.3 | Q1 | 4.3 | |
| Q2 | 4.5 | Q2 | 4.5 | Q2 | 4.3 | Q2 | 4.5 | |
| Q3 | 4.5 | Q3 | 4 | Q3 | 4.8 | Q3 | 4 | |
| Q4 | 4 | Q4 | 4.2 | Q4 | 4 | Q4 | 4.6 | |
| Q5 | 4.5 | Q5 | 4.2 | Q5 | 4.5 | Q5 | 4 | |
| Q6 | 3 | Q6 | 4 | Q6 | 4.5 | Q6 | 4 | |
| Q7 | 4 | Q7 | 4 | Q7 | 4 | Q7 | 3 | |
| Q8 | 4 | Q8 | 4.5 | Q8 | 4.2 | Q8 | 4 | |
| Q9 | 4.5 | Q9 | 4.5 | Q9 | 4 | Q9 | 4 | |
| Q10 | 4 | Q10 | 4.5 | Q10 | 4.5 | Q10 | 4.3 | |
| | 4.1 | | 4.29 | | 4.31 | | 4.07 | 4.1925 |
| | | | | | | | | |
| Average | 0.6 | | 0.79 | | 1.31 | | 1.07 | 0.7625 |
| Increase | 12% | | 16% | | 26% | | 21% | 15% |

## User 3 Results

Purely Virtual

| Self Locati | Value | Possible A | Value | Test Speci | Value | Test Speci | Value | |
|---|---|---|---|---|---|---|---|---|
| Q1 | 3.5 | Q1 | 2 | Q1 | 4 | Q1 | 5 | |
| Q2 | 3 | Q2 | 3 | Q2 | 4 | Q2 | 1 | |
| Q3 | 4 | Q3 | 3 | Q3 | 2 | Q3 | 0 | |
| Q4 | 4 | Q4 | 4 | Q4 | 3 | Q4 | 2 | |
| Q5 | 4 | Q5 | 4 | Q5 | 4 | Q5 | 4 | |
| Q6 | 3 | Q6 | 3 | Q6 | 2 | Q6 | 5 | |
| Q7 | 3 | Q7 | 2 | Q7 | 1 | Q7 | 1 | |
| Q8 | 4 | Q8 | 2 | Q8 | 3 | Q8 | 4 | |
| Q9 | 4 | Q9 | 4 | Q9 | 5 | Q9 | 5 | |
| Q10 | 3 | Q10 | 2 | Q10 | 5 | Q10 | 1 | |
| | 3.55 | | 2.9 | | 3.3 | | 2.8 | 3.1375 |

Hybrid Model

| Self Locati | Value | Possible A | Value | Test Speci | Value | Test Speci | Value | |
|---|---|---|---|---|---|---|---|---|
| Q1 | 4 | Q1 | 5 | Q1 | 4 | Q1 | 5 | |
| Q2 | 4 | Q2 | 4 | Q2 | 5 | Q2 | 3 | |
| Q3 | 4 | Q3 | 4 | Q3 | 4.5 | Q3 | 3.5 | |
| Q4 | 4 | Q4 | 5 | Q4 | 5 | Q4 | 4 | |
| Q5 | 3 | Q5 | 5 | Q5 | 5 | Q5 | 4 | |
| Q6 | 3 | Q6 | 4 | Q6 | 3 | Q6 | 3.5 | |
| Q7 | 4 | Q7 | 5 | Q7 | 2 | Q7 | 5 | |
| Q8 | 4 | Q8 | 3 | Q8 | 4.5 | Q8 | 4.5 | |
| Q9 | 4 | Q9 | 3 | Q9 | 3.5 | Q9 | 3 | |
| Q10 | 4 | Q10 | 4 | Q10 | 5 | Q10 | 2 | |
| | 3.8 | | 4.2 | | 4.15 | | 3.75 | 3.975 |
| Average | 0.25 | | 1.3 | | 0.85 | | 0.95 | 0.8375 |
| Increase | 5% | | 26% | | 17% | | 19% | 17% |

## User 4 Results

tual

| Self Locati | Value | Possible A | Value | Test Speci | Value | Test Speci | Value | |
|---|---|---|---|---|---|---|---|---|
| Q1 | 4 | Q1 | 3 | Q1 | 3.8 | Q1 | 3.5 | |
| Q2 | 4 | Q2 | 3 | Q2 | 3.6 | Q2 | 2.8 | |
| Q3 | 3.5 | Q3 | 3 | Q3 | 2.5 | Q3 | 0 | |
| Q4 | 3.5 | Q4 | 3.3 | Q4 | 2.5 | Q4 | 2.5 | |
| Q5 | 3.5 | Q5 | 3 | Q5 | 2.5 | Q5 | 3.5 | |
| Q6 | 3.5 | Q6 | 3.5 | Q6 | 2.5 | Q6 | 3 | |
| Q7 | 3.5 | Q7 | 3.4 | Q7 | 3 | Q7 | 3.5 | |
| Q8 | 3.5 | Q8 | 3 | Q8 | 3 | Q8 | 2.5 | |
| Q9 | 3.7 | Q9 | 3.2 | Q9 | 3 | Q9 | 3 | |
| Q10 | 2.5 | Q10 | 3.5 | Q10 | 4 | Q10 | 2.5 | |
| | 3.52 | | 3.19 | | 3.04 | | 2.68 | 3.1075 |

Hybrid Model

| Self Locati | Value | Possible A | Value | Test Speci | Value | Test Speci | Value | |
|---|---|---|---|---|---|---|---|---|
| Q1 | 4 | Q1 | 4 | Q1 | 4.5 | Q1 | 4.5 | |
| Q2 | 4 | Q2 | 4 | Q2 | 4 | Q2 | 3.5 | |
| Q3 | 3.5 | Q3 | 4 | Q3 | 4.3 | Q3 | 4 | |
| Q4 | 3.5 | Q4 | 4 | Q4 | 4.3 | Q4 | 4.2 | |
| Q5 | 4 | Q5 | 4 | Q5 | 3.5 | Q5 | 4.5 | |
| Q6 | 3 | Q6 | 3.8 | Q6 | 4 | Q6 | 4 | |
| Q7 | 4.5 | Q7 | 4.5 | Q7 | 3 | Q7 | 4.5 | |
| Q8 | 4.5 | Q8 | 4.4 | Q8 | 4 | Q8 | 4 | |
| Q9 | 4 | Q9 | 4.5 | Q9 | 3.8 | Q9 | 3.8 | |
| Q10 | 4.4 | Q10 | 4 | Q10 | 4.5 | Q10 | 3.5 | |
| | 3.94 | | 4.12 | | 3.99 | | 4.05 | 4.025 |
| | 0.42 | | 0.93 | | 0.95 | | 1.37 | 0.9175 |
| | 8% | | 19% | | 19% | | 27% | 18% |

## User 5 Results

Purely Virtual

| Self Locati | Value | Possible A | Value | Test Speci | Value | Test Speci | Value | |
|---|---|---|---|---|---|---|---|---|
| Q1 | 4 | Q1 | 4 | Q1 | 3.5 | Q1 | 3 | |
| Q2 | 3.5 | Q2 | 2.5 | Q2 | 4 | Q2 | 1 | |
| Q3 | 4 | Q3 | 3.5 | Q3 | 2 | Q3 | 0 | |
| Q4 | 4 | Q4 | 4 | Q4 | 2 | Q4 | 2.5 | |
| Q5 | 2 | Q5 | 4 | Q5 | 4 | Q5 | 4 | |
| Q6 | 5 | Q6 | 3.8 | Q6 | 3.5 | Q6 | 3 | |
| Q7 | 4.5 | Q7 | 4 | Q7 | 2 | Q7 | 2 | |
| Q8 | 4 | Q8 | 2.5 | Q8 | 2 | Q8 | 2 | |
| Q9 | 4 | Q9 | 2 | Q9 | 2 | Q9 | 2 | |
| Q10 | 3.8 | Q10 | 3.5 | Q10 | 3 | Q10 | 1 | |
| | 3.88 | | 3.38 | | 2.8 | | 2.05 | 3.0275 |

Hybrid Model

| Self Locati | Value | Possible A | Value | Test Speci | Value | Test Speci | Value | |
|---|---|---|---|---|---|---|---|---|
| Q1 | 4 | Q1 | 4 | Q1 | 4.8 | Q1 | 4 | |
| Q2 | 4.5 | Q2 | 4.5 | Q2 | 4.5 | Q2 | 2.5 | |
| Q3 | 4 | Q3 | 4.5 | Q3 | 4.5 | Q3 | 4 | |
| Q4 | 4.5 | Q4 | 3.8 | Q4 | 4.5 | Q4 | 5 | |
| Q5 | 3.5 | Q5 | 4.5 | Q5 | 5 | Q5 | 5 | |
| Q6 | 4.5 | Q6 | 5 | Q6 | 4.8 | Q6 | 3.8 | |
| Q7 | 4 | Q7 | 4.5 | Q7 | 3 | Q7 | 3.5 | |
| Q8 | 5 | Q8 | 3.5 | Q8 | 4 | Q8 | 5 | |
| Q9 | 5 | Q9 | 4 | Q9 | 4 | Q9 | 4 | |
| Q10 | 5 | Q10 | 5 | Q10 | 4 | Q10 | 2.5 | |
| | 4.4 | | 4.33 | | 4.31 | | 3.93 | 4.2425 |
| | | | | | | | | |
| | 0.52 | | 0.95 | | 1.51 | | 1.88 | 1.215 |
| | 10% | | 19% | | 30% | | 38% | 24% |