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BSc THESIS

Break free (DI edition): Immersive Virtual Reality Game with Bimanual Interaction Techniques

Theodoros N. Ratzos

Supervisor: **Maria Roussou,** Assistant Professor

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ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ

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ΤΜΗΜΑ ΠΛΗΡΟΦΟΡΙΚΗΣ ΚΑΙ ΤΗΛΕΠΙΚΟΙΝΩΝΙΩΝ

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S.N.: 1115201300148

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ABSTRACT

Virtual Reality games are becoming more and more common, as the technological advancements enable increasingly faster and sophisticated hardware to become affordable to a greater number of people. Our home computers, whether they are desktops or laptops, are gradually getting more powerful and affordable, as time goes on. At the same time, head mounted display (HMD) manufacturers are developing better and cheaper gear for virtual reality gameplay. This has led to a boom of virtual reality games in the video game scene, as more and more game developers choose this new and exciting technology, to serve a unique experience to their customers.

This thesis attempts to underline the core concepts around what really makes virtual reality games special by focusing on bimanual interaction techniques used in VR games. A virtual reality experience was developed to explore the effect of bimanual interactions on immersion and engagement. A series of evaluation sessions with end-users were conducted, at different development phases: formative evaluation with 5 users to aid with further developing the experience and summative evaluation with 19 players who played the final VR game. A mixed methods approach was used to summatively evaluate the effect that bimanual interactions can have on the participants' VR experience: observation of the participants' reactions during gameplay, and a post-experience questionnaire followed by a semi-structured interview were used. The results suggest that the incorporation of proper bimanual interactions within the virtual environment seemed natural to most participants, provided them with a high sense of realism and supported their feeling of immersion and presence in the virtual world. Furthermore, participants reported being engaged and having fun. Nevertheless, further studies are required to be able to determine the generalisability of the results.

SUBJECT AREA: Virtual Reality, Human Computer Interaction

KEYWORDS: bimanual interaction, immersion, presence, video games, game development

ΠΕΡΙΛΗΨΗ

Τα παιχνίδια εικονικής πραγματικότητας όσο περνάει ο καιρός γίνονται όλο και πιο διαδεδομένα, όσο η τεχνολογική εξέλιξη επιτρέπει την δημιουργία όλο και πιο γρήγορου και πολύπλοκου υλικού σε πιο προσιτές τιμές για περισσότερο κόσμο. Οι προσωπικοί υπολογιστές που ο κάθε ένας έχει σπίτι του, είτε είναι σταθερός είτε φορητός υπολογιστής, σταδιακά γίνονται πιο δυνατή και πιο οικονομικοί όσο περνάει ο καιρός. Ταυτόχρονα, οι κατασκευαστές κασκών εικονικής πραγματικότητας (HMD) αναπτύσσουν καλύτερα και οικονομικότερα προϊόντα για την χρήση με παιχνίδια ή εμπειρίες εικονικής πραγματικότητα. Όλα αυτά έχουν οδηγήσει στην ανάπτυξη πολλών νέων παιχνιδιών εικονικής πραγματικότητας τον τελευταίο καιρό, αφού όλο και περισσότεροι κατασκευαστές παιχνιδιών θέλουν να χρησιμοποιήσουν αυτή τη νέα και ενδιαφέρουσα τεχνολογία, ώστε να προσφέρουν μια μοναδική εμπειρία στους πελάτες τους.

Αυτή η πτυχιακή τονίζει τα κύρια σημεία που κάνουν τα παιχνίδια εικονικής πραγματικότητας ιδιαίτερα και εστιάζει στις τεχνικές αμφίχειρης διάδρασης που χρησιμοποιείται σε τέτοια παιχνίδια. Ταυτόχρονα με αυτήν την γραπτή πτυχιακή, αναπτύχθηκε μια εμπειρία εικονικής πραγματικότητας για να ενισχύσει την έρευνα πάνω στην εμβύθιση και την διασκέδαση που προσφέρει η ανάπτυξη καλών αμφίχειρων διαδράσεων μέσα στον εικονικό κόσμο. Η εμπειρία αναπτύχθηκε πάνω στην θεωρητική βάση που πραγματεύεται το παρών γραπτό κομμάτι. Μια σειρά από αξιολογήσεις έγινε κατά την διάρκεια την ανάπτυξης της εμπειρίας, αρχικά από 5 άτομα όσο βρισκόταν ακόμα σε αρχική φάση ανάπτυξης, και αργότερα με 19 άτομα που έχουν συμπληρώσει και ερωτηματολόγιο μαζί με την προφορική αξιολόγηση, για να ερευνηθεί η επίδραση που έχουν οι αμφίχειρες διαδράσεις στην εμπειρία χρήσης τους. Τα αποτελέσματα δείχνουν ότι οι καλές αμφίχειρες διαδράσεις με έναν εικονικό κόσμο, που έχουν μια δόση ρεαλισμού και μοιάζουν σε μεγάλο με φυσικές κινήσεις που κάνει κανείς στον πραγματικό κόσμο και βοηθούν στην εμβύθιση του χρήστη, στο αίσθημα παρουσίας εντός του εικονικού κόσμου, την αφοσίωση στην εμπειρία αλλά και το πιο σημαντικό, να ψυχαγωγηθεί περισσότερο. Παρόλα αυτά θα ήταν χρήσιμο να γίνει περεταίρω έρευνα για εξαγωγή συμπερασμάτων σε έναν πιο γενικό βαθμό.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Εικονική Πραγματικότητα, Αλληλεπίδραση Ανθρώπου Η/Υ

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: αμφίχειρη διάδραση, εμβύθιση, «παρουσία», βιντεοπαιχνίδια, ανάπτυξη ηλεκτρονικών παιχνιδιών

I dedicate this work to all the people that were there when I needed it the most.

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For their valuable help, feedback and motivation while writing this thesis and developing the accompanying experience, I would like to express my never-ending gratitude to the following: first and foremost, I would like to express a special thanks to my supervising professor, Dr Maria Roussou for her invaluable help and support during the time I was studying for and writing this thesis. I would also like to thank my friends, Harry Alisavakis (who graciously gave me permission to use his model for the amphitheatre) and Antonis Danezis who helped me overcome some roadblock along the development phase of the virtual experience and the difficulties that arose while using the needed developing tools. I would also like to say a special thanks to Thanos Soulis, who helped with the evaluation process immensely.

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PREFACE

This written thesis is accompanied by a VR puzzle game that was developed and tested in-house in my university. Therefore, the thesis has two parts, the written part which acts as the theoretical background, and the game itself, which was the main focus of the work done. The game was inspired by a multitude of games, both VR and non-VR that had puzzle aspects and unique interactions.

The inspiration for the thesis was the recent boom of virtual reality games and the potential they have as both a medium of entertainment and education. Those games started appearing more and more since the release of the HTC Vive HMD. The popularity of the games released went up significantly as well and more companies are already developing new and better systems for VR games and applications.

1. VIDEO GAMES

1.1 What you get from games

Although this thesis will not cover the subject of video games in its entirety, since that is a very different subject of discussion, we can start by discussing about what you get while playing a video game.

1.1.1 Positive effects of video games

According to the Discover Magazine article *This is Your Brain on Video Games* [1], video games can arm a person with a wide variety of mental skills, that can help not only in everyday situations, but can also give him an edge in his work place. Some of the skills that a person can develop while playing video games are enhanced pattern recognition, system thinking and patience. These skills are acquired progressively over the of time that a person is playing a game, and those are required in order to have any success in it, whether it is achieving the highest score or beating the main objective.

Additionally, as the article states, “students prosper when the subject matter challenges them right at the edge of their abilities”. So, we see that video games have one of the core principles of learning embedded in them, the proper challenge that motivates people, an incentive to discover and learn new things.

A study which the Discover article cites is Nature’s journal article *Action video game modifies the visual selective attention* [2], which concluded that visual perception is enhanced in action video game players. As the article stated, “on standard tests that measure attention span and information-processing time, Green found that gamers consistently outperformed non-gamers”, which reveals that selective attention and cluster recognition is developed while playing action video games.

Another study that was cited in this article is *The impact of video games on training surgeons in the 21st century* [3] which reveals how playing video games has an impact in surgery training. The study revealed that the video game players had consistently more accuracy and faster completion rate than the non video game players that took part in the same study, and also stated that “regression analysis indicated that video game skill and past video game experience are significant predictors of demonstrated laparoscopic skills”.

As a closing statement, the article in the Discover magazine had a quote from James Gee, a professor of learning sciences at the University of Wisconsin on what to expect from young people from the so called “Pokémon generation”: They’re going to think well about systems; they’re going to be good at exploring; they’re going to be good at reconceptualizing their goals based on their experience; they’re not going to judge people’s intelligence just by how fast and efficient they are; and they’re going to think non-laterally. In our current world with its complex systems that are quite dangerous, those are damn good ways to think.”

Other studies have revealed that video games can be beneficial in education as well. As the magazine article *Positive link between video games and academic performance, study suggests* [4] from The Guardian suggests that video games may have value in terms of

academic performance since the skills are developed in the process that favour learning. “The analysis shows that those students who play online video games obtain higher scores on Pisa tests, all other things being equal. When you play online games, you’re solving puzzles to move to the next level and that involves using some of the general knowledge and skills in maths, reading and science that you’ve been taught during the day.” said Alberto Posso, an Associate Professor at the Royal Melbourne Institute of Technology. However, this does not definitively prove that playing video games were the cause of the improvement, rather than playing video games and higher academic performance have some relation.

1.1.2 Negative effects of video games

After presenting some of the positive effects, there must be a section to underline the negative effects as well.

It is common knowledge that playing video games has the inherent risk of someone getting addicted to them, as the Discovery magazine’s article [1] stated at some point. This has to do with dopamine that is released while playing a game for a certain time. Dopamine is a neurotransmitter that plays a role in how the brain handles both reward and exploration, as stated in the article. Gregory Berns, a neuroscientist at Emory University School of Medicine in Atlanta said: “Dopamine is not the reward; it’s what lets you go out and explore in the first place. Without dopamine, you wouldn’t be able to learn properly.” But of course, dopamine is also involved in the addictiveness of drugs. This way, the very nature of a person’s curiosity and learn process can turn to an addiction to video games, which satisfy this particular need.

There is also research on the subject of violence in video games, and how it affects people, especially in a younger age. In the paper *Effects of Video Games on Aggressive Thoughts and Behaviors During Development* [5] the correlation between playing video games and developing aggressive behavior during development was researched. There are also numerous other studies on the same subject of the correlation between aggressive behavior and violence in video games, but there are also other studies proving that there is no such correlation. In other words, this is a subject of controversy.

There are also other controversies surrounding video games. Video games have been accused of portraying genders in a way of reinforcing sexist stereotypes, displaying overly sexual content and portraying racial discrimination and thus reinforcing those stereotypes as well. Some games are accused of portraying countries and ethnicities with reinforced stereotypical behavior or even disregard historical accuracy. Whatever it is, video games have been the subject of controversy in the past, and will still remain since they are a means of artistic expression for a wide range of people, with a wide range of beliefs.

2. VIRTUAL REALITY GAMES

Virtual Reality Games are slightly different from traditional video games. They have additional freedom of movement and interaction. *The VR Book* [6] gives a very nice definition: “virtual reality is defined to be a computer-generated digital environment that can be experienced and interacted with as if that environment were real”. One of the main differences with traditional video games is the way the gamer interacts with the environment. Usually, a person puts on a virtual reality headset or is standing inside a multi-display environment to be able to see into the virtual world, and he has one or more controllers in order to interact with the world inside the game. However, the display and interaction method are not the only things that VR games have different from other video games, and in this section we will underline those key differences-characteristics.

2.1 Immersion

Immersion is the first thing that sets VR games apart from the others. Although normal video games can immerse the player into the story or the gameplay, it is a very vital ingredient for a good virtual reality experience. “Immersion is the objective degree to which a VR system and application projects stimuli onto the sensory receptors of users in a way that is extensive, matching, surrounding, vivid, interactive, and plot informing” [6].

How immersion is achieved is a combination of how the user interacts with the system and vice versa, whether it is the visual or the audio aspect, or the type of controller the person uses to interact with the system. The user needs to feel like he exists inside the virtual environment, so it needs to be believable (at least in the context of the experience itself). It is also very important that the user’s senses are occupied to the greatest extend possible, so that person can only experience what is happening inside the virtual space. That way, the experience is more vivid, more life-like and the immersion is better. Lastly, what is also important is how the user can interact with the virtual world and how believable the setting or the story that takes place is.

As stated in the work *Measuring and Defining the experience of immersion in games* [7] we can describe immersion as a state that requires concentration, a sense of challenge, control over the game and finally, emotional involvement and real-world dissociation. It also includes other factors such as player skills, clear goals, feedback and social interaction.

“However, immersion is only part of the VR experience as it takes a human to perceive and interpret the presented stimuli. Immersion can lead the mind but cannot control the mind. How the user subjectively experiences the immersion is known as presence” [6].

2.2 Presence

Presence is a much more important aspect for a VR game and any virtual reality experience as well. “Presence, in short, is a sense of “being there” inside a space, even when physically located in a different location”, “it is difficult to describe in words — it is something that can only be understood when experienced” [6].

What separates presence from immersion, is that the latter is the technology that is used to try and trick the user to perceive the virtual world as the real one, to create the so-called

suspension of disbelief, while the former is the feeling that the user is experiencing if the game manages to do just that. “When present, the user does not attend to and perceive the technology, but instead attends to and perceives the objects, events, and characters the technology represents” [6].

So, we see that in order to create an enjoyable and successful VR game or experience, you have to create a strong sense of presence. It is what makes the game or experience more memorable, more fun and will generally have a lasting effect on the user, which will make it more likely for him to try that experience again, or even try other similar applications.

2.3 Interaction

“Interaction is the communication that occurs between a user and the VR application that is mediated through the use of input and output devices” [6]. It includes the type of device/controller through which the user interacts with the virtual world and the type of manipulation and effect the user can have in that world.

This may seem easier than it is at first, but there are complications that are non-obvious. The virtual world cannot model the real one exactly, nor should it. There are real interactions that would be pointless or not entertaining/beneficial for the game or experience. Moreover, inside a game, some ways need to exist for retrieving information on the spot and actions that must take place that are beneficial to the plot or the user’s entertainment (for example GUIs, hints), things that do not usually exist in the real world. Also, natural interactions through use of our hands, cannot be 100 percent mapped to the virtual world, due to limitation of hardware and/or software. “Creating quality interactions, therefore, is currently one of the greatest challenges for VR” [6].

In the following section, we will discuss more about interactions in VR games, as is the objective of study in this thesis.

3. INTERACTIONS IN VR GAMES

In this section we will discuss about interactions inside a VR game or experience and how it is different from the real world.

3.1 Using your hands in the real world

Use of our hands is classified into two main categories: unimanual or one-hand use and bimanual or two-hand use. Which one of those we choose is based on the difficulty of the task itself and how comfortable we are at that task. Unimanual actions are switching the lights on and off, opening and closing the fridge or holding our cup of coffee or glass of water, whereas bimanual are most of our everyday actions, like opening a container of milk or a jar of marmalade. However, bimanual actions can be classified again into two categories, in symmetrical, where both hands do the same thing and asymmetrical, where each hand does a separate movement in conjunction with the other to complete the task, as we can see in Figure 1.

In *Classifying Human Hand Use and the Activities of Daily Living* [10], the author, Aaron Dollar researched the ways humans use their hands, or more specifically their palms, in their daily activities and categorized the different grips and manipulations they use. He showed that there are different kind of hand movements one can use in order to do something, which in his words, would help in robotics applications, prosthetics and other applications. It would be interesting to take a look at the different types of grips and manipulations that are natural for humans to use in their everyday lives in order to determine how to best map those movements with interactions inside a VR game or experience, to make it as close as possible to the real world. These grips are first classified by either focused on power or on control, then whether the palm needs clamping or not, by the shape of the hand while gripping and the position of the thumb and the rest of the fingers. He also researched the frequency at which people really use these grips and manipulations in a day, which can be used to determine what is the most comfortable design for a future controller that can be developed.

In *Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model* [8], Yves Guiard talked about how people use their hands in conjunction with each other. As he suggests, the majority of manual activities involve bimanual actions, in which each hand plays different roles (asymmetrical bimanual actions). He researched the way humans use their hands in order to perform the actions they want, and proposed a model that can help better understand how the two hands cooperate with each other and how we can use this knowledge to take advantage of these manual skills. What we can derive from his work is that there is a lot to be gained from studying human behavior when it comes to using their hands, so that we can create better interactions inside a virtual environment.

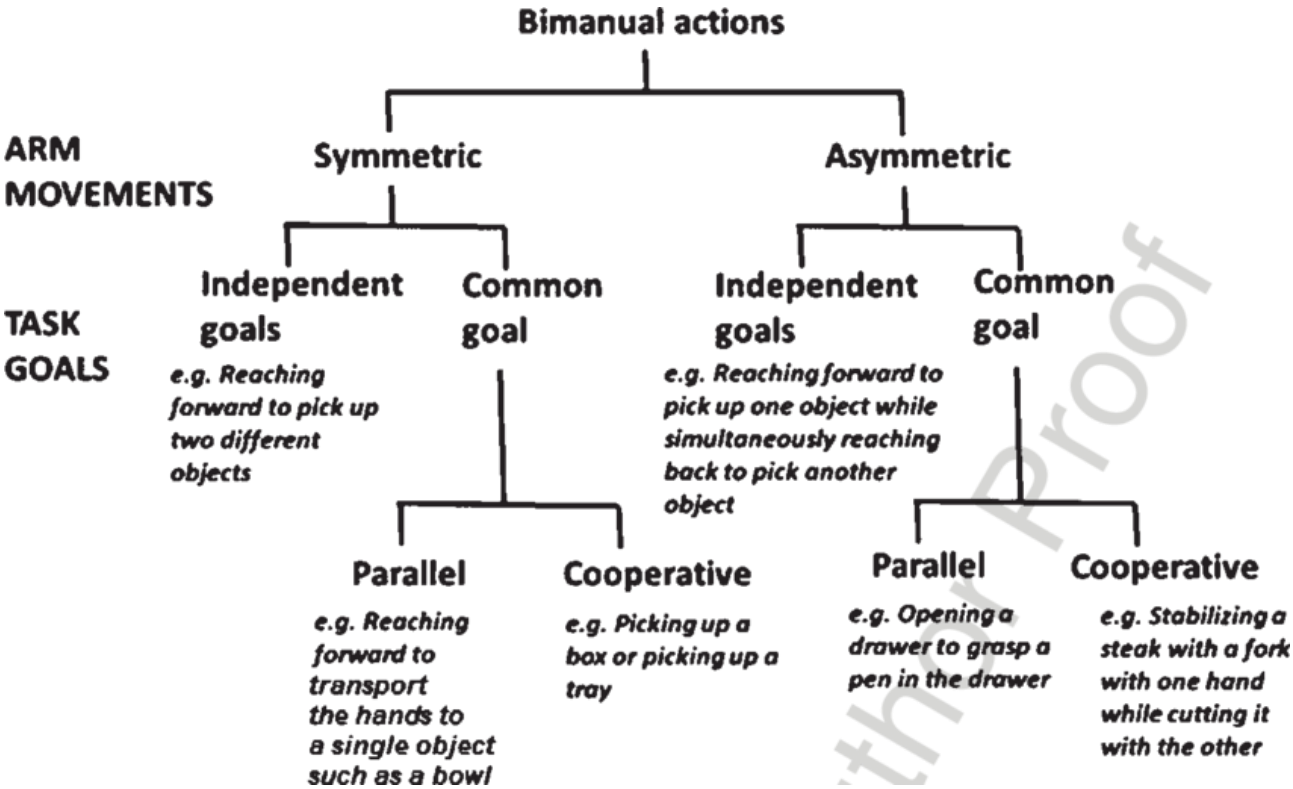

Figure 1: Classification of bimanual actions based on symmetry of arm movements [11]

3.2 Using your hands in the virtual world

As has been established by now, how we interact with objects inside the virtual world is by using one or more controllers that allow us to interact with the world, either by the use of buttons or by having their position tracked or even better, both. The most popular VR sets are the HTC Vive, the Oculus Rift and the PlayStation VR. They differ in what degrees of freedom they allow, but they all feature head tilting and looking-around and controllers that both have buttons and have some form of tracking for hand movement. This means that current HMDs allow us to use our hands like we use them in the real world to a certain degree, but still require us to map different functions to the buttons they feature. Some HMDs, however, allow use to have room-scale movement while playing (i.e. Vive) or map the buttons in a more natural and thus comfortable manner (i.e. Oculus Controller).

In the article/blog post "*How to design a proper bimanual UX in your VR experience*" [9] the author describes, as the title suggests, some ideas about how to design proper interactions in a VR game or experience, in order to have a very good user experience. The author also referenced the work of Yves Guiard [8] as well. In this context, what is important is that there are 3 key principles that define how we use both of our hands in any asymmetrical bimanual interaction:

1. **The left hand provides a frame of reference for the right hand**. As Yves said, you don't only write with your "right hand". "While it is correct that you actually hold the pen with the right hand, left hand and arm are there to give you a frame of reference. You can write straight on each surface, provided that your left arm is there to give you a frame of reference of what is "straight".

2. **The left hand moves on a micrometric scale, while the right hand on a micrometric one**. “The right hand can move very fast, offering little and precise movements, while left hand moves fewer times and at a bigger scale”. “Left hand finds very hard making little and precise movements: it is just not its job. Right hand instead operates at a finer temporal and spatial resolution”.
3. **The left hand moves before the right hand**. “. Left hand provides a frame of reference, performing a macro-motion and then right hand can make its tasks with its finer motions”.

So, what we can infer from these points is that we do not write with one hand, but we write with both, but each hand has completely different tasks from each other. Both hands, therefore, are equally important in writing, because they do different jobs well. That is true for more than just writing, this was just the example the author gave.

As a result, a successful interaction should be either unimanual, bimanual and symmetric or bimanual and asymmetric, following the three key points we talked about. This way we assign to each hand what it is naturally supposed to do, and we keep the frustration to a minimum level, while the mapping is as close to the real world as possible.

3.3 Interactions and affordances

In the paper *Perceiving affordances in virtual reality: Influence of person and environmental properties in perception of standing on virtual grounds* [12], the authors experimented with affordances of a standing platform inside a virtual space. What they did is ask participants to rate how easy it would be to stand on a tilted platform, considering the material that it was made of. What they found was that even though participants knew that they were inside the virtual reality, they perceived the platform as being as easy to step on as if it were real. If we also consider the work of the paper *Affective Interactions Using Virtual Reality: The Link between Presence and Emotions* [13], we can see that people react and perceive the objects inside the virtual world as though they were real, linking textures and properties to them.

What we can derive from all that is that people consider seriously the affordances they are given inside the virtual environment. That means that we should create usable objects that afford *if* or *how* they can be used in order to create a pleasant experience inside our VR environment. We can see this also in the article *Gibsonian affordances as applied to interactivity in VR* [15]. What is exciting is the ability to discover objects that afford some interaction, that we can use in some way. Having objects that afford some use that are non-interactable takes from the experience, and we must avoid it as much as possible.

We propose extending the affordance of objects by allowing them to communicate dynamic use, such as (1) motion (e.g., spray can shakes when touched), (2) multi-step processes (e.g., spray can sprays only after shaking), and (3) behaviors that change over time (e.g., empty spray can does not allow spraying anymore).

In the work *Affordance++: Allowing Objects to Communicate Dynamic Use* [14], they suggested a system where the objects themselves communicated to the person wanting to use it what they wanted them to do with it, which includes motion, multi-step processes and behaviors that change over time. That way, a person was guided on how to use a certain object by having electric muscle stimulators attached to their hands, which controller their hand to a certain extend. That includes helping them grab the object, use the object correctly and disallowing them from picking up or touching an object that should not be touched. While this was a working prototype and a nice suggestion, it works in the real world, but it could

have some use in the virtual world as well. This study underlined the importance of affordances that are communicated to the potential user from the object itself, something that can be done in a VR game or experience. That means that it is important for the game or experience itself to guide the user thought it, but also that the objects that can be interacted with should provide enough visual or any other feedback to the user, as to which interactions they afford and communicate what they can and cannot do with them. This way the user will not get confused or side-tracked while in the VR environment, and he will not experience a "break in presence", which is crucial to a good user experience in VR.

3.4 Actual use of interaction and affordances

In this section we will elaborate more on the HTC Vive, as the thesis was developed on this platform and the design choices that were made for the VR game based on the research that was done.

Image 1: Vive Controllers [16]

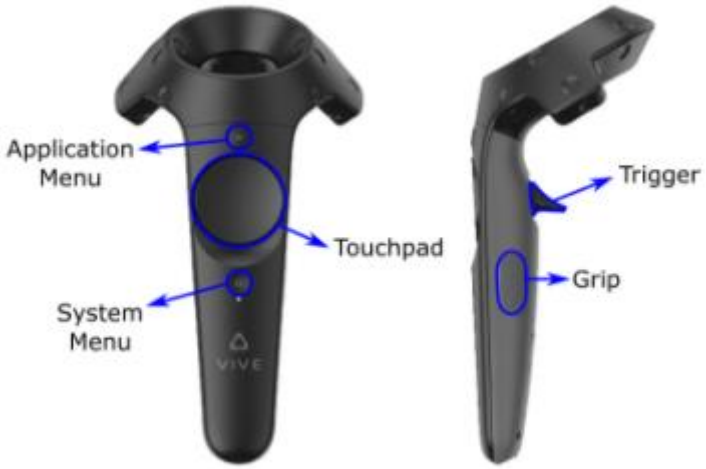

Image 2: Vive Buttons [17]

The controllers are ambidextrous, meaning there is no distinction for left and right before starting an application. They are held like two bars and have the tracking devices inside a ring above the handle. They feature a number of buttons, which are the trackpad, which is used by the thumb and is placed in the front facing the player, the application menu and system menu buttons which are above and below the pad respectively, the trigger button that is use by the index finger and is on the back of the controller and the grip buttons, which can be used in a variety of ways and are places left and right of the controller. We can see how a controller looks in Image 1 and the arrangement of the button in Image 2.

For the controls inside the games, I have compiled Table 1. It shows what buttons are used to trigger certain controls, more specifically what button each game I tested uses for the pickup/drop item command and the use/interact with item/object command.

Table 1: Steam HTC Vive Game's Use of Buttons

Interactions / Buttons	*Pickup/Drop Button*	*Use/Interact Button*
Belko VR	Grip Buttons	Trigger
Nevrosa: Prelus	Trigger	Trigger
Accounting	Trigger	-
Unseen Diplomacy	Trigger	-
The Talos Principle VR	Trigger	Trigger
The Lab	Trigger	Trigger
SUPERHOT: VR	Trigger	Trigger/Trackpad

It is clear that the majority of the games tested have preference for the trigger button as the main input for the game. This is due to the fact that the trigger button is the easiest button to reach and use, it is the most intuitive button on the controllers. As we can see, the only game in the list that had the grip button for picking up objects is Belko VR. That is because in Belko, there are objects that need to be used while you are holding them in your hand already, like a gun or an electric screwdriver. That means that the pickup and the use command need to be on separate buttons, you need to pick up the gun and then press the trigger to fire. Other games have simpler interactions and choose to have one button for all these commands, which makes the game controls simpler and more straight-forward.

The design choice for my game was, in the end, to stick with a simple trigger button for all actions. This was to reduce the time needed for a person to learn the controls. It was also a conscious decision, based on the fact that due to the nature of the game, a puzzle game, at certain points it is required to introduce new aspects of the game, new mechanics. By having simpler interactions, you help the user feel less overwhelmed with new content, and it makes exploring your options less complicated.

On the subject of affordances, I tried and used text hints that point to the area or point of interest, so that the user always has help without the help of an expert or breaking presence to discover what to do next. Audio and visual feedback was implemented as well, usable objects are highlighted when a user hovers the controller over it, and other effects are present when important events are occurring, like a door is opened, or a puzzle was successfully solved.

On the subject of interactions, the interactions that were implemented were the classic steam VR bow and arrow (bimanual asymmetric), a winch for opening doors (unimanual), buttons and levers (unimanual), and other throwable and usable items. While most interactions are indeed unimanual, this will not mean that they will be used in exclusion to one another. The puzzles include more than one object, and more than one interaction to be solved. That means that there may be a time that two objects need to be used in cooperation, in an asymmetrical manner. This will create more elaborate bimanual interactions out of simpler ones, that could be scaled to more puzzles.

4. DESIGNING AND DEVELOPING THE VR EXPERIENCE

4.1 Influences

Before going into depth with how the game was designed and implemented, it would be good to mention some games and applications that I took a lot of inspiration from.

Portal and *Portal 2* from Valve. Those two are great puzzle games that have a number of different mechanics in place in order to overcome the difficulties that are presented during gameplay. The one specific mechanic that stands out, is the one and only portal gun. It adds a whole new dimension of puzzle solving and new challenges to the player, who now has to think outside of the box, he has to "*think with portals*" as the game itself informs you from the moment you start playing. This combined with the dark humor and interesting characters, along with the amazing atmosphere of "aperture laboratories" and the storyline, make for two truly amazing games.

Antichamber. The elements I took from this game are mainly the room-based approach. The levels I created were each unique, meaning that even though you see a scene twice, it has distinct elements and interaction in it. As I have not played the game myself, my experience form it mainly come from reading about it, watching videos and talking about it with friends. The game itself is quite unique, the art style is simple, yet beautiful, and the concept is hugely different from other puzzle games, which is the existence of impossible objects, that have different functions depending on the side of the object that you interact with.

Talos Principle. This is also an amazing puzzle game, which features room-scale puzzles. Placing objects at certain spots and removing them if necessary, opening pathways or disabling opponent's behaviors, this game makes you really think outside of the box. The visuals are also beautiful and not too distracting. The storyline also seems interesting, though I have to confess that I haven't completed this game either.

Tilt Brush. The way you interact with your tools and use both of your hands at the same time, but for different purposes, are the main inspirations I got from this application. Tilt brush is an amazing experience for the HTC Vive, and you can use it to satisfy your creative mind, creating paintings and objects or even entire scenes. It has one of the best interactions and UI systems I have seen in games, and it is a really enjoyable experience altogether.

4.2 Design and Implementation

In this section I will demonstrate how the design choices I made worked in the final version of the VR application itself. I will also show different screenshots from gameplay and from during the time I was developing the experience itself.

4.2.1 Interactions

The interactions include true unimanual, hybrid unimanual, hidden bimanual and true bimanual types.

a. True unimanual:

The interactions that were designed to be truly unimanual, with nothing more in mind than to entertain the player when he chose to interact with those were the books and the chairs inside the office area (see image 3), which were only designed to be thrown around the room. Those interactions were optional, and more of those could be implemented. However, during testing and while observing the users who were in the office scene, we found that almost none had any curiosity to discover whether you could pick up a book or chair. Only 4 out of the 24 people tried out that interaction, but the 2 of those were during early development stages, and they were told that you could interact in this way and another one was during final testing, who was also told so after he asked if he could move the chair. This could be so for a number of reasons, which include the optional nature of the interaction itself, the fact that those items were scattered at the edges almost of the room and that a previous scene included non-interactable books floating in the air (that was in the corridor, see image 4). While those interactions were fun, most people did not get to try them out. A possible fix for this could be to include more items with similar optional behavior, to make the user want to explore similar such items inside of the game. In the end, however, the

Image 3: Office Scene

existence of those items themselves added very little to my particular VR application itself.

b. Hybrid unimanual:

The main interaction here was the Boolean puzzle, which was featured in the game (see image 5). This included a number of logical gates, a number of inputs that the user could switch, to represent zero and one input, and the single output of each puzzle. The interaction with the user was the switch, as mentioned before. The only thing he could do is flip the switch, and change the input, which in itself is a unimanual interaction, since you only need one hand to do this action, in order to light up the output bulb. However, if we see this interaction on a greater scale, each puzzle requires multiple such switch interactions, and since each one is some way apart from each other, most people had the need to alternate between using both hands. That does not make the interaction bimanual. Some people

never used their second hand. That is why I labeled this interaction as hybrid, because the bimanual aspect is optional, and the user decides which type suits him the most.

Image 5: The Corridor

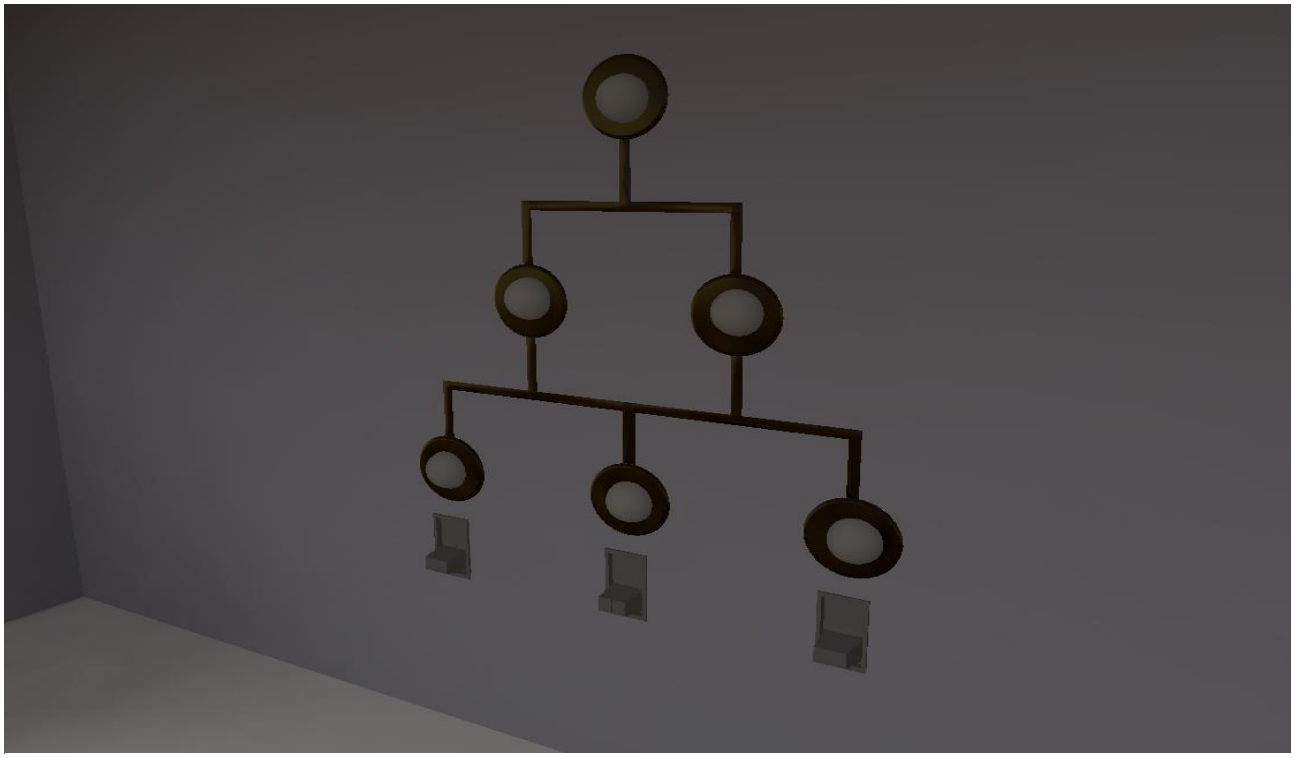

Image 4: The boolean puzzle

c. Hidden bimanual:

The hidden bimanual interaction is the interaction with the keys hanging from the balloons in the office (see image 3). The puzzle aspect here was that the user had to use the correct key on the door, to unlock it and get to the next level. The puzzle was a simple color-match of the door lock and the balloon's color. While the grabbing of the key is unimanual in its core, the whole puzzle demonstrates a bimanual aspect, since the user is obliged to use the other hand's controller to teleport near the door. That means that the two hands work together for a common cause, they just do different things to accomplish it. One observation needs to be added here. I haven't categorized this as a true bimanual interaction due to a small number of people that found a work around the intended behavior. They threw the key, dragging the balloon with it, then proceeded to teleport near it and use it on the door lock.

d. True bimanual:

The two truly bimanual interactions that were featured in the game were the bow and arrow, for the target practice (see image 6) and the climbing wall (see image 7). In these interactions there is no way to do the tasks given without naturally using both hands. In the bow segment, your task is to fire an arrow towards the targets, which light up to indicate whether you hit the correct one or not. This task requires you to hold the bow with your main hand, and nock and release the arrows with the other. As we have discussed in a previous chapter, this is a bimanual interaction by definition. In the climbing segment, the player is forced to climb up a wall, by holding on to rocks that extrude from the surface of the office walls. That means that you must alternate holding on to a rock, and reaching the next one with each hand. If you let go, the physics of the game will make you fall down to the base level again. This is also a bimanual interaction by definition. By observation, the climbing mechanism was the most enjoyable to most people, since almost all of them admitted that they really felt they were at a high altitude and in danger of falling down if they slipped.

Image 6: The bow

Image 7: The climbing wall

4.2.2 Rooms and world

The game is set in the Department of Informatics and Telecommunications of the National and Kapodistrian University of Athens. This was a choice to honor and remember the years of study that took place from my part there and to give something back from the invaluable knowledge I accumulated through that experience. It was also to create a certain rapport with the students of the department itself, if they ever played it themselves. The world was designed to resemble to some degree certain parts of the department, like the entrance and some of the exterior, an amphitheatre and some office space. In the previous section some of the experience's rooms were mentioned, here we will take each one and discuss the design logic behind them and how they connect to each other, to form the world of the game.

a) The department's entrance

The department's entrance (see image 8) was modelled from scratch. It is a rather small scene that exists at two points in the game. At the start when you have to use the bow to enter the amphitheatre and at the end when you have to climb the wall to reach the roof. It was designed to resemble the real department's entrance, so that the player could get a feel that he was entering a university building.

b) Amphitheatre A1

This amphitheatre (see image 9) is one of the most iconic in our department's building. This was modelled and graciously given to me by Harry Alisavakis, who is the original creator and allowed me to use it for this thesis, for which I thank him immensely. This room was used to host the Boolean puzzle and make the user learn to use his controllers and trigger buttons to interact with certain things in the world.

c) Corridor

The corridor (see image 5) was designed to make the user feel threatened and afraid. It is supposed to add a horror aspect to the game, so that the player feels that he needs to

escape there as soon as possible. Also, the idea for the floating books was taken from a previous work I participated in and I have to thank the whole team for this particular inspiration I took. In this scene there is no major interaction apart from the teleportation, it only exists to set the mood and make the player feel somewhat anxious to complete the next objectives faster.

Image 8: The department's (DIT) entrance

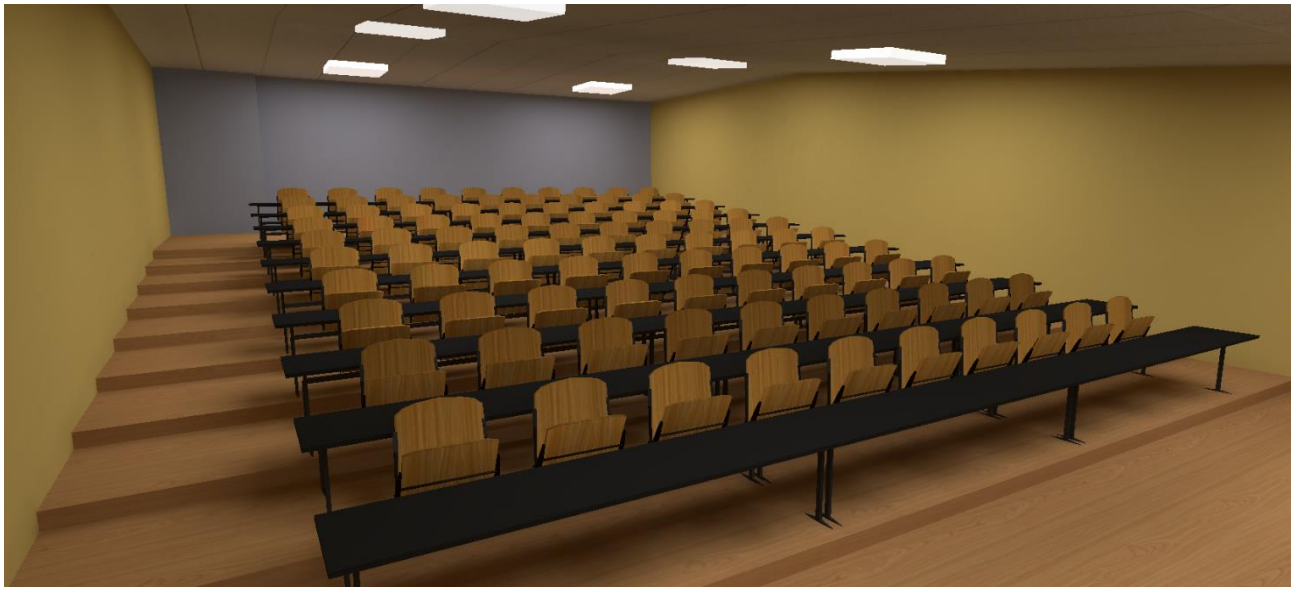

Image 9: Amphitheatre A1

d) The Office

The office (see image 10) was designed to host the optional interactions with the books and chairs and the key puzzle, as we talked about earlier. This rooms was designed to look like a professor's office. Most students have visited some offices while enrolled in this

department. Most times, those visits are for interviews over assignments or to check up on finished or failed exam results.

Image 10: The office room

4.2.3 Visual and audio

The visuals were kept to a quite simple level, with a tendency to keep everything looking as natural and as realistic as possible, to create a deeper impression of realism and presence for the player.

The audio was simple as well, featuring the horror ambience music, and the final outro song. Along with those, several other sound effects were added, for better realism and immersion.

5. EVALUATION

In this section, we will discuss the evaluation process, and discuss the results of the study undertaken. I will omit the early development stages of evaluation in regards to the more bug-fix and technical aspect of it, and it contributed little to the core study of this thesis. I need to stress, however, that this type of evaluation is not in any way of lesser importance than the main evaluation. It simply contributed to another part of the process entirely.

5.1 First main evaluation

The first evaluation was done with 10 participants, 9 male and 1 female. The questionnaire itself will be showcased at a later chapter. Each participant was asked to answer honestly and to the best of his ability to 18 questions in this round. The results are as follows:

Table 2: First main evaluation results

User	Q 1	Q 2	Q 3	Q 4	Q 5	Q 6	Q 7	Q 8	Q 9	Q 10	Q 11	Q 12	Q 13	Q 14	Q 15	Q 16	Q 17	Q 18
1	4	4	5	5	4	3	3	3	4	3	4	4	4	5	5	5	5	4
2	4	4	4	5	3	2	3	4	3	2	3	3	4	4	4	4	5	5
3	5	5	5	4	5	1	5	5	1	1	5	5	4	5	5	5	5	5
4	5	4	3	4	4	3	3	3	2	2	4	5	4	4	5	4	3	5
5	5	5	4	3	5	5	4	5	5	2	4	4	4	4	5	4	5	5
6	5	5	3	5	3	3	3	4	1	1	5	5	3	4	5	5	5	5
7	5	4	3	4	2	3	2	4	3	1	2	3	4	3	3	4	5	5
8	5	5	5	5	4	3	5	3	3	1	5	4	5	4	4	5	4	4
9	5	5	3	4	4	2	4	3	3	1	5	5	4	3	3	5	5	5
10	5	4	5	4	5	3	2	2	3	3	4	3	3	3	4	5	3	4

Table 3: First main evaluation average results

Q 01	Q 02	Q 03	Q 04	Q 05	Q 06	Q 07	Q 08	Q 09	Q 10	Q 11	Q 12	Q 13	Q 14	Q 15	Q 16	Q 17	Q 18
4,8	**4,5**	**4**	**4,3**	**3,9**	**2,8**	**3,4**	**3,6**	**2,8**	**1,7**	**4,1**	**4,1**	**3,9**	**3,9**	**4,3**	**4,6**	**4,5**	**4,7**

The first round of evaluations shows that the experience was able to hold their attention and draw them inside the virtual world. It managed to make the user lose track of time and engage him in the experience. Also, some users were less aware of their surroundings, but not to a great extent. Most users felt present in the virtual world, did not have any urge to stop playing and enjoyed the experience, most of them so much that they would play it again and even recommend it to friends.

5.2 Second main evaluation

The second evaluation was done with 9 participants, one week after the first one, with 6 male and 3 female participants. The experience itself was worked in this week, and the differences were little. The main difference was the ending scene, in which this time, the scene didn't just end when you climbed up the wall, but instead you flew away, which proved to be a significant change. Also, some minor details were corrected, like lighting and some other visual details and more feedback was provided. Finally, another question (Q 16) was added for asking feedback about the audio aspect of the experience. The results were as follows:

Table 4: Second main evaluation results

User	Q 1	Q 2	Q 3	Q 4	Q 5	Q 6	Q 7	Q 8	Q 9	Q 10	Q 11	Q 12	Q 13	Q 14	Q 15	Q 16*	Q 17	Q 18	Q 19
1	5	5	4	5	5	2	5	4	1	1	4	5	4	5	5	5	5	5	5
2	5	5	5	3	4	2	4	1	1	1	4	5	4	3	5	5	5	5	5
3	5	5	2	3	3	3	4	2	4	1	3	5	3	4	4	3	5	4	5
4	5	5	2	4	4	2	4	4	1	1	4	5	4	3	4	5	5	4	5
5	5	5	3	5	5	1	5	1	1	1	5	5	1	5	5	5	5	5	5
6	5	5	4	4	3	4	5	3	2	1	4	5	4	4	5	5	5	5	5
7	5	4	4	5	3	4	3	2	4	4	4	5	4	3	5	4	5	5	5
8	5	5	3	4	3	4	3	4	2	1	4	4	5	2	4	4	5	5	5
9	5	4	4	4	5	4	3	5	3	4	4	4	3	3	5	4	5	5	5

Table 5: Second main evaluation average results

Q 01	Q 02	Q 03	Q 04	Q 05	Q 06	Q 07	Q 08	Q 09	Q 10	Q 11	Q 12	Q 13	Q 14	Q 15	Q 16*	Q 17	Q 18	Q 19
5	**4,8**	**3,4**	**4,1**	**3,9**	**2,9**	**4**	**2,9**	**2,1**	**1,7**	**4**	**4,8**	**3,6**	**3,6**	**4,7**	**4,4**	**5**	**4,8**	**5**

The second evaluation had a better result at engagement and enjoyment overall. The participants were generally more focused, more immersed and noticed less their real-world surroundings. They found the game easier to play, more engaging and had a better experience than the first group. This is, however, to a slight degree, due to the better guidance and feedback given during use of the application.

However, both experiments show that all users enjoyed themselves during the experience, and were typically more engaged during the segments concerning the bimanual interaction that were implemented.

Below is a graph, that illustrates how different the results were during both evaluations for demonstration purposes.

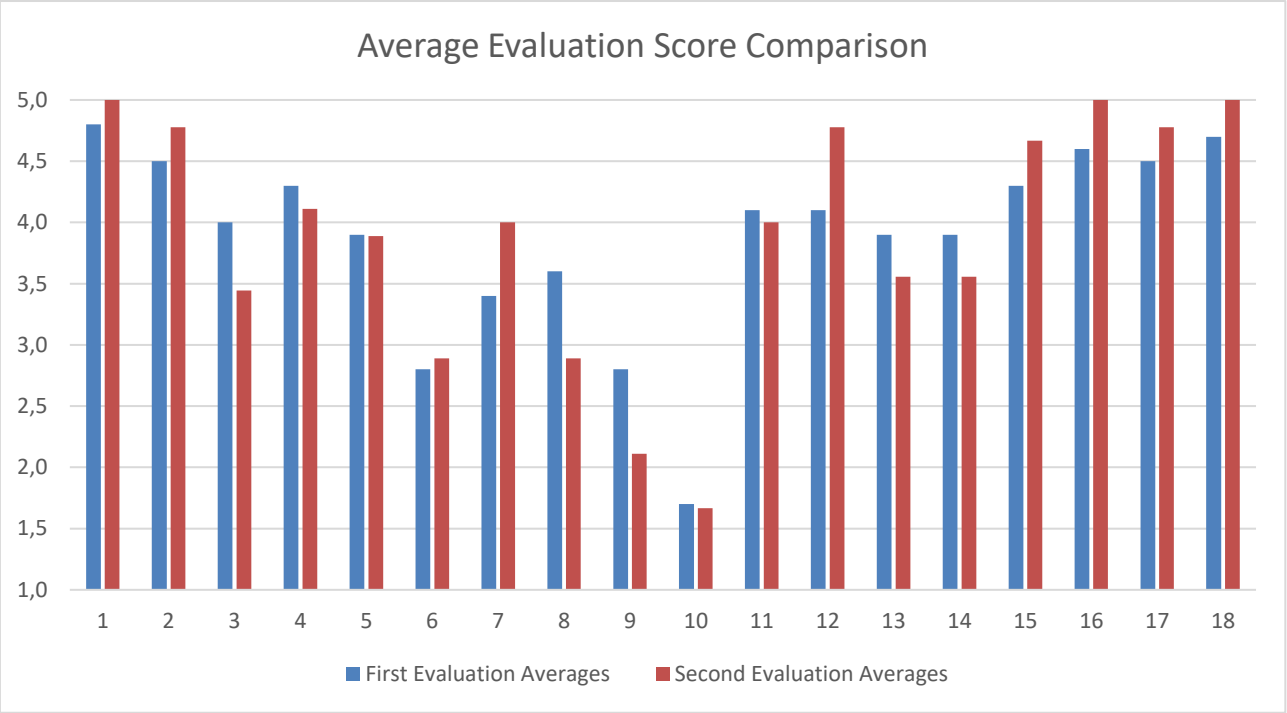

Figure 2: Average evaluation score comparison

At this point we need to point out that question 16 regarding the sound for the second evaluation was removed, and the rest were given numbers to equal those of the first questionnaire.

This graph shows that the second group was slightly more engaged and immersed in the experience, as noted previously.

5.3 Discussion

The results of the study confirm our initial hypotheses. That proper bimanual interactions, when used in an immersive VR environment, can augment the users' engagement and enjoyment. That means that future VR games and applications could take into consideration these results, and allocate more time to design such interactions in order to boost the game's or application's effectiveness, whether it is purely to entertain or educate. What can further be done on this subject is testing this theory on a greater, more refined project, that has a more believable environment and more resources to allocate on designing better, more complex interactions, and test whether this theory still applies. This could help with developing better tools and maybe processes to design better interactions, and as a result better games and applications for everyone.

6. CONCLUSION

According to the results of this thesis' study, we can correlate natural-like and intuitive bimanual interactions to entertainment and engagement from the user's perspective. We can see through user feedback, that a high amount of immersion was achieved and most users were present, lost inside the virtual world, despite it being for a short amount of time.

Having designed the VR experience according to certain standards and adhering to some common best practices we can assume that a similar, better designed and implemented application could achieve much higher success rate, though this remains to be proven.

ABBREVIATIONS - ACRONYMS

VR	Virtual Reality
HMD	Head Mounted Display
(G)UI	(Graphical) User Interface

ANNEX

Below are some images from the evaluation process to demonstrate how it was done and to give an idea how using a VR headset is.

Image 11: A user evaluating the experience. She is holding the VR controllers and wearing the HMD.

Image 12: A user learning how to move in the environment with the help of text hints.

Image 13: A user interacting with the bow inside the virtual environment.

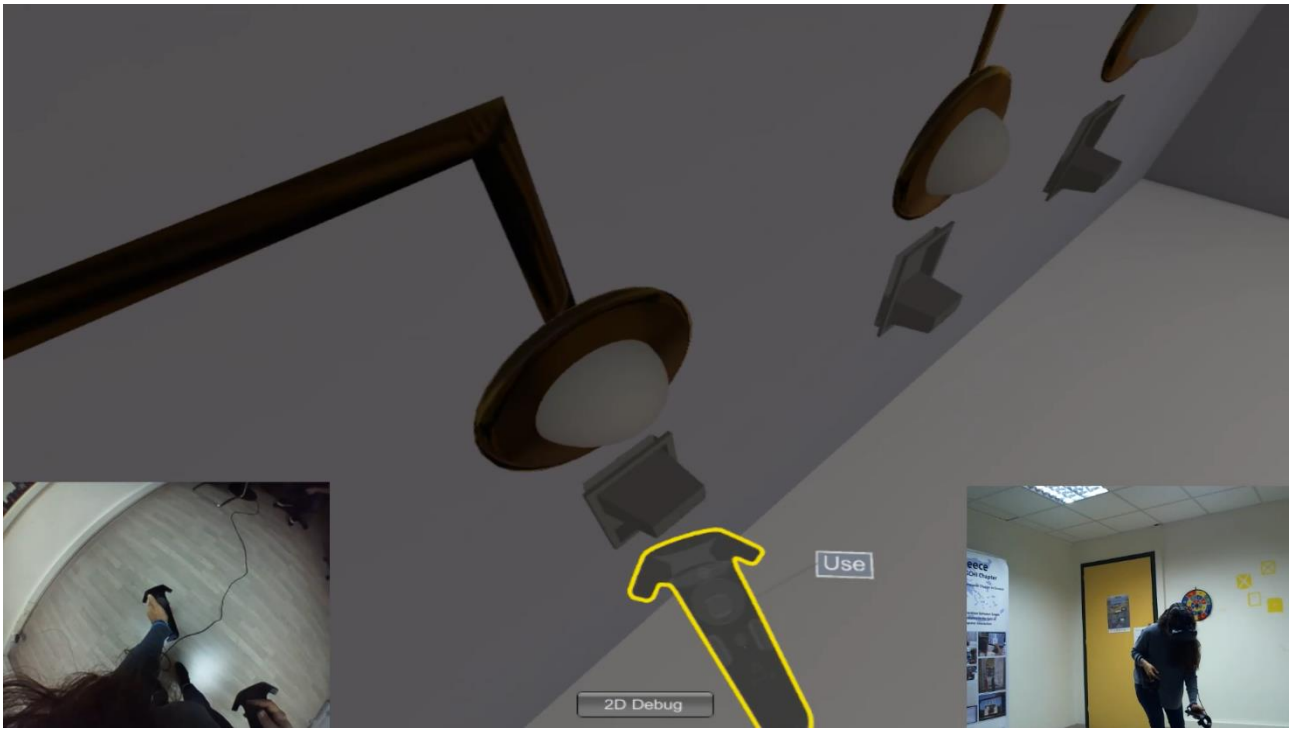

Image 14: A user interacting with the boolean puzzle switches.

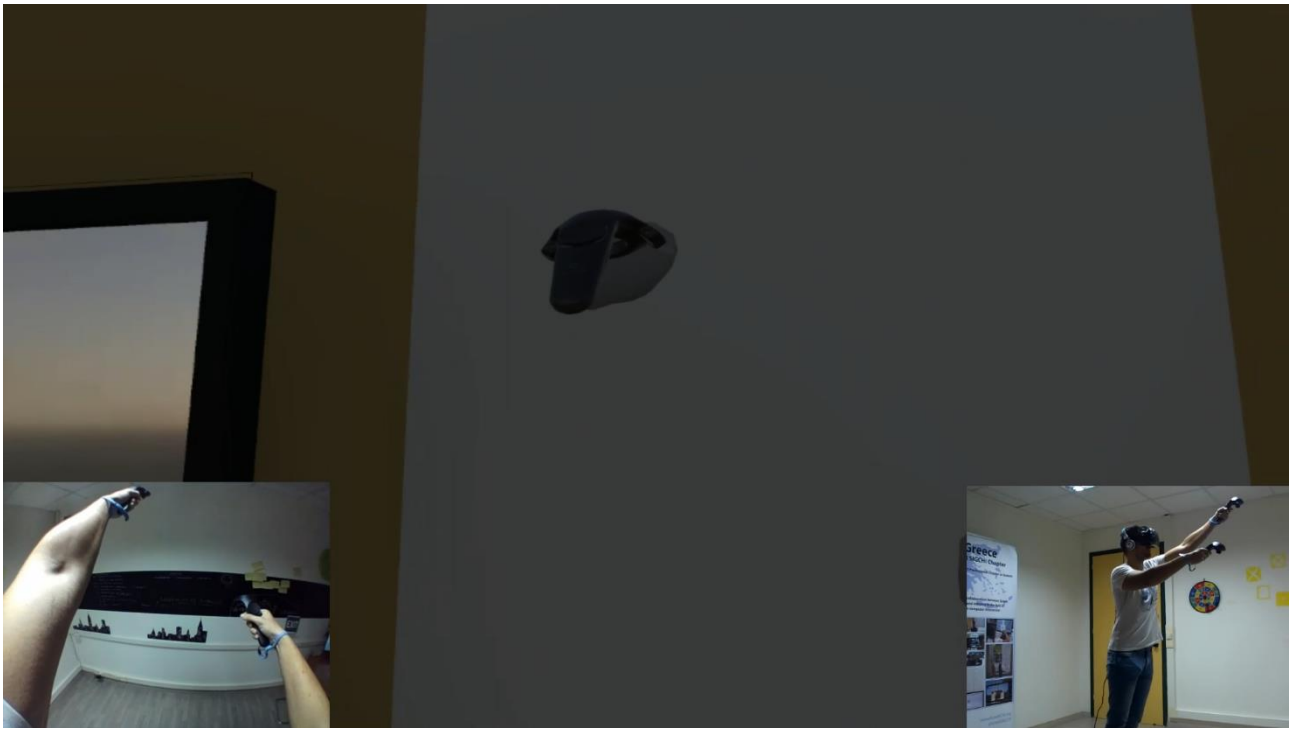

Image 15: A user interacting with the climbing wall.

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