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Navigating 3D virtual environments using peoples' spatial understanding of the physical world

by

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Dear Professor Amin Abbosh

In accordance with the requirements of the degree of Master of Interaction Design in the School of Information Technology and Electrical Engineering, I present the following thesis entitled "*Navigating 3D virtual environments using peoples' spatial understanding of the physical world*". This work was performed under the supervision of Ms Lorna Macdonald. I declare that the work submitted in this thesis is my own, except as acknowledged in the text and footnotes, and has not been previously submitted for a degree at the University of Queensland or any other institution.

Yours sincerely,
Sigurd Sæther Sørensen

Acknowledgements

I would like to thank those who volunteered their valuable time to take part in this study, without whom I could not have conducted this study. Moreover, I would like to thank Thomas Vincent Saly for weeks of creative problem-solving, productive discussions and technical assistance. Liv Karoline Torp Olsen, who provided constant support and made sure I stayed on track in a challenging time; and Lorna Macdonald for valuable insight and countless hours pushing me to do the best work I can. Thank you.

Abstract

This thesis explores whether user-centric tangible user interfaces can provide a useful alternative for navigating 3D virtual environments, by bridging the gap between peoples' spatial understanding of the physical world and their ability to navigate 3D virtual environments. The study draws upon literature from the space of tangible user interfaces, navigation of 3D virtual environments and previous approaches of building alternative interfaces to keyboard and mouse to navigate 3D virtual environments. Furthermore, the study introduces and discusses preliminary research looking to understand people's spatial understanding of the physical world and 3D virtual environments as well as their ability to navigate these 3D virtual environments using conventional keyboard and mouse. These findings informed the design of the prototype VE-SpaND, a tangible user interface aimed to answer whether it can provide a useful alternative to navigate 3D virtual environments. Findings from user testing the prototype suggest that VE-SpaND provide unique advantages to the conventional keyboard and mouse and that it aligns with peoples' spatial understanding of the physical world. Furthermore, the findings indicate that the prototype makes it easier for users with no previous experience to pick up an feel good about navigating 3D virtual environments.

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Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
3D VE	Three-Dimensional Virtual Environment
6DOF	Six Degrees of Freedom
CAD	Computer-Aided Design
DUI	Deformable User Interface
FoV	Field of View
GUI	Graphical User Interface
HCI	Human-Computer Interaction
MVC	Model View Controller
TUI	Tangible User Interface
VE-SpaND	Virtual Environment Spatial Navigation Device

CHAPTER 1

Introduction

Over the last decades, our world has seen rapid development in the field of computer graphics and three-dimensional technology (3D). From the humble beginnings of the personal computer to the powerful smartphones that follow us intimately in our everyday lives, 3D technology has become increasingly omnipresent. The phones, consoles and computer being made today are all capable of high definition 3D games, virtual- and augmented reality (VR & AR). Furthermore, a broad set of industries, such as the medicine-, education-, manufacturing- and design industry have started to implement 3D virtual environments (3D VE) into their operations, and simulated realities have been deemed one of the contributing factors to a possible fourth industrial revolution [1], [2]. In sync with the emergence of new 3D applications across multiple platforms and industries, a rise in the demand for suitable interfaces follow. In search of alternative interfaces to navigate and interact with 3D VEs, researchers have explored a range of domains [3]–[6]. Despite many a promising new interface, we still, heavily rely on handheld controllers and the conventional keyboard and mouse to navigate 3D VEs. One of these promising fields is the domain of tangible user interfaces (TUI) that are physical representations of digital information. TUIs allows users to interact with- and manipulate digital data through a tangible counterpart, which opens up the possibility of using peoples' learned skills, senses, and spatial understanding. Whereas spatial understanding can be found in studies revolving users behaviour in 3D VEs and designing navigational aids, few focus on bridging the gap between users spatial understanding of the physical world and that of 3D VEs [2], [7]. Burigat & Chittaro use Ruddle, Payne and Jones to argue that "*To navigate [a 3D VE] successfully, people must plan their movements using spatial knowledge they have gained about the environment and which they store as a mental map.*"[2], [8]. They also state that people slowly build spatial knowledge of the environment over time [2]. I believe exciting opportunities exist in aligning peoples' spatial understanding of 3D VEs and their ability to navigate 3D VEs with their spatial understanding of the physical world. In bridging this gap, it may be possible for users to navigate 3D VEs as they would interact with the physical world, which might also reduce the time it takes to build spatial knowledge of the 3D VEs. I further believe that TUIs can be a viable option to bridge this gap as TUIs acts as physical representations of digital data, meaning that users can use a physical artefact to interact with digital information directly. Therefore, throughout this study, I aim to explore the following research question: "*Can user-centric tangible user interfaces provide a useful alternative for navigating 3D virtual environments?*".

CHAPTER 2

Background

Overview

To best address the gap between people's spatial understanding of the physical world and navigating 3D VEs, this study draws upon literature related to navigation in 3D VEs, TUIs, and other researchers' explorations of interfaces for navigating 3D VEs. In the space of navigating 3D VEs, I explore key factors that influence users' performance in navigating 3D VEs and what considerations ought to be made when designing interfaces for navigating 3D VEs. Following this, I explore the fundamentals of TUIs, their challenges and advantages as well as design considerations that can make for a better user experience. Lastly, I explore studies where the researchers have built alternative interfaces for navigating 3D VEs, to learn from their findings, technological advantages and disadvantages, their mistakes and how users responded to their design decisions.

Navigation in 3D Virtual Environments

One early milestone in the field of computer graphics came from Ivan Sutherland's doctoral dissertation of 1963 on Sketchpad, which ever-since its introduction have paved the way for GUIs, Computer-Aided Design (CAD) programs and 3D technology as we know them today [9]. In our modern world, computer graphics have become omnipresent, from the radios in our cars and the smartphones we carry with us to the timers on our microwaves, computer graphics follow us wherever we go. Where these devices, for the most part, make use of two-dimensional (2D) graphics, many an industry has emerged from its 3D counterpart. Among these, we find CAD software often used in engineering and architecture to produce technical drawings and 3D renderings and also 3D software capable of creating animations, motion graphics, games, 3D models and movies. Where 2D applications rely on two axes, width (x) and height (y), these types of software allow for a third axis to be used, depth (z). To successfully navigate these 3D VEs, software such as CAD and game engines often require users to move vertically, horizontally and diagonally around objects and rotate them into view, which we refer to as six degrees of freedom (6DOF) [10]. 6DOF allows users to look at what they are building from different angles, move closer to observe objects close up and move out for a better overview, hence navigating the 3D VE. Navigation is *"…the process whereby people determine where they are, where everything else is, and how to get to particular objects or places…"* [11].

Ousland and Turcato highlight five key factors that influence users' performance in navigating 3D VEs, which are: 1. Individual differences, 2. Design of the environment, 3. Design of the interaction device, 4. The travel/moving metaphor, and 5. The task to be performed. They argue using Chen that peoples' performance in navigating 3D VEs relates to their spatial abilities, where people with good spatial abilities generally perform well when navigating 3D VEs [7], [12]. As previously stated, Burigat & Chittaro use Ruddle, Payne and Jones to argue that *"To navigate [a 3D VE] successfully, people must plan their movements using spatial knowledge they have gained about the environment and which they store as a mental map."* [2], [8]. They also argue that building such spatial knowledge of an environment takes a considerable amount of time, which many users may not be willing to spend [2]. One approach of using that spatial knowledge to navigate 3D VEs is by using the two concepts that Ousland and Turcato refer to as landmark- and route knowledge [7]. Landmark knowledge is when users make use of landmarks in the environment to understand their position. They then proceed to map a route between these landmarks to navigate the environment, which is called route knowledge [7]. In terms of the interaction device, they argue that designing an input device that is both easy and effective is problematic, task-dependent and that their findings suggest that a special 3D input device is not required [7]. Besides, they highlight how delays can affect the overall usability of navigation as lag may cause the user trouble when trying to move around and that users found it difficult to understand their position in the 3D VE [7].

Ousland and Turcato also highlight the various metaphors for movement, such as walking, flying and jumping where walking is the easiest one to use and flying provide a better overview and allows for faster movement around the 3D VE [7]. Furthermore, in their paper on navigation in 3D VE, Burigat and Chittaro explore the effects of using navigational aids when navigating 3D VEs. Navigational aids are not part of the five steps as listed by Ousland and Turcato, but they do indeed, as presented in this paper, make an impact on users' performance in navigating 3D VEs [2]. They compare participants' effectiveness in performing wayfinding tasks in a 3D VE using three different navigational aids and its suitability according to the experience level of the user [2]. They study the difference in navigational effectiveness between the two groups: experienced- and non-experienced users, where their findings suggest that navigational aids that are suitable for experienced users may not provide enough support for inexperienced users. They, therefore, highlight that, when designing navigation aids, one should consider the individual's experience navigating 3D VEs [2].

Tangible User Interfaces

One domain which has shown great promise over the last decade is the domain of TUIs which was first introduced back in 1997 by Ishii and Ullmer and revisited by Ishii near a decade later [13], [14]. Ishii's paper on Tangible Bits: Beyond Pixels details what a TUI is, provides the fundamentals of a TUI, as well as their advantages and disadvantages [13]. In short, a TUI is a physical representation of digital information that allows users direct control over its digital counterpart. Where the conventional keyboard and mouse is disconnected from how we interact with objects in our physical world, TUIs offer to extend upon these constraints allowing people to use their learned skills, senses and fine-motor skills to interact with digital information through a physical device. Ishii highlights the basic model of a TUI using the model view controller (MVC) principle, where the control is made tangible, and the view consists of both an intangible and tangible subcategory [13]. This separation of the view is what allows the TUI to fully utilise what Ishii refers to as the double feedback loop [13]. When a user interacts with the TUI, the first loop will provide users with passive haptic and visual feedback in our physical world, followed by the second loop that provides digital feedback [13]. This means that users do not have to wait for digital computations to determine the outcome of their actions as users will get immediate haptic feedback from physically interacting with the device. A GUI is by nature meant for general purpose use, dynamically altering the content on the screen to facilitate the purpose of the application. In contrast, TUs, more often than not, are special-purpose devices, tailored to specific areas [13].

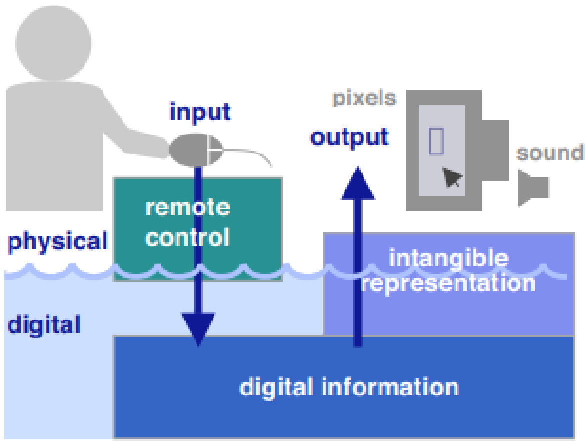


Figure 1: Graphical User Interface [13]

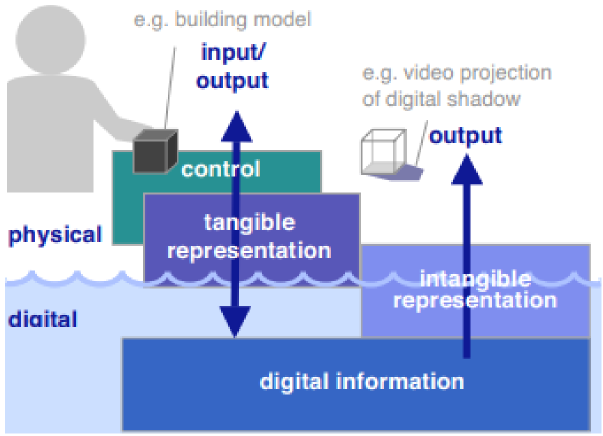


Figure 2: Tangible User Interface [13]

Where Ishii tells us about the makings of a TUI, how it is inherently different from a GUI and its advantages and disadvantages, Bakker and Niemantsverdriet present the Interaction-Attention Continuum, looking at the various levels of attention we can interact with a device [15]. The Interaction-Attention Continuum spans from fully focused attention to entirely outside our field of attention in the three levels, namely, *focused*-, *peripheral*-, and *implicit* interaction [15]. They argue that, alongside an increasingly more omnipresence of computing in our society, so also increases the need for designing interactions which blend into our everyday life [15]. As such, they state their belief that interfaces should work on different levels of attention to better be able to blend into our everyday lives [15]. Moreover, they argue that designers, when designing for interactions to span the continuum, should take into consideration the context and location of the interface for it to blend into our everyday lives properly [15].

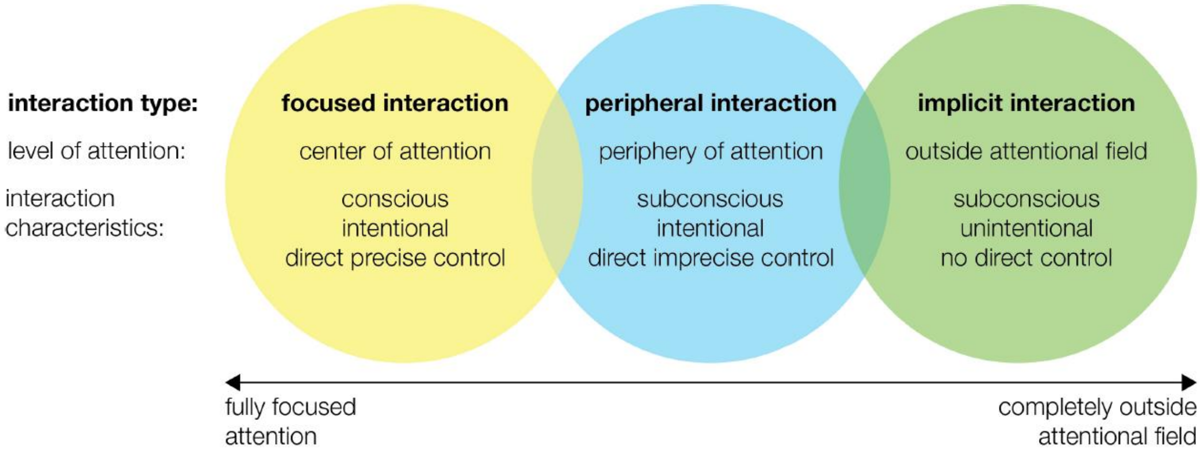


Figure 3: Interaction-Attention Continuum [15]

Where Bakker and Niemantsverdriet suggest considering the three levels of attention when designing interactions, Benford *et al.* presents their framework on creating *expected*, *sensed* and *desired* interactions [16]. The authors argue that "...*previous taxonomies tend to assume that the user's focus is on the computer interface, and that physical I/O devices are peripherals, that is, they are tools to get at what you're interested in, and not the focus of interest in and of themselves.*" [16]. As such, they highlight that the physical form of a device, per the previous taxonomies, can be justified solely based on their function as an input device [16]. In contrast, an increased focus on special-purpose TUIs can lead with the design of the artefact over being determined by functionality alone [16]. In their framework, they highlight how the physical form of a device determines both suitable- and possible interactions with the artefact, a concept they refer to as *expected movements* [16]. Furthermore, the authors present the *sensed movements* of an interface, which are the interactions a device can detect using its sensory capabilities, and how to bridge the gap between the *sensed* and *expected*, which does not always overlap [16]. Benford *et al*. also suggest that designers should implement rest spaces into their interfaces which should be easily identifiable by users to allow users to readjust, prepare and rest [16]. Finally, they present the *desired* movements which, in short, are what we would like the interface to be capable of doing and how it overlaps with both the *expected*- and *sensed* movements [16].

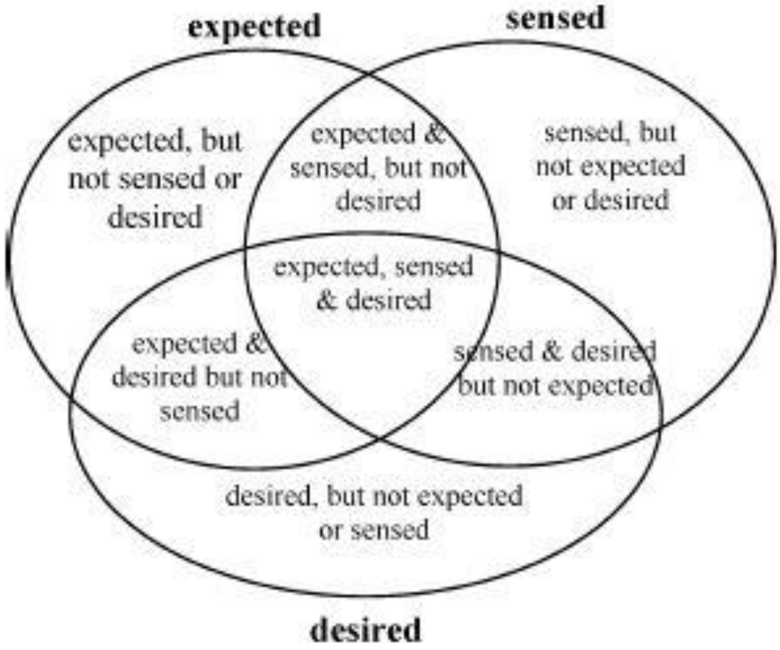


Figure 4: Expected, Sensed and Desired Movements [16]

Related Work

Many researchers have explored various fields in pursuit of alternative solutions for navigating 3D VEs, such as TUIs, Deformable User Interfaces (DUI) and gesture-based interactions [3]–[6]. As previously stated, the form of a device is tightly knit to its capabilities and what users expect when interacting with it [16]. In exploring different technologies, researchers also start with a different set of expected movements, thus also having to bridge the gap between expected and desired movements differently. ZeroN, by Lee *et al.*, approaches navigating 3D VEs from the desired action of manipulating physical 3D objects which are not restricted by gravity [3]. ZeroN is a levitating TUI with 6DOF, where users can move the TUI around in mid-air, and once the user lets go of it, the device holds its position [3]. The authors explore the opportunities and challenges of a TUI that for the user seemingly defies the laws of gravity [3]. Although ZeroN provides a unique set of interactions, other problems emerge, such as technology-specific issues where the TUI drops from the magnetic field if tilted slightly in the wrong direction and graphics lag which confuses the users [3]. Moreover, the lack of physically visible relationships between objects confused some users in terms of how they should proceed to interact with it [3].

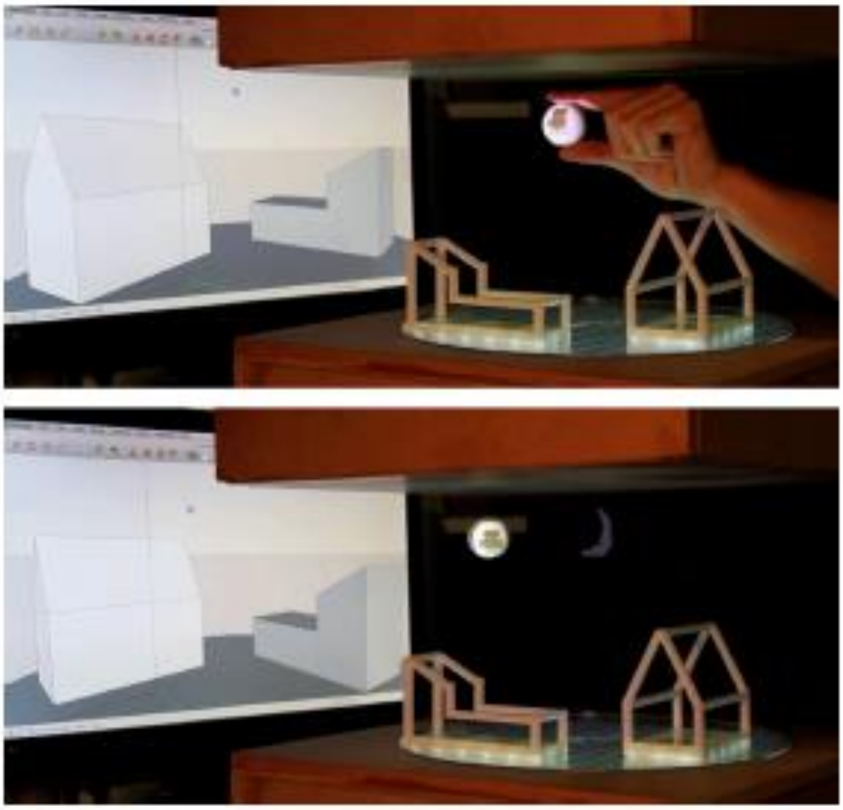


Figure 5: ZeroN [3]

Another approach is the DUI prototype BendID presented by Nguyen as a flexible input device to manipulate and navigate 3D VEs [4]. Nguyen found that, although BendID provided a more intuitive experience to its conventional mouse and keyboard counterpart, it is necessary to consider size, noise, sensitivity and scalability for better user experience [4]. Leflar and Girouard explored a similar approach, where they compared two different bend gestures inspired by console controllers and mouse and keyboard to control a 3D VE [5]. They found that, although participants preferred a device mapped similar to a console controller, users found it confusing when a physical bend direction did not align with the direction displayed on the screen [5]. Moreover, in the least preferred set, users were often found to be confused on which interaction to use and that the interface was restrictive in only allowing one command simultaneously [5].

Furthermore, the authors highlight that the most frequently used controls should be mapped to the most accessible part of the interface to avoid user fatigue and that if the functionality is not convenient enough, users will avoid using them [5].

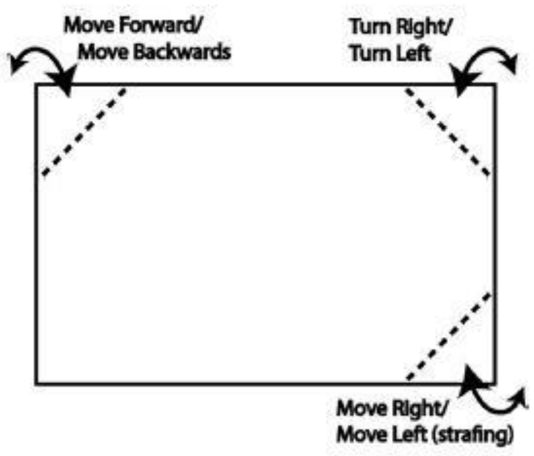


Figure 6: DUI - bend gestures of set A [5]

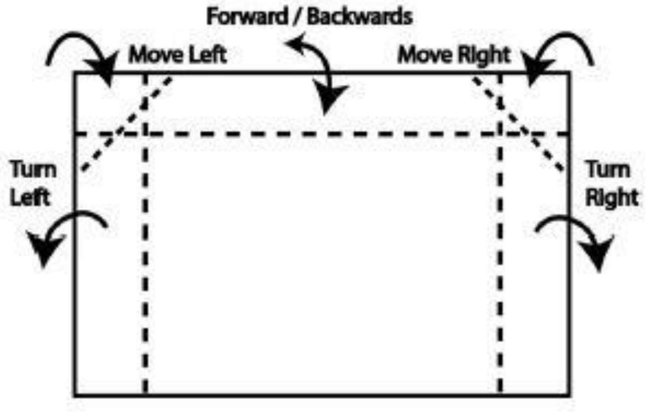


Figure 7: DUI - bend gestures of set B [5]

Another approach is to use gesture-based controllers, such as the leap motion, to navigate 3D VEs as explored by Fanini [6]. Fanini argues that the benefit of a gesture-based controller opposed to conventional keyboard and mouse is that the gesture-based controller can track specific joints of the human body in a physical 3D environment, thus enabling a computer to sense motion, orientation and 3D positioning [6]. In this way, the controllers can be accurately mapped according to how we interact in our physical world. Whereas this study does not present any user testing, Fanini still successfully emphasise the possible scalability and multi-purpose use of the system as it draws upon our learned skills of utilising our body to manipulate what is in front of us [6]. Outside the world of academics, some companies and individuals have built other alternatives to navigating a 3D VE, such as the SpaceMouse, TAC.TILES and 3D-Spheric-Mouse [17]–[19] However, I have been unable to find any credible resources or studies relating to these devices' usability and user experience or how they perform compared to a conventional keyboard and mouse. Where TAC.TILES may take some getting used to, given its many controllers, both SpaceMouse and 3D-Spheric-Mouse seem to try to bridge the gap between our physical world and the 3D VEs.

Background Analysis

These combined works, as presented above, provide a broad background in terms of what to consider when exploring a new interface to navigate 3D VEs using peoples' spatial understanding of the physical world. Where Burigat and Chittaro state that it takes a considerable amount of time to build spatial knowledge of a new environment, Ousland and Turcato's five key factors can help identify how I can design an interface to increase users' performance navigating 3D VEs [2], [7]. Moreover, per Ousland and Turcato's argument that peoples' spatial abilities relate to their performance navigating 3D VEs, although some will always excel over others, using peoples' spatial knowledge of the physical world may level the playing field [7]. Given that we all grew up learning to interact with the physical world around us, we have all become experts at navigating and interact with our physical environment. Think of the last time you effortlessly put the coffee brewer on while at the same time having an entirely focused conversation with a friend or relative. Years of training have taught us to interact with physical objects using our peripheral attention, meanwhile giving our full attention to a task more demanding of our attention.

Although per Ousland and Turcato's five key factors, I do not have direct control over the design of every 3D VE, it is possible to consider landmark- and route knowledge when building an interface [7]. A User's horizontal field of view (FoV) of 3D VEs, as seen through the monitor, is often up to 90 or 100 degrees, meaning that the remaining 260-270 degrees are outside of the FoV [20]. With a restricted FoV, users' ability to locate landmarks and plot routes between them may decrease, thus potentially also decreasing their performance navigating 3D VEs [7]. By drawing the digital world out into our physical world, users' can make use of their eyesight's FoV, which is close to 200 degrees [21]. This is also in line with Ousland and Turcato's suggestion of having two views of the environment, one standard and one overview map of the environment and also providing users' with cues for orientation and motion in the real world [7].

As for the metaphor of the five key factors by Ousland and Turcato, it is possible to consider multiple metaphors for different contexts of use [7]. However, to avoid restricting the interface to a subset of 3D applications and software, it ought to at least be capable of the flying metaphor as this is the only metaphor that provides users with 6DOF. Navigational aids, at least for 3D games, can be found both in the environment and the GUI [22]. While it may not always be applicable to implement navigational aids in the environment and GUI, it is possible to build a device with navigational aids in mind to increase user performance when navigating 3D VEs [2].

The core focus of this study revolves around the third step of Ousland and Turcato's five key factors, the design of the interaction device [7]. They argue that a special-purpose 3D input device is not required, as designing such an artefact to be both easy to use and effective in its task, is problematic and task-dependent [7]. The argument that a special-purpose 3D input device is not required is part of what many other researchers, including myself, aim to prove wrong by exploring promising technologies in pursuit of a suitable interface. Moreover, they emphasise the negative impact of delay on the user experience, where lag may cause users to become confused while navigating 3D VEs [7]. Although it is impossible to negate all computer delay entirely, a core advantage of TUIs is the double feedback loop, which can make the downsides of computer delay less harmful to the user experience [13]. Furthermore, by allowing users' to interact with a physical device directly, it falls on the designer to build a suitable interface for people to interact with, rather than users' having to learn the ins and outs of the abstraction layer of the device. In doing so, users would be able to interact with the artefact as they would any other physical object, using their spatial understanding of our physical world.

By considering the various levels of attention, as presented in the Interaction-Attention Continuum, an artefact could be built to provide different functionality when used differently or based on the task at hand [15]. No doubt, in replacing a conventional keyboard and mouse, certain advantages will forfeit where new ones will emerge. It is worth considering how combining certain functionalities with a level of attention could be made to replace some benefits of the keyboard and mouse. Furthermore, by exploring the expected and desired movements, in addition to how they could change at various levels of attention, it would be far easier to understand what the system ought to sense and also how to bridge the gap between the three [16]. Moreover, per the suggestion of Benford *et al.*, implementing rest spaces to avoid fatigue can by using a TUI be done physically, taking advantage of our peripheral vision and FoV to let the user know of its existence and how to get there [16], [21].

As for the many studies exploring alternative interfaces to navigate 3D VEs, they provide valuable data on both advantages and disadvantages with every alternative in addition to general considerations that ought to be made. Where ZeroN indeed have found a novel way of interacting with 3D VEs mid-air, they also faced both technological and interface legibility challenges [3]. It is worth considering how exploring an unknown form of interaction can bring forth new legibility challenges, shifting or challenging the expected movements of an interface. Moreover, as per Nguyen's work, it bears to note how size, sensitivity, scalability and noise can change the intended user experience [4]. Furthermore, it is possible to affect the overall user experience, whether people like the interface and what they expect from it by building the artefact around different metaphors [5]. Moreover, to avoid a mismatch, one should consider how the interface aligns with peoples' expectations, the placement of core functionality and how that changes peoples' expectancy of how the device is mean to be used [5].

By carefully considering mapping the artefact's functionality to peoples' spatial knowledge of the physical world, how to implement navigational aids and Ousland and Turcato's five key factors, a TUI can help bridge the gap between the expected, sensed and desired and offer interactions at various levels of attention.

CHAPTER 3

Methods & Implementation

Method

I conducted this study using the research through design approach, where the central knowledge-generation process revolves around ideating a design and building a prototype to contribute new knowledge to the world of academics [23]. In bringing forth the abstract ideas and concepts in the form of an artefact, participants can interact with-, observe, reflect and share in the research's understanding of these concepts and therefore also more easily able to discuss the ideas [23]. Moreover, a design approach requires critical thinking to produce a prototype for the real world and to consider real-world constraints which abstract concepts do not necessarily come across [23]. Furthermore, in making a concept tangible, participants may physically interact with the artefact and compare alternative solutions in a controlled environment, allowing for an in-moment experience and reflective feedback on the pros and cons of each alternative, their usability and the user experience. An iterative design process is a great way to ask questions that were not part of- or known when framing the initial problem, but that emerged throughout the research process [23]. Through this approach, I explore the following research question:

"*Can user-centric tangible user interfaces provide a useful alternative for navigating 3D virtual environments?*"

User-centric, in this context, means focusing on the user and their needs and desires [24]. It also relates to using peoples' spatial understanding of the physical world, where I explore a design that meets the user's spatial knowledge rather than the user having to facilitate and comprehend the inner workings of the interface. A *TUI*, as stated in the background of this thesis, is a physical artefact and a tangible representation of digital data, with direct control over its digital counterpart [13]. A *useful alternative* refers to not necessarily a better version of conventional options such as keyboard and mouse or console controllers, nor a replacement of said options, but rather an option worth further exploration. *Navigating* is, as previously stated, "*the process whereby people determine where they are, where everything else is, and how to get to particular objects or places…*", where in this context it specifically refers to doing so in a 3D VE [11]. Lastly, a 3D VE is a computer rendered environment that make use of the three axes, x, y and z to build complex images that, even though displayed on a 2D screen, fools our eyes to see them as 3D.

Whereas the research question is the most specific goal of this study, it also bears to note the underlying aims of the study. To best answer the research question a solid knowledge of peoples' spatial understanding of both the physical world and 3D VEs needs exploring. This aim is essential to attain knowledge revolving the relationship between the two perceptions and how a TUI can bridge the gap between them. Moreover, to explore participants' expected and desired movements of an interface, it is helpful to examine how inexperienced and experienced users navigate a 3D VE, how they differ and how it relates to their spatial knowledge. This study does not aim to find a suitable method for interacting with the 3D objects found in 3D VEs, nor is it aimed at producing a production-ready solution, but rather a prototype suitable to attain valuable new knowledge to the world of academics. Moreover, to allow for full control when designing the artefact, the type of 3D VEs explored is limited to those generated in the game engine Unity, meaning that the prototype has not been applied to CAD software, 3D games or other 3D applications. Furthermore, only abstract and simplistic environments were used and not any large-scale immersive environments to avoid sophisticated navigational aids located in the environment.

Ethics

This study complies with the Guidelines of the ethical review process of The University of Queensland and the National Statement on Ethical Conduct in Human Research under approval number 2018002067 as provided by the University (see appendices A-

C). Moreover, participants were informed of their right to withdraw at any time, before, under, or after participation.

Participants

Participants were selected based on the following two criteria:

1. *(Non-users)* People who have no previous experience using a 3D software;
2. *(Regular users)* People with limited experience using 3D software, preferably less than or equal to four years, who either actively use or have previously used 3D software.

These criteria were chosen, first and foremost to ensure two different points of view, and secondly, to avoid any deeply rooted biases from highly skilled professionals. Participants in the former group *(non-users)* provide value through their ability to review an interface's usability based on their conceptualisation of a 3D virtual environment based on their spatial knowledge of the physical world, rather than what has been taught. The latter group provide value through software familiarity, a generalised understanding of 3D virtual environments, and a frame of reference which allows them to critically review interfaces according to their efficiency in performing desired tasks. A limit of four years of experience was set as a participant with four years of experience would be able to have a bachelor's degree in their field and possibly some industry experience. The reason of which more experienced participants were not sought after is due to how lesser experienced people are arguably more susceptible to change and less likely to have found their preferred tools and routines due to being newcomers in their field. Any other demographics or psychographics were seen as non-relevant in terms of restricting participation for this study, as a wide selection of participants is seen as beneficial to understand different viewpoints.

Participants were recruited from a pool of personal connections and their extended network of relationships. These participants were contacted through face-to-face conversations, private online messages and some through word of mouth. A total of eight participants were recruited throughout the study, four participants in the first group *(non-users)* having no previous experience in using 3D software, and four others in the second group *(regular users)* having a varying degree of prior experience. Participants in this study are all current residents in Australia and have different cultural backgrounds from Europe, North America, Asia and Oceania. The overall pool of participants consists of four female participants and four male participants; where non-users consists of three female participants and one male participant, and regular users comprised of one female participant and three male participants. Participants' age spans between 20-40 years of age.

By not including participants with extensive experience in their fields, this study is limited by its group of participants by lacking an industry expert viewpoint and not being able to explore and use best practices from the industry. Moreover, the study does not include any elderly participants, whose computer- and 3D familiarity may be different from the selection of this group.

Prototype Introduction

Based on the background research of this thesis and the findings of the preliminary research, detailed in chapter four, I designed and built the prototype VE-SpaND (Virtual Environment Spatial Navigation Device). With VE-SpaND I set out to explore: How well the prototype aligned with participants spatial knowledge of both the physical world and 3D VEs; How it compares to conventional keyboard and mouse; Whether it helps users better understand their position in the 3D VE and if it is a useful alternative to navigating 3D VEs.

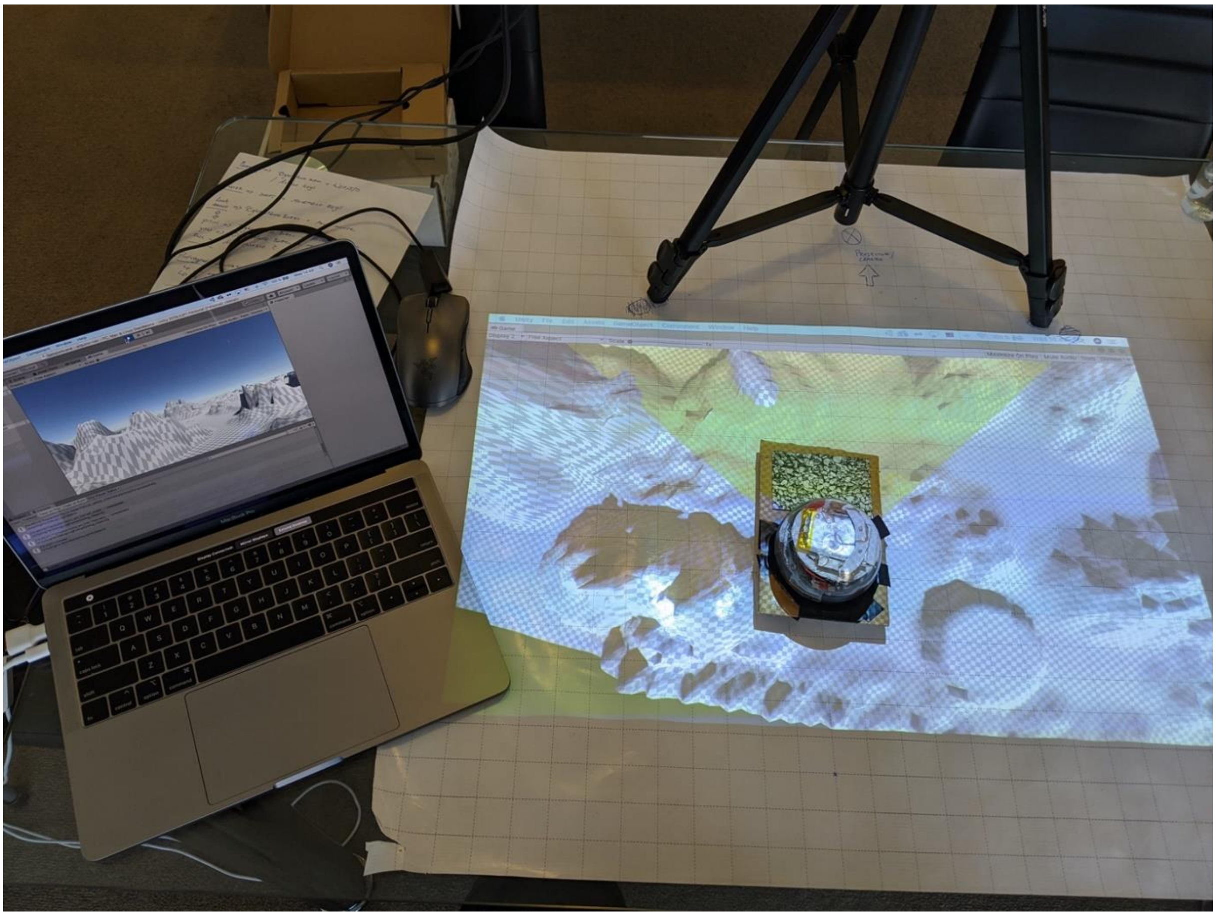


Figure 8: VE-SpaND connected to a Macbook Pro

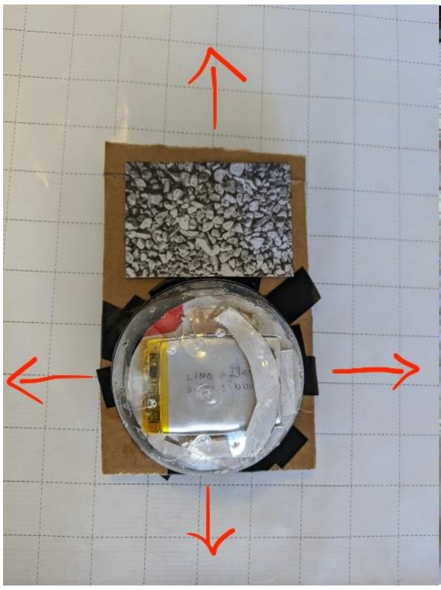
VE-SpaND is a TUI that acts as a physical representation of the primary virtual camera in Unity. The image above (Figure 8) displays two virtual cameras, the primary camera on the screen of the MacBook Pro and the secondary camera projected onto the table. VE-SpaND can be broken down into two parts, the physical controller as seen laying on the table, and the display- and tracking device, pointing down from above. Referring back to Ishii's explanation of TUIs, using the MVC principle, the physical controller is both the controller as well as the tangible representation of the view, where the projected- and MacBook Pro screens are both intangible representations of the view [13]. The physical controller and the display- tracking device can both be further broken down into two subcategories each, where the physical controller consists of a sphere and a base and the display- tracking device consists of a projector and a physical camera. The two following sections on hardware & software and form & functionality further details the functionality of each component.

Form & Functionality

Figure 9: VE-SpaND physical controller base

Figure 10: VE-SpaND physical controller sphere

The physical controller of VE-SpaND, as previously mentioned, consists of a base (Figure 9) and a sphere (Figure 10). The base has been built using cardboard and black electrician tape, forming a sunk pit to place to the sphere in, to avoid it rolling away. Moreover, a fiducial marker was attached on the base to allow the physical camera to track its position when moved in different directions on the table. The sphere was built using a plastic Christmas bulb, cut open to place the necessary electronics inside. Using a plastic ball and cardboard to construct the prototype was not the intention, as there exist better materials suited for its purpose that would provide a better user experience and more sturdy construction. However, due to restricted workshop access as a result of COVID-19 restrictions, I had to make do with whatever I could get my hands on. Despite this, In the end, I was successful in constructing a prototype using these materials that were capable of attaining research value.



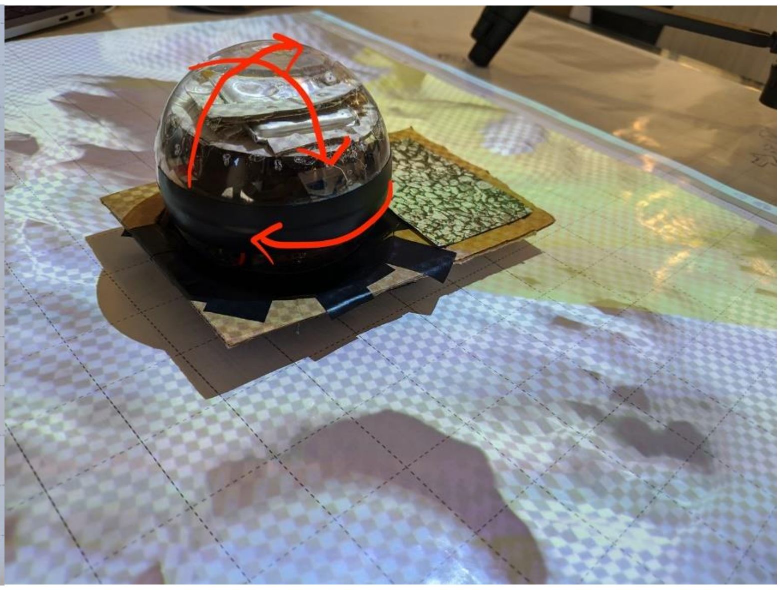


Figure 11: VE-SpaND base movement capabilities

Figure 12: VE-SpaND sphere movement capabilities

The sphere and base of the physical controller provide users with a comprehensive set of interactions. Users can move the base (Figure 11) in any horizontal direction, which in turn will drive the primary virtual camera in the same direction. The further away from the centre, users move the physical controller, the more velocity it picks up going in that direction. When users run the physical controller to the middle, all movement stops until they again reach a certain distance from the centre. Moreover, they can interact with the sphere (Figure 12) to rotate the primary virtual camera in any of the three axes, x, y and z (roll, pitch and yaw). Although the primary virtual camera will turn when the sphere is rotated, this rotation will not interfere with the angle of the base, as the base will always keep level with the table. Furthermore, the rotation of the sphere will hold its position until it is rotated to a different angle. When users rotate the sphere on the x and y axes, they will rotate with a one-to-one relationship, where 360 degrees in the physical world is equivalent of 360 degrees in the 3D VE. As for the z-axis, when users reach a certain threshold, the rotation will keep going until the sphere is brought back from that threshold. Whereas the intention was to implement functionality for vertical movement by pressing down and lifting it slightly up, I did not find a reliable method of doing so with the electronics and materials available to me.

Hardware & Software

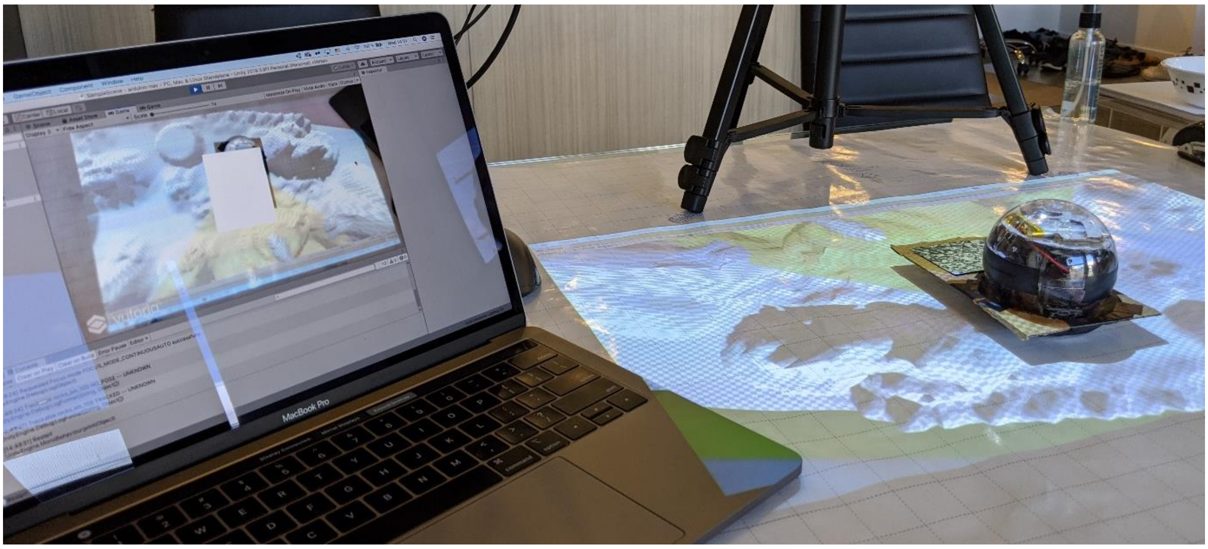


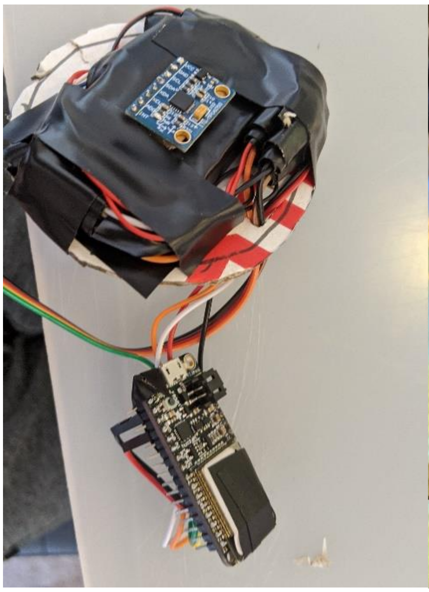
Figure 13: Unity tracking the fiducial marker. The white square on the screen shows the marker being tracked

VE-SpaND utilises a Logitech C9-series web camera and the Unity library Vuforia to track the position of the fiducial marker attached to the physical controller (Figure 13). The web camera is placed on top of an Asus projector and aligned to track the physical controller in the same area as the projector projects. Moreover, the projector and web camera that together make up the display- tracking device is placed opposite to the user, pointing down from above, giving the user more available space (Figure 14 & 15).

Figure 14: Display- tracking device

Figure 15: Projector setup

The sphere of the physical controller contains an MPU-6050 3-axis gyroscope and accelerometer, an Adafruit Huzzah32 microcontroller and a 3.7v 1500mAh LiPo battery (Figure 16 & 17). The Huzzah32 utilises the MPU6050_tockn library to retrieve rotational data from the accelerometer which it processes locally before sending the results over Bluetooth to a 13' 2019 edition Macbook Pro, where a Unity script catches the data and translates it to data suitable for the 3D VE.



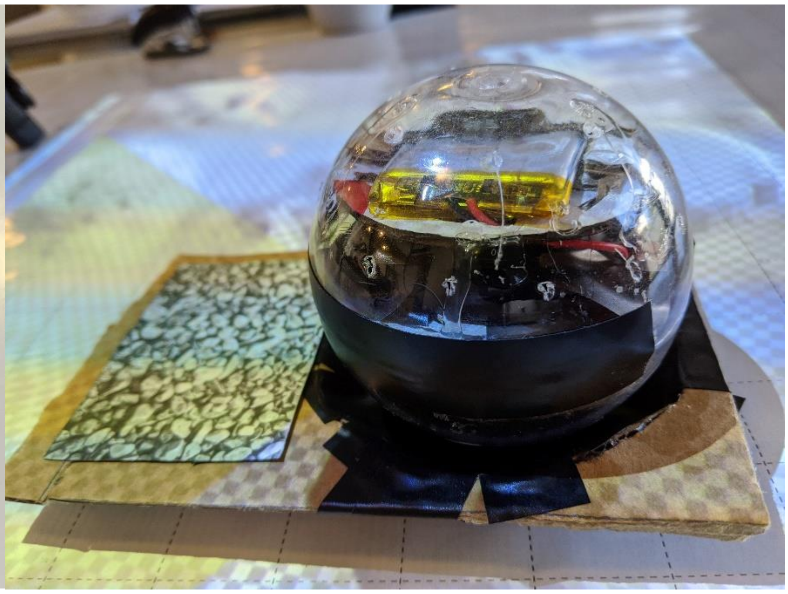


Figure 16: Huzzah32 and MPU-6050

Figure 17: Side-view of Physical controller with a battery in the top compartment, MPU-6050 in the middle compartment and Huzzah32 in the bottom compartment

Process

Throughout this study, data was collected in two steps, first through the preliminary research and secondly through prototype user testing. For the preliminary research, I set up a two-part semi-structured interactive interview with participant observation and a speak-aloud protocol, designed around participants interacting with the 3D software Unity using regular keyboard and mouse (see appendices D-F). As for the prototype test, due to COVID-19 restrictions, I opted to conduct two separate studies, in-person and remote. To the extent it was possible, I held in-person user tests to let participants interact with the physical prototype. Where an in-person study was deemed unethical, or against restrictions, I sent a folder containing video footage of the prototype and had participants answer questions from remote (see appendices G-I).

Preliminary Research

The preliminary research was set up as a qualitative study to explore participants' spatial understanding of the physical world, 3D VEs and how they relate to each other. Because spatial knowledge is abstract and may be challenging to put into words, I thought it best to conduct the study as an interactive interview where participants could use physical shapes to elaborate on their perception. Moreover, as spatial knowledge is based on our learned experience, that is unique to the individual, a semi-structured open-ended interview would allow for chasing down new leads as they appear [25]. Furthermore, to understand participants' thought pattern, choices and struggles when navigating a 3D VE, I used the speak aloud protocol so that the users' thoughts could be recorded. Moreover, I set up a camera to videotape the participants' hands as they interacted with both the physical shapes and the computer when navigating the 3D VE as not all data would come through using audio recordings alone. However, all video footage was lost while transferring it to the computer.

For the preliminary research, I had most participants interact with Unity using a Microsoft Surface Pro 4. However, as the computer broke midway through, a 13' 2019 edition Macbook Pro was used for the rest of the study. This change may have affected participants' ability to navigate the 3D VE as the Surface Pro used a Norwegian QWERTY keyboard and the Macbook Pro a US-international QWERTY keyboard. Moreover, both the screen sizes and pixel ratios of both machines are different from each other, which may have given users on one computer a better screen resolution and overview than others. Furthermore, the difference between an Apple and Windows device may be confusing to some, as the modifier keys are different on both systems. The effects of changing the computer midway through are unknown, but not likely to have any significant impact on the study outcomes. In both instances, users were handed a Razer

Lancehead mouse to interact with as their primary pointer device in combination with the built-in keyboard of the computer.

To ensure better communication between myself and the interviewees' I used the terminology *3D space*, *3D environment* and *3D objects* to distinguish between the elements seen on screen. Moreover, to clearly connect these elements to those of our physical world to avoid confusion, I used an analogy for each, where the *3D environment* was the equivalent of Earth or the ground we stand on, 3D space to the air around us or the actual space engulfing Earth, and 3D objects as the things we see around us.

As an introduction to the interview, I asked participants about their experience with 3D VEs of any kind. Moreover, I had regular users respond to their experience related explicitly to 3D software and the input devices of which they were familiar or had tried. I included these questions to get a frame of reference for each participant when analysing the rest of the data afterwards, to be better able to evaluate each participant's response.

The first part of the interview revolved around the participants' ability to navigate a 3D VE and their spatial understanding of the 3D VE, our physical world and how they relate. I introduced them to the game engine Unity and had them perform a set of tasks in the environment (Figure 18), five menial and two more complex tasks. I prompted participants to speak out loud their train of thought as they attempted these tasks, which I then combined with an observation of their actions.

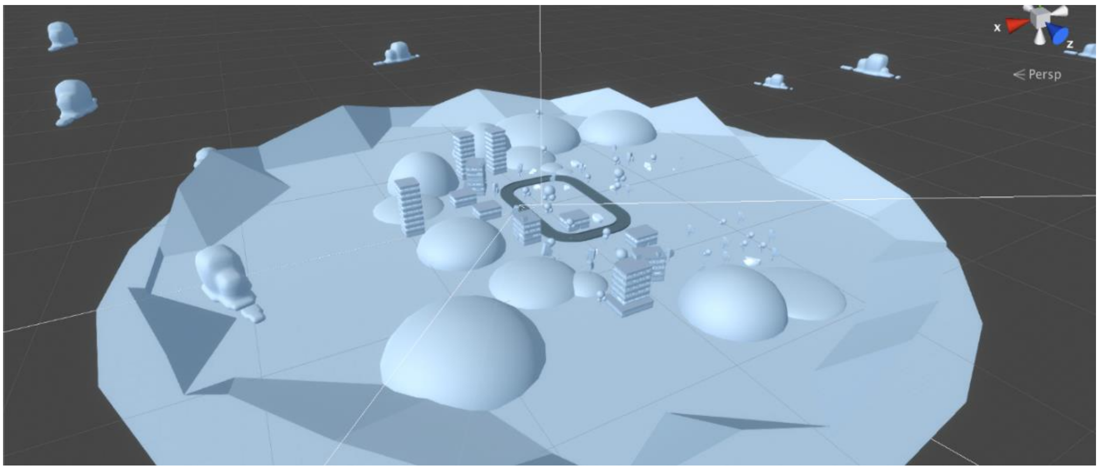


Figure 18: 3D Environment in Unity [26]

The first five tasks prompted participants' to locate and use core Unity navigational interactions, such as zoom, rotation and pan. For the non-users, these tasks would give me insight into whether the interface made sense to them, where they struggled and if some interactions were more difficult to find than others. For the regular users, I aimed to observe whether they used any methods unknown to me and if they shared in using the same approach. The two more complex tasks asked users to navigate to specific locations in the environment. Through these tasks, I could observe how the non-users wanted to use- and how they ended up using the interface to navigate. Moreover, I could see which interactions or interaction combinations they found to be difficult and what made sense to them. As for the regular users, I set out to observe other faster methods of navigating the 3D VE. Through this information, I could see the strengths and weaknesses of the conventional keyboard and mouse to perform these tasks, what confuses the users and ideal methods of navigation that I could build a new interface around.

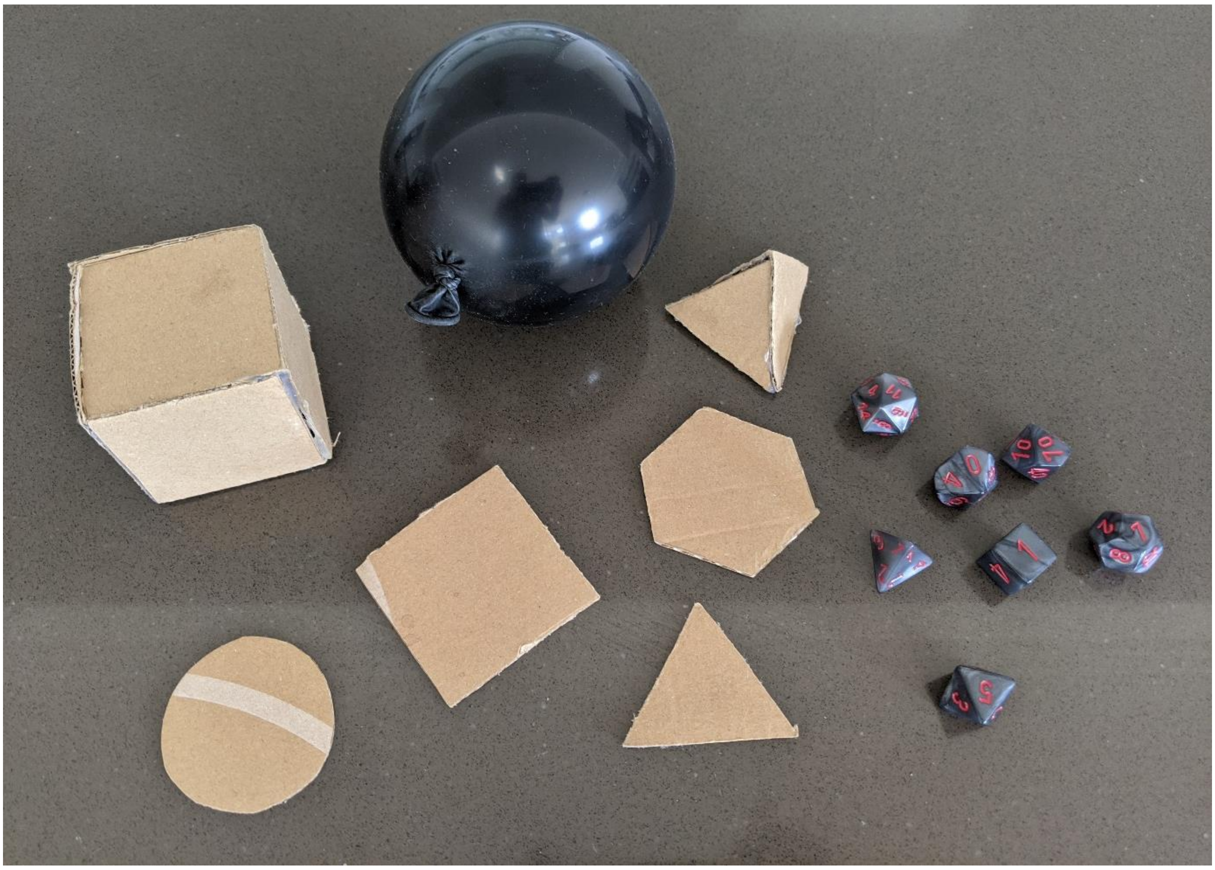


Figure 19: The shapes users were given to explain their spatial understanding

After the participants completed these seven tasks, I followed up with a series of questions related to their experience, starting with any issues they encountered performing these tasks. Moreover, I had participants interact with- and explain their spatial understanding of the 3D *environment* and *space* using a set of physical shapes (Figure 19). The purpose of these shapes was for participants to more easily be able to demonstrate their spatial knowledge. Furthermore, I had participants use the same forms to express their spatial understanding of our physical world, the *space*, *environment* and *objects* around us. Then I asked participants to pick a shape that would act as an interface instead of the mouse and keyboard and demonstrate how they would like to interact with the device. By combining the knowledge of their spatial understanding of the physical world and 3D VEs, I could analyse how they relate to each other for every participant and how to bridge the gap between them.

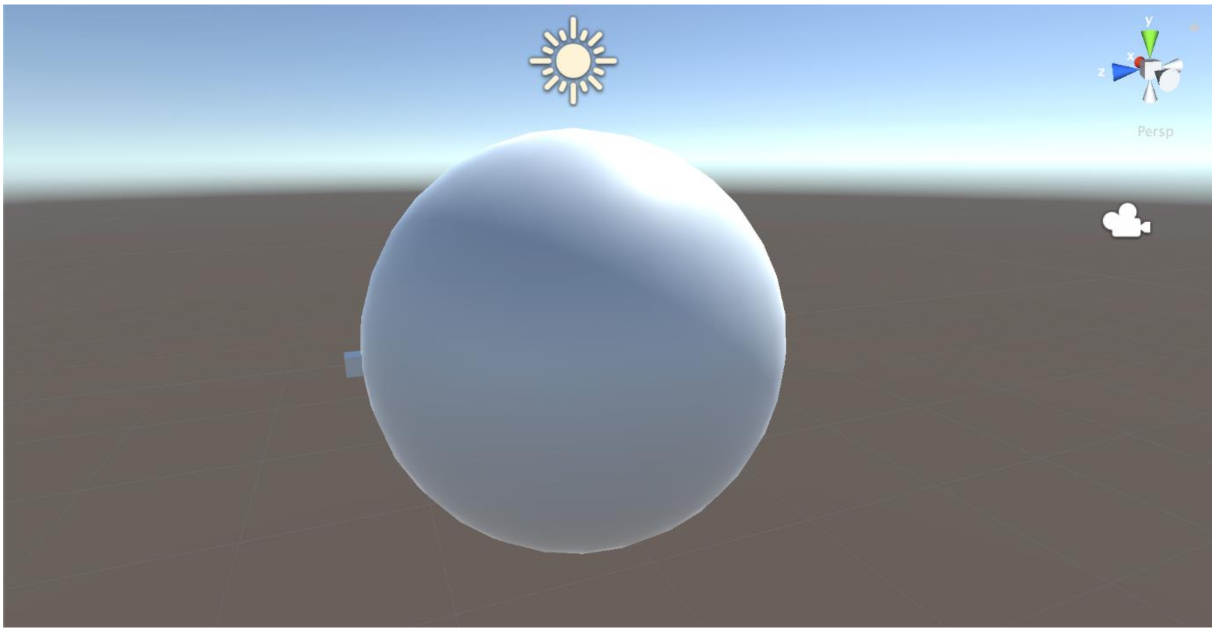


Figure 20: 3D Model in Unity

The second part of the interview revolved around the participants' ability to navigate a 3D VE around a single *3D model* (Figure 20) and their spatial understanding of the *3D model* and how it relates to our physical world. I had users perform two complex navigational tasks related to navigating around- and positioning themselves in a specific location on the sphere. Here too, I prompted participants to speak out loud their thoughts as they proceeded with the tasks. After the participants completed the tasks, I asked them whether they had any issues navigating and again to pick a shape from the physical objects and demonstrate how they would like to interact with the *3D model*. These tasks and questions would provide insight into the difference in how participants chose to navigate when faced with a single *3D object* versus a *3D environment*. Lastly, I gave the participants a chance to explain their ideal method to interact with a 3D VE if there existed no limitations what so ever. This last question would provide insight into the participants desired actions and not be restricted by the physical shapes from before or having to account for how it would be technically feasible and affordable.

The responses from the preliminary research were then analysed to find similarities and outliers in the data, which, in combination with the background research could form the basis for a new TUI using peoples' spatial understanding of both the physical world and 3D VEs.

Prototype User Testing

The prototype user test was, similarly to the preliminary research, set up as a qualitative study, where I aimed to explore whether the device was built according to participants' spatial knowledge and if it provided a useful alternative to navigate 3D VEs. Due to COVID-19 restrictions, I was unable to conduct all user tests in-person. Therefore, where it was possible to do so, I conducted user tests in-person and where in-person testing was deemed unethical, I held them remotely. The in-person user tests consisted of a semi-structured open-ended interview where I gave participants a set of tasks and had them respond to their experience afterwards. As for the remote interview, I sent participants two videos to watch that displayed the tasks being carried out by myself and then had them respond to the questions provided.

At first, I had participants interact with the environment in Unity that they had navigated in the preliminary research, to give them a frame of reference when comparing the prototype to a conventional keyboard and mouse. Participants were asked to perform a series of core navigational tasks in Unity and then move freely around until they felt comfortable with the interface. In revisiting these interactions, users would have the interface and its capabilities fresh in mind, allowing them to better reflect on the pros and cons of the conventional keyboard and mouse. From there, I asked a couple of questions related to the mouse and keyboard, how it felt to navigate using them and if they were confused by anything. These questions were asked to bring forth an unbiased view of the conventional interface before introducing my prototype.

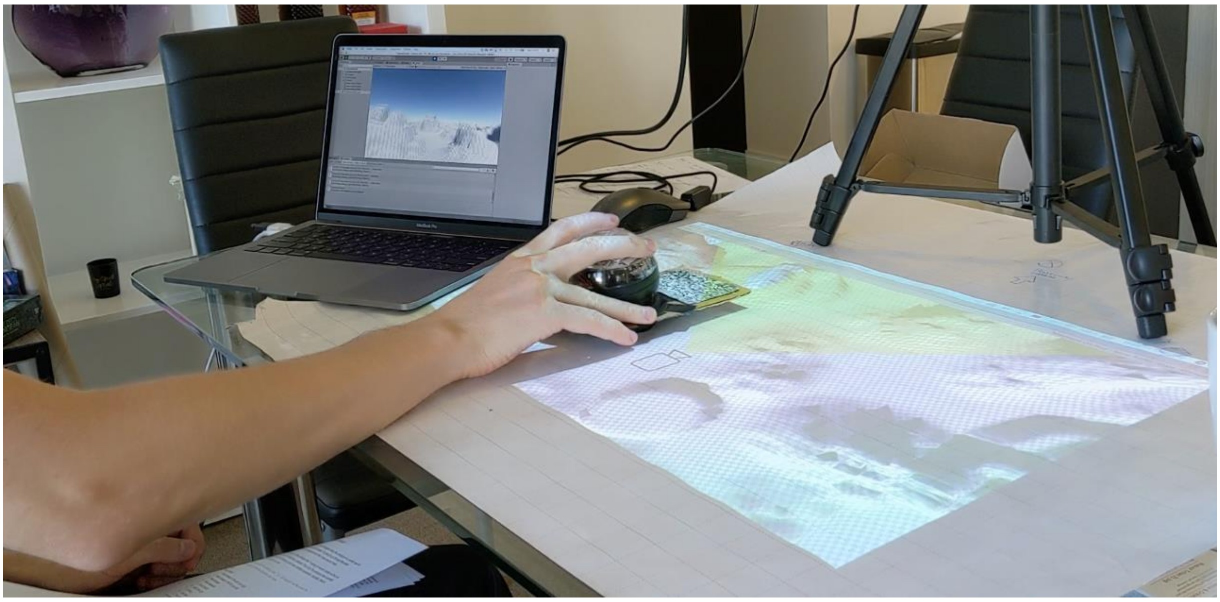


Figure 21: Person interacting with VE-SpaND

After users were comfortable interacting with Unity using keyboard and mouse, I introduced them to the prototype VE-SpaND, where users were asked to perform the same tasks as with the keyboard and mouse (Figure 21). In repeating the same tasks with the prototype, users would be able to compare the alternatives based on each interaction. Then, users were again asked to move around in the environment (Figure 22) until they felt comfortable navigating with the device. In doing so, they would explore the prototype in a free moving form and get a feeling of the overall user experience of the prototype.

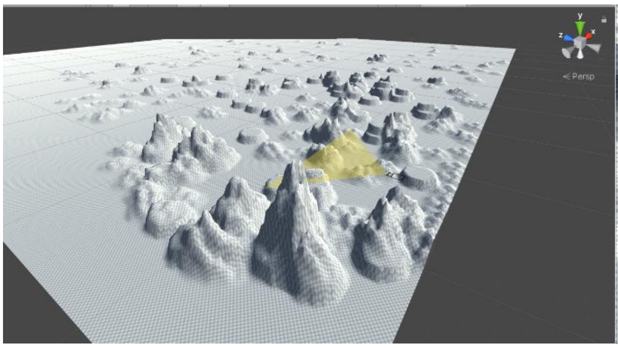


Figure 22: VE-SpaND test 3D VE

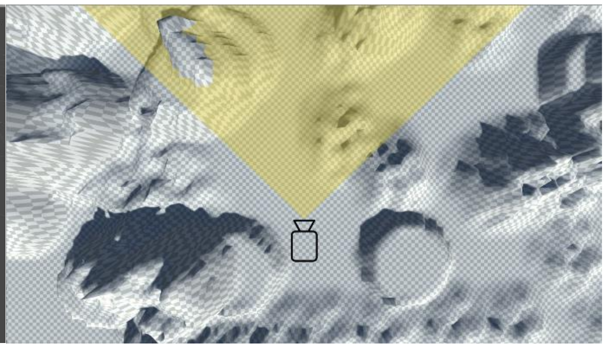


Figure 23: VE-SpaND top-down table view

Once the users felt comfortable navigating the 3D VE using both VE-SpaND and keyboard and mouse, I proceeded with the core interview. The first couple of questions were equal to those asked after participants interacted with the 3D VE using keyboard and mouse, how it felt to navigate and if something was confusing to them. I asked these questions to see if there was an immediate difference in responses between the two alternatives. After having asked the duplicate questions, I asked straight up which option they would prefer using to navigate a 3D VE and why. This question would make users choose an alternative based on their experience using both before reflecting on them. The next question asked participants to evaluate the best use for VE-SpaND, whether it was by itself or in combination with keyboard and or mouse. Through this question, I aimed to find which functionality participants felt VE-SpaND lacked and whether it should be combined with existing alternatives or take on their functionality. As for the following questions, I had users reflect on various aspects of both options, benefits of each alternative, how they help users learn to navigate a 3D VE and how they help users understand their position. These questions would further have participants evaluate aspects of both options and how they relate to each other. As for the last questions, I asked users if they could change anything on the prototype, what it would be. This question was aimed to dig deeper into VE-SpaND's issues and to use the thoughts that had emerged from the previous questions to criticise the prototype.

COVID-19 Disclaimer

It bears to note that during the proceedings of this thesis, COVID-19 was officially declared, by the World Health Organization, a world pandemic. To stop the virus from spreading a set of strict restrictions were put in place by the Australian government as well as most countries over the world that limited non-essential outings and physical, social interactions. Therefore, to continue any face-to-face physical studies would be unethical, potentially dangerous and forbidden by law, hence resulting in having to compromise when determining methods of data gathering. With that said, some in-person research was conducted before COVID-19, and studies conducted with those who live in the same household were still permitted to be in-person. Moreover, in-person technical assistance was near impossible, and access to tools and equipment was severely limited. These limitations made building and user testing a physical prototype increasingly more difficult. As such, these restrictions and constraints explain some odd research- and design choices that otherwise would have been done differently to achieve better results.

CHAPTER 4

Findings

Preliminary Research

Introduction Questions

From the first question of the initial findings (see appendix D), I found that the regular users participating in this study have between one to just short of five years of experience, where most have between three to four years. As for 3D, in general, such as 3D games and VR, participants span from fifteen to thirty-four years of experience. Non-users, on the other hand, responded, having no experience using 3D software and everything from six months to twenty years of experience with 3D in general.

From the second question, which I asked only the regular users, given that no non-users had previous experience with 3D software, as per the intention when recruiting them, participants responded that they have previously used Unity, Maya, Unreal Engine, 3DMax and Blender. Every regular user had tried at least three different software, whereas one participant had tried five different software.

In terms of their input devices, regular users all rely on the conventional keyboard and mouse when working with 3D applications, where two users occasionally also used a drawing pad, and one had previously tried the SpaceMouse mentioned in the background research of this thesis. One participant highlighted the benefit of precision using a mouse; another said they did not know of any other solutions, and a third mentioned that keyboard and mouse is the cheapest option.

3D Environment Navigation Tasks

When asked to scroll in and out, all regular users went straight for the middle mouse button, where one participant mentioned that they believe it is the standard practice to use the middle mouse button to scroll. Moreover, every non-user also tried to use the middle mouse button to zoom. However, one participant first tried to use CTRL in combination with the middle mouse button to zoom. When asked why they did so, the participant said that some Adobe software requires the user to hold down CTRL to zoom. Another participant stated that it is the conventional method of zooming in and out in games.

As for turning 360 degrees to the left and right, two regular users went for the right-click; one tried to use the mouse but pressed the wrong button a few times before doing it right, and the fourth used the axes in the top-right corner of Unity. All but one non-user struggled somewhat to find the correct button to rotate, where the one who made it on the first try mentioned how it is similar to how games do it. Moreover, One non-user became confused about their position when rotating.

From the third task, three regular users used the right mouse button to rotate 360 degrees up and down, and the last used a combination of the axes in the Unity GUI and the right mouse button. Moreover, two participants commented on the interaction, where the first (RU2) said "*That's a bit tricky.*", "*I don't think I ever really do that.*", and the second one (RU3) said "*…it's not that common.*", "*… you don't really need to do that as much*.". Two non-users had no issue performing the task, where a third struggled to the extent that I had to tell them how. The last non-user tried first to use the middle mouse button before they realised it was wrong and then decided to use the right mouse button.

When asked to pan sideways, all regular users held down the right mouse button and used it in combination with the A and D keys, where one participant also used the shift key to move faster. As for the non-users, two participants managed to perform the task without issue, holding down the middle mouse button, where one had learned how to do it from clicking the wrong button in a previous task. A third non-user panned using the arrow keys on the keyboard, and a fourth could not figure out how to do it till the point I stepped in and told them how.

As for panning vertically, one regular user used the axes in the Unity GUI, another used E and Q while holding down the right mouse button. A third participant could not figure out how to do it but commented that they usually just flew up instead and then looked down. The method of the last user does not come through in the audio recording. Non-user, on the other hand, faced some issues trying to pan vertically, where only one succeeded at the task, and the other ones could not figure it out.

In the sixth task, participants were asked to navigate to one of the mountains in the 3D VE and face inwards. Three regular users used a combination of the right mouse button and WASD keys to fly to their position, where one used the ALT key to rotate rather than the mouse as the other two did. The last regular user scrolled out and panned sideways until they could find the object they were looking for which they then selected and pressed F to move to it. As for the non-users, three participants used the scroll wheel to zoom in towards the location and the right mouse button to rotate their direction. The last non-user panned using the middle mouse button, turned with the right mouse button and moved closer, utilising the arrow keys.

As for the seventh task, participants were asked to locate a cart on the race track. Two regular users chose to look for the cart in the file hierarchy and double click it to move directly to it. Another used the same method as before, holding down the right mouse button in combination with the WASD keys. The last regular user zoomed out to get a better overview of the track, then proceeded to zoom in until the cart could be seen, clicked the cart then pressed F to move straight to it. Three non-users used a combination of panning, rotation and scrolling to arrive at the position, where one also used the arrow keys occasionally. The last non-user did not use the scroll wheel to move in closer as the others, but instead the arrow buttons.

Post-Navigation Questions

In response to if they encountered any issues while navigating the 3D VE, each regular user mentioned a separate issue. One did not remember the keys as well but said that they would quickly catch up. Another noted that rotating over their head felt strange. A third forgot how to pan vertically, and the fourth got mixed up in terms of controlling where the camera looks in the scene due to familiarity with other software. One non-user mentioned how it was difficult to grasp how the speed of the camera worked when you get in closer versus further away, and that it was difficult to remember that panning was the middle mouse button. Another said they did not expect that rotating was located on the right mouse button and that panning felt natural as it was similar to other tools they used. A third non-user mentioned that it was difficult to move in straight lines, as in the camera is fixed on a distant point in the environment which is difficult to grasp where is, that determines how you move. The fourth non-user noted that the difficult thing was to get to know what is what and remembering what they have to click. Moreover, the same participant said they got attached to just using the mouse and did not think much of how to use the keyboard.

When asked what shape best represents the *3D space*, two regular users chose a cube, where one said that anything can be made from cubes and that it has the three dimensions easily identified. The second one (RU4) who chose a cube noted that "*…the outside space I've never really worried about…"* but that they could put textures on the inside of the box. A third regular user said they would pick a 90-degree triangle, as they only need the x-, y- and z-axis. The last regular user chose a sphere as they felt it looked the most like space. One non-user chose the sphere but stated it was because it was the largest object of those available, given that it is impossible to see the actual shape of space. Moreover, the same participant said that if they were to use general computer knowledge, they would choose a cube. The second non-user chose the sphere as it resembled a globe or a planet. The third non-user chose a twelve-sided die, and the fourth chose a twenty-sided die. Both gave similar reasoning, where it is about knowing which side of the sphere you are on and that more sides give more possible directions to move.

As for choosing a shape to represent the *3D environment*, one regular user said a flat square as the environment in the scene was on a plane. Another would pick a cube as most things can be made from cubes, and a third would choose a sphere as they always try to relate the virtual world to the physical world. Two non-users chose shapes to be as close to the actual environment as possible, where one picked a flat circle, and the other narrowed it down to three shapes, flat circle, flat hexagon and a sphere. A third non-user picked the 20-sided die as it was a more detailed version of the 12-sided die the user picked for the previous question. The last participant would choose a sphere as it would allow them to interact with it using panning, moving, scaling and rotation, just like in sci-fi.

For the fourth post-navigation question, participants were asked to pick a shape that best represents space, as in the space engulfing our Earth. All four regular users chose a cube, where one (RU3) said: "*…everything 3D is like [a] cube taking up space…*", and another noted that we are inside of the cube. A third regular user mentioned their first thought was a sphere, but that a cube would give them the x, y and z-axis. As for the non-users, one participant chose the sphere, explaining that we are all in different spheres or bubbles, such as the house we were sitting in at that moment. Another said that they would not choose any shape as space is not one particular shape. A third would choose the largest shape as there is no perfect representation for space and that its more about the volume. This participant (NU2) further said: "*…space in my head can be an infinite amount providing you can keep going in that direction. Whereas when you are starting to put objects into that space, that's when it starts to differentiate because this takes up x amount of space…*". The shape of the fourth non-user (NU1) does not come through in the audio recording, but they stated that "*…the way humans interact with space is usually not very three-dimensional…*". "*…you take the lift or stairs to go up…*" and "*…most of interactions is on [the] horizontal plan or a vertical plan…*".

When asked to pick a shape to represent physical 3D objects, three regular users would choose a cube, where one stated that one could combine a lot of cubes to make any object. One of these three participants also mentioned that if the object were round, they would choose a sphere instead. The response from the fourth regular user does not come through in the audio recording. As for the non-users, three participants chose a square, two cubes and one rectangle, where the one choosing the rectangle said that most objects could fall under a rectangle. One of the non-users (NU3) who chose a cube said: "*…just looking at things around me, there's more squared things than there are round* *things*.”. The other participant that chose a cube referred to the old 2D games and how one could technically create a sphere out of tiny cubes, but then changed their mind to triangles as a triangle would allow for more angles. The last non-user (NU4) chose a sphere, stating that: “…*here in our real world a round ball is a good representation because all perspectives no matter where you are on the ball will work based on your distance to things, whereas on the screen its nice to have something to understand perspective with*.”.

In the sixth post-navigation question, I asked participants to choose an object to use as a controller instead of a mouse and keyboard. Two regular users chose a sphere, as it fits nicely into one hand and because it can be rotated and left in that rotation, whereas cubes or triangles will have to be moved in 90-degrees each time. The other two regular users chose a cube as it could potentially do the most things and because it has edges to understand the orientation which a sphere could not. Moreover, one of the participants highlights how a square would stay exactly where you left it. Three non-users chose the sphere, saying that it is a more smooth way to navigate, fits better in the palm of your hand and gives much flexibility and allows for multiple interactions. The last non-user chose a 12-sided die, referring back to being able to move in straight lines.

3D Model Navigation Tasks

At this point, participants were asked to open up another file, containing only one single object and then navigate around the object till they found a small cube attached to it and position themselves in front of the cube. One regular user used the ALT key and the left mouse button to rotate in combination with the middle mouse button to pan and zoom to locate the cube. A second one used a combination of panning and rotating using the middle- and right mouse button and the third tried to anchor to the object, but could not remember how so they ended up using the right mouse button in combination with the WASD keys. How the fourth regular user navigated did not come through in the audio recording. Two non-users chose to locate the cube using a combination of the right mouse button to rotate and the middle mouse button to pan. Another non-user opted for the hand tool in Unity to pan sideways and rotated using the right mouse button. The last participant used a combination of zooming with the scroll wheel, the OPTION key with the left mouse button to rotate and arrow keys to pan further.

When trying to rotate around the object, one regular user chose to use the WASD keys with the right mouse button and had to readjust the camera angle a couple of times which they found cumbersome. Another regular user zoomed out with the scroll wheel and used the ALT key with the left mouse button to rotate around the object. A third user started to glitch inside of the object and had to zoom out, then rotated and panned using the middle- and right mouse buttons. Three non-users used a combination of panning and rotating using the middle- and right mouse buttons, whereas the last used the CMD and left mouse button in addition to the arrow keys to go around the object.

Post-Navigation Questions

In terms of what issues participants faced when performing the two tasks, one regular user said that having to lift and put down the mouse over and over became annoying. Another stated that the rotation does not follow the object closely, and they forgot how to rotate for a second. A third regular user was zoomed in to close and did not know what they were looking for anymore, and that there is a faster way to rotate around, but they could not remember it. The last regular user knew it was possible to lock onto the object and rotate, but could not remember how. One non-user said that it did not feel smooth and that they lost their position trying to go around. Moreover, they felt that rotating and panning to get around was a hassle. Another non-user said it was clunky and time-consuming, where a third said it did not flow naturally. The last participant said that the perspective changes when they just wanted to go in a straight line between two points.

As for an object to use instead of keyboard and mouse to interact with the model, two regular users chose a cube, one a sphere and the last one would pick something the resembled the object on the screen, but said that a 20-sided die would be a nice middle ground. All non-users chose the sphere, where one participant said its because the object on the screen is a sphere, and another stated that the sphere allows for more flexibility.

As the last question, I asked participants how they would like to navigate a 3D VE if there existed no limitations. Three regular users mentioned they would like to use Virtual Reality as it would position them inside of the 3D environment, which would make it easier to visualise the area. Moreover, one of them said they would use it in combination with some type of glove for touch interactions, to manipulate things with their hands. One of them also said that it would open up many buttons on the keyboard and mouse as you no longer would need it to look around. The last regular user (RU4) said they would like a direct link to their mind, as "*…the most difficult thing about working … in a 3D environment and working with different engines, is just getting used to the different tools, in general, because they take a while to learn.*". The participant further said "*…I'd rather have it respond to how I'm doing. Let the tool respond to what I'm doing, instead of trying to figure out what someone else have made a tool like.*". As for non-users, one said they would like to use a hologram that they could touch. Another said they would like to use their hands because they can control that and know how it works already. The third non-user said a screen was the most accessible, but that VR would be exciting as you could pick up and place things where you wanted them. The last non-user (NU2) said that "*The whole idea of telepathy and telekinesis is. I find it very interesting.*", "*…then you don't really have to try and get a physical object to do what you hope is going to happen. Instead, you can literally just think I want this to rotate around*.". Moreover, the same participant said: "*I do like to touch though even if it's just to understand better. Because it's all good that I can think about something like I can think about … the fur on like a dog. I can think all I want, but unless I actually touch it, I don't really know what it is.*".

TUI prototype

The findings in this section have been combined from the remote and in-person user testing. The participants are the same people that took part in the preliminary research, although one regular user was unable to participate at this time. Three participants took part in the in-person user test, one regular user and two non-users, and four participants participated remotely, two regular users and two non-users.

After the participants had performed- or viewed the video of the first tasks, which revolved around navigating the 3D VE using a keyboard and mouse, I asked them how it felt to navigate using that interface. All regular users said it felt normal or fine as the interface and interactions are similar to what they are used and other software. One regular user mentioned that the acceleration was a bit annoying as they had no control over the specific speeds, but that, in general, it did not feel much different from gaming. A for the non-users, two of them noted that it is a standard way to navigate across software, although one said they were not comfortable using any 3D software. Another non-user mentioned that they felt they had no control and the last participant said it was more efficient now when they used both the keyboard and mouse instead of only one of them at a time. However, the same participant also noted that they had some issues remembering how to move forward, up and to the side, but that it probably would become more natural over time.

In the second question, participants were asked if they found anything confusing or unnatural when navigating using mouse and keyboard. One regular user noted that not remembering the keyboard shortcuts could cause some issues, where another said that doing fine-manoeuvres with the WASD keys while holding down the right mouse button could be somewhat tricky. The third regular user said that it felt unnatural to pick up the mouse and reposition it to do sharp- or long turns. One non-user that it was challenging to move backwards and forwards in straight lines and another asked if it was possible to pull out a shortcut map to help with remembering. A third non-user said they would need a lot of guidance and tutorials to get started and that the interactions felt complex. Also, the same person said that the way the keyboard and mouse work do not map well with the way the human mind thinks of navigating a 3D space. The last non-user mentioned that it felt strange to hold down both the right mouse button and move with the WASD keys, but that it also made sense to turn around and move at the same time.

However, the participant pointed out that holding down SHIFT to move faster moved to fast for them.

In terms of how participants felt it was to navigate using VE-SpaND, one regular user said it would take some getting used to and that the prototype seemed more like a tool. Another regular user said it they believe it would feel natural and nice, whereas the last regular user said it felt nice and smooth and that they only needed to use one hand. In contrast, the same participant noted, with the mouse and keyboard two hands are needed, and strange shortcuts are often required. As for the non-users, one participant mentioned that it looks relatively fluid, but that the lag between the prototype and pc would distract a lot. Also, the participant noted that it could benefit from an audio-visual barrier or edge to avoid users from venturing outside of the projected area. Another non-user mentioned that it felt better than the mouse and keyboard and that when they interacted with the prototype, they used movements they were used to from using the mouse. A third non-user said that it was a lot easier than a keyboard and mouse as they only had to focus on one thing and not to remember which functionality was on the mouse or keyboard. Moreover, they said it was much more intuitive in that if they wanted to go sideways, they push it sideways, and that up and down on the sphere makes them look up and down. The last non-user (NU1) said, "*This new way of navigation feels natural and maps to the way I would be thinking of navigating around a 3D space*.", and that moving on a 2D plane and use the sphere for navigating the 3rd dimension was very intuitive.

After having asked how it felt to navigate using VE-SpaND, participants were asked if anything felt confusing or unnatural to them. One regular user (RU1) said that they did not encounter any issues as it works the way they expected it to, stating that "*If you push it forward, you go forward. If you pull it to the right, then, surprise, you go to the right*." Another regular user noted that it looks delicate, but that they are unable to comment without holding the device. The same participant also said they were confused about how the range of movement is going to increase, as it seems limited. A third regular user (RU2) had a similar comment that "*Translation seems limited to a set area which would seem confusing to me as to how would work with an environment that grows larger as* *you build it*.". Furthermore, they mentioned that the action of rotating the sphere forwards to look down might cause the user to have to lift the wrist and arm of the table, making the operation uncomfortable. Also, they said that when rotating the prototype, they would have to keep rolling the ball to get a long rotation and that it would seem more comfortable to have a rotation limit that once reached would keep rotating and a button to reset the rotation. As for the non-users, one participant mentioned that they did not find anything confusing, but that the current state of the prototype was a bit wonky. Despite this, they also mentioned that they understood its purpose and that it felt quite natural to use. Another non-user noted that the sphere sat too loosely, making it too sensitive when moving the base around. A third non-user said nothing felt confusing and that it felt natural and intuitive to use, whereas the fourth mentioned that the projected size of the 3D VE was rather large and could be narrowed down.

In response to which alternative participants preferred to navigate a 3D VE, conventional keyboard and mouse or VE-SpaND, and why, one regular user chose keyboard and mouse as they were already familiar with it. Another would choose the prototype for an environment that does not expand or require lots of movement vertically. Otherwise, they would trust in the capabilities of the keyboard and mouse. The third regular user preferred the prototype, although the downside is the space required. The participant also made a note of VE-SpaND freeing up one hand and that they would not need to remember many shortcuts. One non-user picked keyboard and mouse due to familiarity with the interface but noted that with a bit of practice, they could learn to use the prototype quickly. Another non-user (NU1) said "*Definitely the prototype. It maps very well to the way I think of navigating a 3D space. The concepts of the mind go along with how the prototype works, whereas the keyboard and mouse would require specific training to get started*.". A third non-user chose the prototype as it is easier for them that have no previous experience, only one thing to focus on, and it just makes more sense to them. The last non-user (NU4) said: "*Apart from being a bit unstable, I think the prototype is better because it follows the natural perception of my mind."*.

When asked whether VE-SpaND would be most beneficial on its own or in combination with a keyboard and or mouse, RU1 said: "*…the whole point for me is to only use [the* *prototype]…"*, but that a mouse would still be required, as the current solution lack some features such as selecting objects. A second regular user felt it would do best in combination with a keyboard to access shortcuts, but that it would require the prototype to have a click functionality. The last regular user thought it would best be paired with a keyboard or another device that provided finer movements and something that added a Numpad style keyboard for quick access. All non-users also thought the prototype would be most beneficial in combination with a keyboard as the keyboard would provide extra functionality. However, one non-user mentioned that it would still be necessary with a touchpad or mouse to use the menus and click things. Another non-user suggested that specific modifier keys on the keyboard could alter the prototype's behaviour so that the sphere could control both rotation and zoom.

In the fifth and sixth question, I asked participants what benefits they saw with the prototype that a keyboard and mouse do not have and vice versa. All regular users mentioned the click functionality or precision of the mouse as its benefit that the prototype does not have. As for VE-SpaND, they said it was entertaining, brought all navigation controls to one hand and that they do not need to translate the action they would like to perform. RU1 further pointed out that "*[To] select objects within the scene is something I can imagine is hard with [the protype].",* and that the prototype would take up much additional space on the desktop. Furthermore, RU1 said that "*And also, if you already know the shortcuts on the keyboard, I think it will be easier to use. But that is only when you already know the shortcuts*.". One non-user mentioned that the current advantages of the mouse and keyboard are that they do not lag as much, that they provide more options, and do not require as much space. NU3 said that the benefit of VE-SpaND was that "*…it is only one thing to focus on. You don't have to divide your attention to both hands and two different tools.*". Moreover, NU3 also said that the mouse as of now was more stable but that they still would prefer the prototype as it made more sense to them. A third non-user mentioned that the mouse operates in 2D where the user has to think 3D, whereas the prototype operates in 3D and lets the user think in 3D. Moreover, the same participant noted that as of now, the mouse felt more smooth and take up far less space on the desktop. The last non-user said the prototype felt more intuitive and natural to use with their hands, whereas the mouse is more accessible, cheap, takes up less space and is familiar to most.

When asked which alternative they believe would be the better option for a beginner to learn to use a 3D software, all participants chose VE-SpaND. However, one regular user said, if you want to work professionally, some organisations may not accept the prototype as a medium, but that it might work as a stepping stone to learn 3D software. Another regular user mentioned that it would by far be easier for a child to learn if they have not previously had any interaction with a keyboard and mouse. Furthermore, one non-user (NU2) said that "*[VE-SpaND] could easily be learned by a beginner as there are less keys to deal with and not overwhelm the user with too many options.*". Another (NU1) said: "… *I would definently go with the prototype. One reason I haven't properly attempted 3D design of software is because of the learning curve. I think with this prototype I can easily get started with the software but of course along with a keyboard.*".

As for which alternative helped the user best understand their position in the 3D VE, one regular user said they were about the same, at least from what they could see without interacting with the prototype. Another mentioned that the projected screen, acting as a minimap, gave them a bit more control over what was around them, which the mouse and keyboard did not provide. A third regular user said the prototype seems like it is very connected, but that to maintain the rotation it currently has to be held in place. Two non-user said that both alternatives were about the same, where one (NU2) said "…*however, I can definently see how this prototype could be used to view 3D items in the 3D world in a much more effective way than a keyboard and mouse*.". Furthermore, the other non-user continued with that knowing your position in the 3D world is not based solely on the mode of navigation, but also environmental cues, directional arrows, camera angle and so on. A third non-user (NU3) stated that "…*that would be the [prototype], no doubt. Because it makes that much more sense to me because I have no experience with navigating in a software like this in the normal way.*". Moreover, the last non-user (NU4) chose "*[The prototype], because I wasn't suddenly inside a mountain or under the ground.*".

Finally, I asked the participants if they could change anything about the prototype what it would be and if they had any final thoughts, they would like to share. The first regular user mentioned that it should be capable of vertical movement and there should not be a limit on the yaw axis where it continues to rotate, but instead be a one-to-one relationship when rotated. Another regular user noted that the rotation needs to be held in place to maintain the camera rotation, the device would benefit from a click function and that it may be better to hold the device from the side. The third non-user said that adding shortcut keys to the prototype would be helpful. As for the non-users, one mentioned that the projector should be removed or replaced by multi-lens built-in projectors. Moreover, adding more keys to the prototype would be beneficial, as with the Razer Naga mouse. Another non-user said it worked well for navigation but that there might not be a need for a keyboard if the prototype could interact with 3D objects. A third non-user said that the sphere should be less sensitive to avoid the rotation floating out of control but at the same time be sensitive enough to support the finer movements. The last non-user mentioned that it would be worth considering ergonomic design, such as the size of the sphere and how it might be different for a man and a woman.

CHAPTER 5

Discussion

Preliminary Research

From the navigational tasks at the start of the interview, it became apparent that some buttons make more sense to users than others. The findings show that using the scroll wheel to zoom in and out makes sense to all users, regardless of previous experience. Although the scroll wheel is mostly used for scrolling, some software may teach participants to, in certain situations, view the scroll wheel as a method for zooming in and out. As for rotating the view horizontally, three regular users opted for the same approach, even though one struggled somewhat to find the correct button, which indicates that they have been taught the same approach to rotate horizontally. As for non-users, using the right mouse button, as chosen by the regular users, to rotate, did not immediately make sense to three of them. Although it can be taught, as seen with the regular users, these findings suggest that the interaction does not come naturally to new users. With that said, as one non-user pointed out, it works similarly to how one would rotate the camera in certain 3D games, which could mean that the interaction makes more sense to those with more experience with 3D games. Rotation on the vertical axis, on the other hand, although all regular users quickly completed the task, seemed, per their quotes, not to be a standard interaction. Non-users seemed to catch on quickly as they used the knowledge learned from the previous task to perform this task, where only one non-user struggled to complete the task. Even though the interaction did not necessarily come naturally to them, it does not seem to take long for non-users to learn. As for horizontally panning, regular users seem to use default to the more advanced approach of using the right mouse button in combination with the A and D keys. Non-users, on the other hand, used different approaches to panning, but none of them found the same approach as used by regular users. Up to this point, most non-users only focused on utilising the mouse and not the keyboard, which might be why two of them used the middle mouse button to pan sideways. In terms of vertical panning, every regular user went with a different approach, which suggests that vertical panning is either not often used or that they have not been taught one standard approach for doing so. On the non-user side of things, only one non-user managed to pan vertically. A common struggle to pan vertically may indicate that it is not apparent enough how to do so, or that there exist more optimal methods that remove the need for vertical panning altogether. From the more complex tasks, it became apparent that most regular users default to navigate using the WASD keys combined with the right mouse button, which may be what they have been taught. This approach allows them to rotate the camera while panning- and moving on the horizontal axes, which provide them with much flexibility navigating the 3D VE. As an example, while they hold down the W key to move forward and simultaneously holding down the right mouse button, the forward direction will shift according to the direction the user rotates to by moving the mouse. As for the non-users, most of them used the scroll wheel to move further from or closer to their destination. Using the scroll wheel to move on the third axis of the 3D VE is a far less efficient method to navigate as zooming only moves closer or further away from a set anchor point in the 3D VE and does not change the position of the anchor point itself. All virtual camera interactions in Unity happens according to the set anchor point. Meaning that even if the user has zoomed to view an object up close, if they then decide to rotate, the virtual camera will rotate according to the position of the anchor point which may be far outside what the user can see on the screen. However, that non-users chose to zoom to move closer and further away may suggest that they either do not know of any other ways to do so or that they desire to use the zooming metaphor to navigate the third axis. As for the last task, regular users opted for alternative methods to locate the object, suggesting that they are not reliant on one method alone, but instead picks the most suitable approach for each task. Non-users kept to the interactions they had already discovered, where they were all successful in completing the task. However, many faced the issues explained above regarding how zoom does not change the location of the anchor point. Several challenges came forward when participants were asked what issues they had encountered trying to navigate the 3D VE. Based on the response from the regular users, even though they quickly caught up, there was an issue in terms of remembering the various button combinations. Also, one regular user highlighted how rotating 360 degrees up or down felt rather strange, further indicating that this interaction may not be a standard way to interact with the 3D VE. One non-user noted the struggle of grasping the changing speeds of the virtual camera as they moved closer or further away from objects in the 3D VE, which could mean that the software does not indicate well enough why and when it happens. Similarly to the regular users, two non-users said they had difficulties remembering the various button combinations, which may suggest that the keyboard and mouse interface have few ways of reminding the user of- or visualise their function. One non-user noted that it was difficult to move in straight lines as the camera seemed to be fixed at a distant point, which is in line with the issue previously explained regarding the anchor point of the virtual camera. Moreover, participants seemed to use a similar approach when navigating around the 3D model later in the interview, which suggests that there might not be a distinct need for different navigation approaches for the environment and model. However, the interactions with the environment and model may still be different from each other.

In terms of participants spatial understanding of the virtual *3D space*, three regular users chose shapes with the three axes easily identifiable, cubes and 90-degree triangles. These choices may be in line with what 3D software courses teach and that the software continually reminds users of the three axes through its functionality and GUI. However, one regular user did explain the outside area as not that important. Moreover, the last regular user chose a sphere referring to it as the one looking most like space. As for the non-users, one chose the largest object as space is vast, and it is impossible to know the shape of it. A second chose a sphere as it looked like a planet, and the last two chose a twelve-sided- and a twenty-sided die, as each side provided a new perspective and possible direction to move. As for the *3D space* engulfing Earth, in the physical realm, all regular users, for various reasons, chose a cube. As for the non-users, one did not choose a shape as space as we know it does not have a shape, and another chose the largest object as space is vast. Another user chose a sphere, explaining that we are all in different bubbles. The fourth non-user said that we humans usually do not interact with space in a three-dimensional way, where most of our interactions happen on a vertical- or horizontal axis. All but one regular user chose a cube for both types of *3D space*, although there was only one mention for each question, from two different participants, that they chose the shape due to the three axes, x, y and z. However, the focus seems to revolve more around what is inside of both *3D spaces*, rather than the *3D space* itself. A pattern for this focus emerges in several places, such as, where several participants, both regular- and non-users, noted either for the virtual or physical *3D space* that, space as we know it, does not have a shape. Similarly, one regular user stated that the virtual *3D space* is not that important, and two others, one regular- and one non-user said it was more about objects taking up a certain amount of space. Additionally, another non-user explained our actions in the physical world as usually not very three-dimensional, where we are going upstairs or over to that building. These combined seem to form a pattern of focusing on what is inside of space and how much space it takes up instead of focusing on space itself. With that said, some regular users still indicated that they care about having access to the three axes in that space, x, y and z.

As for participants spatial understanding of the 3D VE, three different though patterns emerged from the regular users' responses. One regular user chose the object most similar to the environment in the scene; another chose a cube as most things can be made from cubes, and the third user chose a sphere as they want to relate everything to the real world. Two non-users also chose a shape most similar to the environment, although they had slightly different perceptions of what that shape was. A third non-user chose a 20-sided die as it was a more detailed version of the 12-sided die they used to explain the *3D space*. The last non-user chose a sphere based on its possible functionality in terms of interacting with the 3D VE. Although these findings indicate several different approaches to understanding a 3D environment, a pattern emerges around choosing an object similar to the environment itself. This pattern seems to suggest that these participants want the physical shape to be a real-world representation of the digital environment, drawing the digital out into the physical realm. If so, they might approach the connection of the physical and digital worlds from a digital to a physical perspective. In contrast, one of the regular users approaches the connection from a physical to digital perspective, as they try to relate everything in the digital realm to our physical world. Whereas the other responses talk little of the digital- to the physical relationship, the one regular user choosing a cube seems to relate to the most fundamental building block and how they would go about building- or explaining the environment themselves using these blocks. These findings are interesting when compared to the physical shape participants chose as an alternative to the mouse and keyboard for navigating the 3D VE. Where participants want a physical shape to resemble the environment on screen closely, the majority would like to interact with that environment using a sphere, suggesting that there is a gap between their understanding of the environment and how they prefer to interact with it. Whereas the advantages of the sphere were made clear, as a smooth way to navigate, fits better in hand and provide flexibility, others chose the cube as it can provide better orientation and not stray from its rotation.

In choosing a physical shape to represent any physical 3D object, three regular users picked a cube, as cubes can make up any other objects. Although one said, they would change to a sphere if the object were round. Three non-users also chose square objects, two cubes and one rectangle, although one changed their mind saying that a triangle as multiple triangles allow for more angles than cubes do. These findings show that most participants, both regular- and non-users, find a square object capable of representing most physical objects around us. However, where regular users tend to use cubes as fundamental building blocks with the three axes identifiable, non-users seem to think of the square as a container where all objects can fit inside. As for the last non-user that chose a sphere, was more focused on the perspective than the shape itself. The participant said that a sphere could be a good representation in the real world as we see the sphere from a distance which allows us to comprehend where- and where from we are looking at the sphere. In contrast, they said that on the screen there should be something that indicates the perspective, as our distance and perspective to the sphere on the screen may be far different from how we interact with an object in real life. This response indicates that the perspective on proximity may be relevant in terms of choosing a physical representation to a digital object. When compared to the objects participants chose as an alternative to mouse and keyboard to interact with the 3D model, there seems to be a difference in how non-users understand the object and how they would like to interact with it. Whereas the responses are similar for regular users, non-users, for the most part, chose squares to represent the 3D object and spheres to interact with the object. With that said, their response may be biased as the model on the screen was a sphere.

From the last question, asking participants how they would like to navigate a 3D VE if there existed no limitations, a couple of patterns emerge. Three regular users and one non-users would like to use VR to be in the environment themselves. A desire to be in the environment may suggest that participants find perspective important and that the 2D screen does not provide a sufficient perspective to understand the 3D VE and its contents. It may also mean that, by being in the environment, they could use their learned skills and senses to locate and interact with the environment. Two participants also noted that they would like to have a brain interface so that the tool itself could adjust to the user instead of the user having to learn the tool. These responses indicate that the current tools are complex and that it may be difficult to remember how to perform specific tasks, especially if they are different from software to software. Furthermore, two participants noted that they would like to use physical touch to interact with the environment. This further emphasises the desire of using their learned skills and senses to interact with the 3D VE and have the tool adapt to the user, as they already know how to use their skills and senses to interact with the physical world.

TUI prototype

When asked how it felt to navigate a 3D VE using a keyboard and mouse, it came as no surprise that regular users thought it felt fine. Although the preliminary research shed some light on advantages and disadvantages using keyboard and mouse to navigate 3D VEs, regular users have had years to become accustomed to navigating 3D VEs using the mouse and keyboard interface. Non-user, on the other hand, still, for the most part, found it challenging to navigate 3D VEs using a keyboard and mouse. Despite this, one non-user mentioned that it felt more efficient to use a combination of the keyboard and mouse than only one at a time as they had done in the last interview and that they would probably get used to it over time. Still, some issues persisted, such as a feeling of having no control or problems remembering the shortcuts. Regular users highlighted similar issues, such as not remembering shortcuts, it is unnatural to lift the mouse and reposition it to do long- or sharper turns, and more delicate movements using the WASD keys with the right mouse button. Besides, another non-users noted that they would need much guidance to get started as the way the mouse and keyboard work does not align well with how they think of navigating a 3D VE. These findings suggest that, although mouse and keyboard still is a reliable option for navigating 3D VEs, it can be daunting and time-consuming to learn as they offer a vast array of functionality at the cost of having to translate the desired actions into a combination of shortcuts.

As for VE-SpaND, two regular users stated that the prototype was natural and smooth, where one mentioned that it removes the need to use both hands. However, another regular user said it would take some getting used to and that it seemed more like a tool, suggesting that the prototype does still lack in some aspects. Moreover, the non-users found VE-SpaND to be fluid, easier than keyboard and mouse by only having to focus on one thing, and more intuitive and align well with the way they think of navigating a 3D VE. These findings suggest that the prototype makes sense to use and to some extent, feels natural to use both for regular- and non-users. However, the prototype still has some challenges to overcome, such as the lag between the computer and projected screen, and letting users know when they venture outside of the projected screen. Moreover, it would be interesting to know why one regular user though it would take some time getting used to, why they felt it was more of a tool currently and why the prototype feeling like a tool has a negative connotation to it. Being a tool, in this context, might mean that the prototype's abstraction layer is not abstract enough and therefore is still just another tool to be learned. Participants were further asked about whether anything felt confusing or unnatural when using the prototype which shed some light on a couple of issues with the current version of VE-SpaND. Two regular users commented on how the prototype's range of movement would scale according to an environment that increases in size and that rotating the sphere in some directions might be uncomfortable for the user. One regular user also said that it would be nice if the sphere had a rotation limit that once reached would keep rotating the view and a reset button to reset the rotation. This functionality is part of the current prototype, but only on the yaw axis. A couple of non-users commented that the prototype, in its current state, was a bit wonky where the rotation was too sensitive when the base was moved around, where a third indicated that the projected area could be narrowed down. Where the latter comments revolve around technical improvements, the former speak of some missing core functionality for the prototype to be useful in expanding environments. This might suggest that the prototype needs a zoom functionality to work at different levels of detail and an ability to relocate in a large environment with ease.

In terms of participants preferred interface to navigate 3D VEs, two regular- and three non-users chose VE-SpaND, where one regular- and one non-users would pick mouse and keyboard due to familiarity with the interface. However, one regular user continued to highlight VE-SpaND's disadvantage by saying they would choose VE-SpaND only in situations where the environment does not gradually expand and does not require vertical movement. These disadvantages suggest that although the prototype may be intuitive, in its current form, it does not cover all the nessecary functionalities needed by a regular user. Moreover, given that two participants chose the keyboard and mouse, VE-SpaND might not offer a good enough upgrade for them or cover a broad enough set of functionality to feel that it is worth investing time learning to use a new device. Where this question uncovered some disadvantages of VE-SpaND, it also highlighted some advantages of the prototype. One regular user commented that the prototype, for the most part, only required one hand, which removed the need to remember many shortcuts. Three non-users mentioned how VE-SpaND makes sense to use and aligns well with how they think about navigating the 3D VE in their mind. These indicate that VE-SpaND may be better aligned with peoples' spatial knowledge of the physical world than the mouse and keyboard and as a result, to a degree removes the need for button combinations specific to navigation in 3D VEs.

Questions four to six was intended to further elaborate on the shortcomings of VE-SpaND and its advantages and disadvantages compared to keyboard and mouse. From the responses of regular users, it became apparent that they missed certain features provided by either the mouse or keyboard, such as to click and select objects and quick access via keyboard shortcuts. The majority of responses from regular- and non-users tell that they would like VE-SpaND to be paired with a keyboard, but also that the prototype, in that case, ought to have a click functionality. Moreover, several participants commented that one benefit of VE-SpaND is to only focus on one hand, but that it required the prototype to have a click functionality. Furthermore, a couple of participants made suggestions that the prototype could have a Numpad style keyboard or that modifiers on the keyboard could alter the functionality of the prototype. The fact that no participants mentioned that the prototype should be combined with a keyboard or mouse to assist in navigating the 3D VE indicates that VE-SpaND, for the most part, performs navigation well. However, the responses specifically mention the missing click function and that the prototype would benefit from all the button combinations of the keyboard. Participants also highlighted the benefit of using a mouse and keyboard as accessible, cheap, more precise, familiar to most and takes up less space where VE-SpaND would require an additional device on the desktop and a rather large one at that. However, they also commented that VE-SpaND is entertaining, brings all controls to one hand and VE-SpaND lets them think 3D and operate the device in 3D whereas for the mouse and keyboard they have to think 3D and operate in 2D. Although mouse and keyboard certainly have their advantages, these findings suggest that VE-SpaND makes more sense in terms of navigating 3D VEs, but falls short with its missing functionality which is where the keyboard and mouse shine. This prompts the question of whether VE-SpaND should absorb the functionality of a mouse and or keyboard to allow full control using one hand, or if it should move down a different path, distinguishing itself from the conventional interface and solely focus on navigation in 3D VEs.

As for what alternative would be the better option for beginners to learn to use a 3D software, all participants chose VE-SpaND. However, one regular user mentioned that if they later wanted to work professionally, companies might require them to learn to use a mouse and keyboard. Two non-users highlighted how VE-SpaND might help beginners to learn 3D software by not overwhelming them with too many options which could make for a smoother learning curve. This suggests that although VE-SpaND may provide a more comfortable start for beginners to learn 3D software, due to its missing functionality, they may later have to learn how to use a mouse and keyboard after all. Participants were further asked which alternative they believe would best help users understand their position in the 3D VE, where three participants, one regular- and two non-users said they were about the same. One of these non-users highlighted how understanding their position comes down to more than just the mode of interaction, such as environmental cues, navigational aids and perspective. One regular user mentioned that the projected screen gave them a better understanding of what was around them, and two non-users said VE-SpaND made more sense to them, where one also said that they did not get lost as they did with the mouse and keyboard. Whereas non-users indicate that they have an easier time navigating using the prototype, it might not be as a result of understanding the 3D VE better through using VE-SpaND, but rather that the prototype allows them to navigate in a manner that makes sense to them. Regular users, on the other hand, may already be well enough versed in translating their desired actions to the interface's capabilities that they do not get lost in the same way that some non-users have mentioned. However, one regular user comments that the projected screen gave them a better understanding of what was around them, which the keyboard and mouse do not provide, which was the only regular user who tested in-person. It might be that remote users did not get the full experience of seeing the projected screen in their peripheral vision while navigating and therefore not thought of how it could help them understand their position better. However, it might also be that some user does not feel the need to understand their surroundings better to know their position in the 3D VE.

CHAPTER 6

Conclusion

Recent technological developments, such as the domain of TUIs, offers exciting opportunities for novel interactions with the digital realm. Where conventional interfaces such as keyboard and mouse long have provided users with familiar interactions across a wide array of applications, more sophisticated software with broad sets of available actions have had to become creative in implementing advanced button combinations for quick access to core functionality. As such, learning to use some of these software has become a daunting task, made more challenging when people need to learn several similar software which all utilise slight variations of the same button combinations. This is especially true for the 3D software industry, where navigating 3D VEs requires the user to translate their desired actions into multiple-button hotkey combinations to navigate the 3rd axis, where most other applications only require users to interact with flat contents on the screen. Many researchers have attempted to explore alternative approaches to navigating 3D VEs, gathering valuable data to further the field. Despite these studies, we still, for the most part, use a conventional keyboard and mouse to navigate 3D VEs. I believe there exist exciting opportunities in bridging the gap between peoples' spatial knowledge of our physical world and that of the 3D VEs to build new interfaces suitable to navigate 3D VEs. Throughout this study, I have explored the following research question: "*Can user-centric tangible user interfaces provide a useful alternative for navigating 3D virtual environments?*". In pursuit of the answer to this question, an interview was conducted to attain data on peoples' spatial understanding of the physical world and 3D VEs and how users expect and desire to navigate 3D VEs. Data gathered on participants' spatial knowledge was then used to inform the design of the TUI prototype VE-SpaND to allow users to interact with 3D software using their spatial knowledge of the physical world.

From this study, I found that although a mouse and keyboard offers a vast number of shortcut possibilities, it can be challenging for users, particularly new ones, to remember and master these key combinations to navigate 3D VEs. Furthermore, the study found specific interactions such as rotating the camera to look up or down (pitch) over a certain threshold and vertical panning, felt unnatural to users. In these cases, regular users would instead opt for the more advanced approach of combining the WASD buttons and the right mouse button. This combination allows users to adjust their camera on the horizontal and vertical axis simultaneously to moving in a forward, backwards or sideways direction using the keyboard buttons. Instead of vertical panning, regular users would rotate the camera upwards holding down the right mouse button and then move in that direction holding down the W key. This type of interaction flows naturally and comes naturally to most regular users. However, no non-user was able to locate these button combinations by themselves as most non-users found it challenging to use both the keyboard and mouse simultaneously. On several occasions, non-users got lost or frustrated as the interface did not work according to their expectations when they tried to navigate the 3D VE. Moreover, when asked to navigate on the 3rd axis of the 3D VE, most non-users used the scroll wheel to move in closer or further away, likely using their knowledge from other software where zoom means to move in closer. However, observations of non-users navigating the 3D VE indicated that navigating the 3rd axis using the scroll wheel caused them several issues down the line, as the scroll wheel, in software such as Unity, zooms in on a specific invisible point in the 3D VE rather than move the point around. Whereas a keyboard and mouse still offers a reliable and flexible alternative to navigate 3D VEs, the interface can be daunting to learn as it requires users to translate their actions into a set of complex button combinations to navigate 3D VEs efficiently. Furthermore, the buttons on a mouse and keyboard provide few indicators to their functionality in some software, where some, such as the scroll wheel, may not work as expected.

In an attempt to bridge the gap between peoples' spatial understanding of the physical world and their ability to navigate 3D VEs, I constructed the TUI prototype VE-SpaND. From user testing the prototype, I found that VE-SpaND offers some benefits the conventional keyboard and mouse does not and vice versa. Several participants highlighted the benefit of only needing to focus on one hand to navigate, which can be helpful to non-users, as most of them struggled to use the keyboard and mouse simultaneously. Another benefit pointed out is how it made sense to use, where users stated that it felt intuitive, fluid and smooth and aligned well with how they thought of navigating 3D VEs. As for the mouse and keyboard, on several occasions, it became apparent that VE-SpaND does not offer as broad a set of functionality as the keyboard and mouse, nor does it offer a click functionality. Whereas VE-SpaND lacks certain functionalities, participants commented that it would be most useful in combination with a keyboard, if a click functionality were to be implemented. However, the findings also suggest that users would like VE-SpaND to have both buttons and click functionality, which in theory would absorb some advantages of the mouse that further emphases users' desire to use only one hand. This desire may be a result of VE-SpaND currently, as pointed out by regular users, lacking core functionality to move vertically or scale with environments that increase in size, where they know a set of keyboard shortcuts could fix the issue. Whereas many regular- and non-users have commented that VE-SpaND makes sense and feels natural to use, some would still choose to use keyboard and mouse. This may be due to remaining challenges for VE-SpaND to overcome and that VE-SpaND is not a fully functioning finished product. These are issues such as the rotation being too sensitive, which affected the overall user experience when moving the base around, and the current lag between the projected screen and physical controller. In addition to considering the ergonomic design of the device as currently, some interactions may cause discomfort, such as using the sphere to rotate may require the user to lift or twist their wrist to perform the desired action.

The overall positive feedback revolving VE-SpaND, how it makes sense and aligns with how users think about navigating a 3D VE, suggest that VE-SpaND does help bridge the gap between peoples' spatial understanding of the physical world and their ability to navigate 3D VEs. Also, VE-SpaND seems to have had a considerable impact on non-users ability to be able to pick up and navigate 3D VEs more quickly, stating that it makes more sense and feels more intuitive. Also, one participant commented that the prototype lets them think in 3D and operate in 3D versus the mouse and keyboard where they have to think 3D and operate in 2D. Furthermore, VE-SpaND's benefit, as per participants comments, of bringing all functionality to one hand so that users do not have to remember advanced button combinations, indicates that it provides useful advantages that a mouse and keyboard do not provide. However, due to VE-SpaND's current lack of functionality, users stated that they thought it would prove most valuable in combination with a keyboard, given that it had a click functionality. Thus, in its current state, VE-SpaND does not provide a complete set of functionality to replace the mouse and keyboard to both navigate and interact with the 3D VE. It does, however, suggest that a user-centric tangible user interface can, indeed, provide a useful alternative for navigating 3D VEs. However, it bears to note the limitations of this study. Due to the user testing being conducted under COVID-19 restrictions, only but a few participants were allowed physical access to VE-SpaND, which may have impacted the results. Despite this, the results of the in-person user tests are, for the most part, similar to those performed remote, indicating that it may not have had a significant impact on the results. Moreover, it is worth considering the prototype's inability to move vertically and how this may have affected the outcomes of this study.

Future Work

In terms of future work, specific to VE-SpaND, the technical limitations as pointed out by participants ought to be fixed. Issues such as making the sphere less sensitive when moving the base, implementing a vertical movement functionality and consider how to decrease the size of the device. Also, it is worth considering using a different technology than image tracking as it has proven to be somewhat unreliable and may hinder users from performing specific interactions with the physical device. Future work should also look into the current lag between the projected screen and physical controller and how it can be improved to make for a better user experience. Also, the prototype still lacks in terms of ergonomics, where specific interactions might be uncomfortable to the user. Furthermore, VE-SpaND would benefit from a study regarding whether the device should absorb the functionalities of a mouse and or keyboard as suggested or if there is a third path that would make VE-SpaND more useful. As of now, VE-SpaND has been built specifically for Unity, drawing upon the toolkit provided by the software to manipulate the different axis and position of elements directly. Whereas other 3D software offers similar control, it is worth considering how VE-SpaND can break loose from one type of 3D software so that its advantages can be used in other 3D applications. Although each software has its unique differences, there seem to be only minor differences in navigating various 3D VEs. Therefore, VE-SpaND could, in theory, be useful to a wide array of 3D applications, but is currently restricted due to its technical implementation. Furthermore, a longitudinal study comparing the effects of people learning to navigate

3D VEs using the two alternatives could prove useful in determining whether VE-SpaND could smoothen the learning curve of 3D software. As for future work using peoples' spatial understanding to navigate 3D VEs, I suggest to further look into how using the interface at different levels of attention could affect to what degree people make use their spatial understanding, as this was not part of this study. Also, given that participants wanted to use VR or AR to be in the environment and physically touch 3D objects, it would be interesting to study how a TUI could be combined with either of these technologies and how that would affect the translation of spatial understanding from the physical to the digital realm.

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Appendices

Appendix A – Public Evaluation of Interactive Technologies

THE UNIVERSITY OF QUEENSLAND

Sub-Committee Human Research Ethics Approval

Project Title:	Public evaluation of interactive technologies
Chief Investigator:	Dr Benjamin Matthews
Supervisor:	Dr Benjamin Matthews
Co-Investigator(s):	A/Prof Stephen Viller, Dr Marie Boden, Dr Jessica Korte, Dr Chelsea Limming, Dr Arvindam Dey, Ms Lorna Macdonald, Mr Peter Worthy
School(s):	School of Information Technology and Electrical Engineering, The University of Queensland
Approval Number:	2018002067
Granting Agency/Degree:	None
Duration:	30 November 2019

Comments/Conditions:

- HREA Form, 04/10/2018
- Participant_Information_Sheet_evaluation, 4/10/2018
- Participant_Informed_Consent_Form_evaluation, 4/10/2018
- Public evaluation of interactive technologies, 4/10/2018

Note: if this approval is for amendments to an already approved protocol for which a UQ Clinical Trials Protection/Insurance Form was originally submitted, then the researchers must directly notify the UQ Insurance Office of any changes to that Form and Participant Information Sheets & Consent Forms as a result of the amendments, before action.

Name of responsible Sub-Committee:
University of Queensland Engineering, Architecture and Information Technology, Low & Negligible Risk Ethics Sub-Committee
This project complies with the provisions contained in the *National Statement on Ethical Conduct in Human Research* and complies with the regulations governing experimentation on humans.

Name of Ethics Sub-Committee representative:
Professor Deanna Kemp
Chairperson
University of Queensland Engineering, Architecture and Information Technology, Low & Negligible Risk Ethics Sub-Committee

Signature ______________________ Date **22/10/2018**

Appendix B – Participant Information Sheet

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Participant Information Sheet

Public evaluation of interactive technologies

Research Lead

Dr Ben Matthews

School/Department

School of Information Technology & Electrical Engineering

Background to this project

The purpose of this study is to evaluate and improve interactive technologies that have been designed to support particular aspects of people's lives. As a participant, you have been invited to a public exhibit of interactive technology designs in order to provide your own perspective, from your own experiences, as to the merits and shortcomings of these prototypes. During the exhibit, your interactions and responses will become data for the research team to analyse in order to improve the technologies being designed. This data may include field notes, audio recordings of your responses, and photographs. You may also be invited to participate in "take home" activities that ask you to reflect on how the functionalities or possibilities afforded by the technologies may intersect with your daily life.

Aims of the project

The aims of the study are to gather formative feedback on the concepts, implementation and fidelity of the technology prototypes in order to improve them, and better understand how to better design for these domains. Specifically, we are aiming to:

- evaluate the technologies (many of which are mobile apps or embedded systems) with respect to the problem domains they have been developed to address
- document the perspectives, needs, values and requirements of members of the public to the range of interactive systems students have designed and prototyped
- to critically analyse the application and results of this process, paying particular attention to the potential for improvements to the designed prototypes

What you have to do

You will be invited to join an exhibit where you will be asked to provide feedback on design prototypes based on your own experiences. This may include interactive workshop activities, interview questions, or performing hands-on tasks with the prototypes.

Data we are collecting

Please note that all data collected will be stored on password protected devices or servers, and accessible only to the research team. The types of data may include

1. Field notes taken by researchers during the exhibit.
2. Audio recordings of interviews and workshop activities conducted.
3. Photographs that have been taken during scheduled workshop activities.
4. Artefacts or other materials that you voluntarily share with us.
5. Any other information that you may volunteer to us for inclusion in the study, including the outcomes of any "take home" activities you choose to participate in and share with us.

Throughout the analysis of this data and its presentation in research results, we will protect your identity and not disclose it to any parties not involved in the research project. While you are participating in the workshop activities, you are free to withdraw your material contributions.

Confidentiality

All information collected from you will be de-identified and/or allocated a code to enable the alignment of all data collected. Information that is obtained will be strictly confidential and will only be accessed by the researchers.

Any information published or otherwise made public will not disclose your identity or your participation in this research project. All information will be de-identified before it is published.

Some de-identified information may be shared with other members of the Co-Innovation Research Group at the University of Queensland for the purposes of assisting with analysis and writing research papers. The information that is shared will be limited to data that has been de-identified and has the lowest chance of identifying you.

Risk to you

There are no risks to you participating in this study beyond those that exist in normal daily life.

Participation is voluntary

There are no direct benefits to you in participating in the study.

Your participation is entirely voluntary. You don't have to be in this study if you don't want to, and you can ask to stop at any time. There are no negative consequences should you wish to stop, data collection will cease immediately and any data collected from you or about you will not be included in the study.

Ethics clearance

This study adheres to the Guidelines of the ethical review process of The University of Queensland and the National Statement on Ethical Conduct in Human Research (approval number 2018002067).

You are welcome to discuss your participation in this study with a representative of the research team.

If you would like to speak to an officer of the University not involved in the study, you may contact the Ethics Coordinator on 3365 3924.

Need to know more?

For further information about this study or if you wish to stop your involvement in the study please contact the Lead Investigator:

Dr Ben Matthews
School of ITEE
University of Queensland
Phone 07 3365 2185
Email matthews@uq.edu.au

Appendix C – Informed Consent Form

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

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Informed Consent Form

Public evaluation of interactive technologies

Dr Ben Matthews (Lead Investigator)

Participation Consent

I have been provided with and have read the information sheet relating to this research project, and give my consent to participate in this study based on the understanding that:-

1. I am aware of the general purpose, methods and demands of the study.
2. My participation in this study is voluntary and I am free to withdraw from the study or refuse to take part at any time, without any negative consequences.
3. Audio recordings will be taken. These recordings will be accessed only by the investigator doing this particular project, the Investigator's Supervisors and any other person authorised by the Investigator.
4. Photographs may be taken during scheduled activities. These photographs will be de-identified prior to analysis and presentation.
5. All information that I provide or that which is recorded or otherwise collected will be kept confidential and will not be identifiable. De-identified information (including photographs) may be made available in publications or on project websites.
6. There is no reimbursement or payment for participation.

I have read the information about this project and give my consent to proceed in accordance with the information completed on this form.

Participant Name: ____________________

Participant Email: ____________________

Signature ____________________ Date ____________

This study adheres to the Guidelines of the ethical review process of The University of Queensland and the National Statement on Ethical Conduct in Human Research (approval number 2018002067). Whilst you are free to discuss your participation in this study with the investigator (Dr Ben Matthews, contactable on 3365 2185), if you would like to speak to an officer of the University not involved in the study, you may contact the Ethics Coordinator on 3365 3924.

Appendix D – Interview Protocol 001

EvaluationID	User Interview 001
Who	1. People with no prior experience using 3D software. 2. People with limited experience using 3D software (<= 4 years) who either actively use or have previously used 3D software.
Aims	1. Understand people's mental models around 3D space 2. Understanding people's spatial awareness
Dates	01 October 2019 =>
Creator	Sigurd Sæther Sørensen
Research Domain	Tangible User Interface and Virtual 3D Spaces
Research Question	How can tangible interactions be used to navigate a virtual 3D space?

Preparation Before The Participant Arrives

Prepare the following material for the user testing session:

1. Consent Forms (including extended consent form)
2. Audio recording device
3. Video recording device
4. Interview Questions Sheet
5. Physical representations of shapes

Interview

1 Intro Questions

1. How long experience do you have with 3D software?
   - 3D world as in 3D games, 3D modelling software, 3D game engines, VR, AR, or other physical or digital representations of a 3D environment.
2. Which of the following 3D modelling software have you previously used? Unity, Unreal Engine, AutoCAD, Sketchup, Maya or Blender?
3. What input device or devices do you currently use with the software?
   a. Why do you choose to use this or these input devices?
   b. What do you believe are the benefits and limitations of this or these input devices?

c. *If mouse + keyboard* > On this computer, can you show me where and when you use the mouse and where and when you use the keyboard, both in the 3D environment and interface menu?

4. Have you tested other input devices?
   a. *If yes* > which device did you try and what was its benefits and limitations?

2 Speak Aloud - 3D environment

Introduction:

To make things consistent and to avoid misunderstandings, I'm going to refer to that area you see in the middle of the screen as a virtual 3D environment and all the rest, the dark area, you see on the screen as the virtual 3D space. If I'm going to use an analogy, the virtual 3D environment is earth, a tangible item, whereas the virtual 3D space is like air or our own universe, which you cannot see or touch.

Tasks:

I'm going to ask you to perform a series of tasks that I wish for you to perform in this software. The goal of this is for me to understand what is seen as confusing or feels unnatural to you. So, I would like you to explain out loud what you are doing, why you are doing it and especially if something is confusing, explain why and what you expected to happen.

Getting Started:

1. Zoom in or out
2. Turn 360 degrees to the left or right
3. Turn 360 degrees up or down
4. Pan sideways
5. Pan up or down

More complex tasks:

1. Navigate yourself to the edge of the 3D environment, so that your position is above those mountains, and turn around so that you are looking towards the center.
2. Find the car on the race track and position yourself right behind it.

Post-tasks Questions:

Issues encountered:

1. What were the biggest issues you faced navigating this 3D space?

Next, I want to make a connection between the shapes in front of you here and the virtual 3D space you just navigated through on the computer.

1. If you were to pick one shape from among those in front of you, which one do you feel best represents the virtual 3D space you just navigated through on that screen?
   - Why did you pick this shape?
   - Can you tell and show me what makes this object a good representation of a virtual 3D space to you?
2. Can you pick the shape that you feel best represents the virtual 3D environment as seen on the screen?

- Why this shape?
- Here too, can you explain and show me what makes this shape a good representation of the virtual 3D environment to you?

Moving away from the computer and the virtual 3D space entirely, next we are just going to focus on these shapes and our own world.

1. If you are not limited to the screen, but rather were to pick a shape to explain the physical 3D space we both are in here and now, what shape do you feel best represents this 3D space?
    - [if shape = different] Why did you pick a different shape this time?
    - Can you show and explain to me what makes this shape a good representation of the 3D space both of us are in now?
2. Can you pick a shape to represent any physical object in our physical 3D space?
    - [if shape = different] Why is this shape different from the last one?
    - Again, can you tell me what makes this shape a good representation of any physical 3D object?

Next, we are looking at the connection between our physical world and the digital world on the screen.

3. If you were to use any of these shapes instead of a mouse and keyboard to move around in the virtual 3D space, which shape would you use?
    - Pretend that this shape now is connected to that computer, can you show and explain to me how this shape could be used to move around in the 3D space? Please do speak out loud about what you would expect to happen on the screen as you interact with the shape.

3 Speak Aloud - 3D model

Introduction:
This part of the interview is going to be a lot shorter than the last part. My goal for this part is to understand whether the same answers apply to navigating a 3D model

Tasks:

1. Navigate yourself around the sphere to find a small cube and position yourself so that you are looking straight at it.
2. Rotate around the object either way you like until you come back to the cube.

Post-tasks Questions:
Issues encountered:

1. What were the biggest issues you faced navigating this 3D space?
2. Can you pick a shape that you would use instead of a mouse and keyboard to interact with and move the virtual 3D model around?
    - Again, pretend that this shape now is directly connected to the virtual 3D model on the screen. What would you expect it to do as you interact with the physical shape?

Open-Ended last question:

1. If there existed no limitations such as a monitor, mouse, keyboard etc., how would you prefer to work and interact with the 3D software?

Appendix E – Information Sheet 001

INFORMATION SHEET

How tangible interactions can be used to

navigate virtual 3D spaces

Investigator team

Sigurd Sæther Sørensen, *Main Researcher*

Ben Matthews, *Chief Investigator*

Lorna Macdonald, *Project Supervisor*

Invitation

You are invited to participate in a study exploring people's perspectives on how tangible interactions can be used to navigate virtual 3D spaces. The study is being conducted at the School of Information Technology and Electrical Engineering at the University of Queensland as a student thesis project in the Master of Interaction Design.

Why have I been invited to participate in this study?

For this stage of the study, we are seeking adults who are willing to share their perspectives on this area of technology development by being part of an interview.

'What if I don't want to take part in this study, or if I want to withdraw later?'

Participation in this study is voluntary. It is completely up to you whether or not you participate. If you wish to withdraw from the study once it has started or decline to answer particular questions, you can do so at any time without having to give a reason.

'What does this study involve?'

If you agree to participate in this study, you will be asked to sign the Participant Consent Form.

The first goal of this interview is to discover a gap in the current solutions for navigating virtual 3D spaces that will inform the development of a series of prototypes throughout the thesis project. The second goal of this interview is to seek out people that are interested in participating in the extended study, which will include a diary study and testing of several physical prototypes. The extended study will last until the thesis delivery date in June 2020, but participants are free to withdraw at any time.

This initial interview will involve questions regarding your experience using 3D software, such as Unity or Unreal Engine, how you use the software and the challenges you have faced when learning to use the software. The interview will be conducted in groups of two or on an individual basis. You are not required to be an active user of any 3D software, but should either currently be learning to use it or previously have learned to use it. Participation is expected to take between 30-45 minutes. After the interview have finished, you will be offered the option on whether you would like to take part in the extended study.

The interview will be recorded in a video and audio format to be used in analysing the information from the interview. The video recording will not include your face, but rather be positioned to include your hands, the table top and the computer. You may request to not have footage or audio recordings during the interview, if so the investigator will not take any footage or recordings.

'Are there risks to me in taking part in this study?'

You will be asked to share information about your experiences and expectations of emerging and future technologies. You might find the discussion inconvenient or potentially emotionally upsetting. You can decline to answer any question that you do not wish to answer without having to give a reason.

'Will I benefit from the study?'

Participating in the study will not directly benefit you. This study aims to further knowledge and may improve how we design technology in the future.

'How will my confidentiality be protected?'

All the information provided by you in the study will be confidential. Any information you give us will be stored securely and only shared with people within the research team. Audio and video recorded interviews will be transcribed, removing all identifying information and then the audio and video files will be destroyed. Any published data will have information which identifies identity removed. We will store the data for up to 5 years.

'What happens with the results?'

After analysis, the grouped findings from all participants will be used to help design a system for helping people to remember items. It will be written up for a student report. In any publication, information will be provided in such a way that you or your location cannot be identified. You can also receive a copy of the results if you like.

'What should I do if I want to discuss this study further before I decide?'

When you have read this information, you can discuss the study with the local researcher and ask any questions:

Sigurd Sæther Sørensen
0413 665 557
s.soerensen@uqconnect.edu.au

'Who should I contact if I have concerns about the conduct of this study?'

This study adheres to the Guidelines of the ethical review process of The University of Queensland and the *National Statement on Ethical Conduct in Human Research*.

Whilst you are free to discuss your participation in this study with project staff (contactable on 0413 665 557), if you would like to speak to an officer of the University not involved in the study, you may contact the Ethics Coordinators on +617 3365 3924 / +617 3443 1656 or email humanethics@research.uq.edu.au.

Thank you for taking the time to consider this study

Appendix F – Information Sheet Video 001

EXTENDED CONSENT FORM

How tangible interactions can be used to

navigate virtual 3D spaces

Investigator team

Sigurd Sæther Sørensen, *Main Researcher*

Ben Matthews, *Chief Investigator*

Lorna Macdonald, *Project Supervisor*

'What does this extended consent form revolve?

This document is a voluntary extension of the official Informed Consent Form which the main researcher has given you. This document asks your consent to being taken video recordings of throughout the interview. This is due to the interview consisting of both physical and digital interactions which could be better analysed from a video recording than audio recordings alone.

The video footage will not include your face, but rather be positioned to capture your hands, the table top and the computer of which you are interacting with.

'What if I don't want to sign this extended form or if I want to withdraw from the study at a later point?'

Allowing the researcher to take video recordings of the interview is completely voluntary. You may choose to not have the interview video recorded. If you wish to withdraw from the study once it has started or decline to answer particular questions, you can do so at any time without having to give a reason. Moreover, if you choose to withdraw all notes as well as video and audio recordings will be deleted.

'How will my confidentiality be protected?'

All the information provided by you in the study will be confidential. Any information you give us will be stored securely and only shared with people within the research team. Audio and video recorded interviews will be transcribed, removing all identifying information and then the audio and video files will be destroyed. Any published data will have information which identifies identity removed. We will store the data for up to 5 years.

'What happens with the results?'

After analysis, the grouped findings from all participants will be used to help design a system for helping people to remember items. It will be written up for a student report. In any publication, information will be provided in such a way that you or your location cannot be identified. You can also receive a copy of the results if you like.

'What should I do if I want to discuss this study further before I decide?'

When you have read this information, you can discuss the study with the local researcher and ask any questions:

Sigurd Sæther Sørensen
0413 665 557
s.soerensen@uqconnect.edu.au

'Who should I contact if I have concerns about the conduct of this study?'

This study adheres to the Guidelines of the ethical review process of The University of Queensland and the *National Statement on Ethical Conduct in Human Research*.

Whilst you are free to discuss your participation in this study with project staff (contactable on 0413 665 557), if you would like to speak to an officer of the University not involved in the study, you may contact the Ethics Coordinators on +617 3365 3924 / +617 3443 1656 or email humanethics@research.uq.edu.au.

Participation Consent
I have been provided with and have read the information sheet relating to this research project, signed the consent form and give my consent to also allow the researcher to take video recordings of this study.

Participant Name: ____________________

Signature: __________________________

Date: __________

Appendix G – User Interview 002

EvaluationID	User Interview 002 – Prototype Test
Who	1. People who just started out learning to use a 3D software either with a professional or recreational goal in mind. 2. People with limited experience using 3D software (<= 4 years) who either actively use or have previously used 3D software.
Aims	1. Whether people find the introduced device easier to use for navigational purposes than the standard solution. 2. Whether the device helps people better understand their position in the virtual 3D space. 3. Whether the device is an appropriate addition to the toolset of 3D software users.
Dates	29 April 2020 =>
Creator	Sigurd Sæther Sørensen
Research Domain	Tangible User Interface and Virtual 3D Spaces
Research Question	"Whether a Tangible User Interface could be a viable alternative to navigating a virtual 3D world".

Preparation Before the Participant Arrives

Prepare the following material for the user testing session:

1. Consent Forms
2. Interview Questions Sheet
3. Audio recording device
4. Computer (/w mouse)
5. TUI Prototype

Introduction

Before we begin, I would like to inform you that this interview is completely voluntary which means that you may withdraw at any time, whether it is before, during or after the interview. If you wish to withdraw during or after the interview, please let me know so that I can have all data deleted.

[Hand over consent form and information sheet]
Please take some time to look over this information sheet before you sign the consent form. The provided information sheet explains how your data will be treated

and if you have any questions at all, please don't hesitate to ask. Also, before we begin, are you comfortable with me taking an audio recording of this interview?

Today, you are going to be testing a prototype that I have built to explore whether a tangible user interface can be a viable alternative to navigate a 3D world. Prior to testing the prototype I'm going to let you navigate around a virtual 3D world using standard keyboard and mouse. Then I will let you navigate around a similar 3D world using the prototype I have developed, and lastly, I will ask you some questions based on your experience.

Prototype Test & Interview

1 Standard Interface

Introduction:
For this first part, I just want you to get a bit familiar with how it feels like to navigate around a virtual 3D space using the standard keyboard and mouse. This is to give you a bit of context and a frame of reference when moving on to the prototype so that you can more easily compare the two solutions.

Tasks:
I'm going to give you a couple of tasks to let you get a sense of how it feels to navigate around using the standard interface, to give you a sense of context, before I let you test the prototype.

Getting Started:
1. Move sideways to the right (pan right)
2. Move sideways to the left (pan left)
3. Move forwards
4. Move backwards
5. Look to the left
6. Look to the right
7. Look up
8. Look down
9. Find a way to move faster

Free Movement:

10. Take one lap around the racetrack.
11. Move around the 3D space for a bit until you get a sense of how it feels to navigate using a mouse and keyboard.

Post-tasks Questions:
General Feedback:
1. How does it feel for you to navigate around using a keyboard and mouse?
2. Was there anything that felt confusing or unnatural when doing these tasks?

2 Prototype Test & Speak Aloud

Introduction:
For this part I want you to navigate in a similar way to what you did when using a keyboard and mouse, but now with this prototype. I'm going to give you the same tasks as I did before and then let you move around freely.

There are a couple of limitations to the prototype that I'm going to mention briefly so that you know what is happening and what to do if you encounter them. First of all, the prototype do currently not have any functionality for moving up and down (vertical movement). Secondly, there is currently no way to zoom in our out. Third, the camera that is tracking the device is not working properly, so if the software does not respond to your interactions it may have lost track of the device. If so, lift the device closer to the camera then put it back down to the surface.

Tasks:
Getting Started:
1. Move sideways to the right (pan right)
2. Move sideways to the left (pan left)
3. Move forwards
4. Move backwards
5. Look to the left
6. Look to the right
7. Look up
8. Look down
9. Find a way to move faster

Free Movement:

10. Move around the 3D space for a bit until you get a sense of how it feels to navigate using the device.

3 Interview Questions

General Feedback:
1. How does it feel for you to navigate around using this device?
2. Was there anything that felt confusing or unnatural when doing these tasks?

Comparison:

3. Which way did you prefer to navigate the 3D space, keyboard and mouse or the prototype?
    a. Why do you prefer that option?
4. Do you believe the prototype would be most beneficial when used:
    a. by itself;
    b. in combination with a mouse;
    c. in combination with a keyboard;
    d. in combination with both a mouse and keyboard;
    e. other. Please elaborate.
5. Which benefits do you see this prototype having that a keyboard and mouse don't have?

6. Which benefits do you see a keyboard and mouse having that this prototype doesn't have?
7. For a beginner to learn the software, which alternative do you believe would be the better option?
8. Which alternative did you feel helped you best understand your position in the virtual 3D world?

Closing remarks

9. If you could change anything on this prototype, what would it be?
10. Any other thoughts you would like to share?

Closing

That was my last question. Thank you very much for participating in my study, I greatly appreciate you spending your time to help me.

Before I leave, I would like to remind you that this interview is voluntary. At any point, if you would like to withdraw, please let me know so that I can delete all of your data.

Thank you for your time and have a pleasant day!

Appendix H – User Interview 003

EvaluationID	User Interview 003 – Prototype Test
Who	1. People who just started out learning to use a 3D software either with a professional or recreational goal in mind. 2. People with limited experience using 3D software (<= 4 years) who either actively use or have previously used 3D software.
Aims	1. Whether people find the introduced device easier to use for navigational purposes than the standard solution. 2. Whether the device helps people better understand their position in the virtual 3D space. 3. Whether the device is an appropriate addition to the toolset of 3D software users.
Dates	29 April 2020 =>
Creator	Sigurd Sæther Sørensen
Research Domain	Tangible User Interface and Virtual 3D Spaces
Research Question	"Whether a Tangible User Interface could be a viable alternative to navigating a virtual 3D world".

Preparation Before the Participant Arrives

Prepare the following material for the user testing session:
1. Consent Forms
2. Interview Questions Sheet
3. Video of Unity
4. Video of TUI Prototype

Introduction

Before we begin, I would like to inform you that this interview is completely voluntary which means that you may withdraw at any time, whether it is before, during or after the interview. If you wish to withdraw during or after the interview, please let me know so that I can have all data deleted.

Please take some time to look over the information sheet you have been provided before you sign the consent form. The provided information sheet explains how your data will be treated and if you have any questions at all, please don't hesitate to ask.

Today, you are going to view a video of a prototype that I have built to explore whether a tangible user interface can be a viable alternative to navigate a 3D world.

Please follow the steps down below as the interview has been structured in a specific way to ensure valuable results.

Prototype Test & Interview

1 Standard Interface

Introduction:
For this first part, I just want you to get a bit familiar with how it feels like to navigate around a virtual 3D space using the standard keyboard and mouse. This is to give you a bit of context and a frame of reference when moving on to the prototype so that you can more easily compare the two solutions.

Interactions:
I'm going to go through a couple of interactions to let you get a sense of how it feels to navigate around using the standard interface, to give you a sense of context, before you watch the prototype video.

Please open up and watch the following video: "*Keyboard & Mouse – 3D Navigation*" and then answer the questions under the Post-tasks Questions section below.

Getting Started:

1. Move sideways to the right (pan right)
2. Move sideways to the left (pan left)
3. Move forwards
4. Move backwards
5. Look to the left
6. Look to the right
7. Look up
8. Look down
9. Find a way to move faster

Free Movement:

10. Take one lap around the racetrack.
11. Move around the 3D space for a bit until you get a sense of how it feels to navigate using a mouse and keyboard.

Post-tasks Questions:
General Feedback:

1. How do you believe it feels to navigate around using a keyboard and mouse like shown in the video?
2. Was there anything that you believe would feel confusing or unnatural when navigating around like shown in the video?

2 Prototype Test & Speak Aloud

Introduction:

For this part I'm going to show you how to navigate using the prototype in a similar way to what we did when using a keyboard and mouse. I'm going to go through the same interactions as with the mouse and keyboard and then move around freely.

There are a couple of limitations to the prototype that I'm going to mention briefly so that you know what is happening and to avoid any confusion. First of all, the prototype does currently not have any functionality for moving up and down (vertical movement). Secondly, there is currently no way to zoom in our out.

Please open up and watch the following video: "*TUI – 3D Navigation*" and then answer the questions under part 3 Interview Questions down below.

Tasks:

Getting Started:

1. Move sideways to the right (pan right)
2. Move sideways to the left (pan left)
3. Move forwards
4. Move backwards
5. Look to the left
6. Look to the right
7. Look up
8. Look down
9. Find a way to move faster

Free Movement:

10. Move around the 3D space for a bit until you get a sense of how it feels to navigate using the device.

3 Interview Questions

General Feedback:

1. How do you believe it feels like to navigate around using this device?
2. Was there anything that you believe would feel confusing or unnatural when navigating around using this device?

Comparison:

3. Which way do you believe you would prefer to navigate around a 3D space, keyboard and mouse or the prototype?
    a. Why do you prefer that option?
4. Do you believe the prototype would be most beneficial when used: (please explain why you believe so)
    a. by itself;
    b. in combination with a mouse;
    c. in combination with a keyboard;
    d. in combination with both a mouse and keyboard;
    e. other. Please elaborate.

5. Which benefits do you see this prototype having that a keyboard and mouse don't have?
6. Which benefits do you see a keyboard and mouse having that this prototype doesn't have?
7. For a beginner to learn the software, which alternative do you believe would be the better option?
8. Which alternative do you believe helps you best to understand your position in the virtual 3D world?

Closing remarks

9. If you could change anything on this prototype, what would it be?
10. Any other thoughts you would like to share?

Closing

That was my last question. Thank you very much for participating in my study, I greatly appreciate you spending your time to help me.

Before I leave, I would like to remind you that this interview is voluntary. At any point, if you would like to withdraw, please let me know so that I can delete all of your data.

Thank you for your time and have a pleasant day!

Appendix I – Information Sheet 002 & 003

INFORMATION SHEET

Whether a Tangible User Interface could be a viable alternative to navigating a virtual 3D world.

Sigurd Sæther Sørensen, *Main Researcher*
Ben Matthews, *Chief Investigator*
Lorna Macdonald, *Project Supervisor*

Invitation

You are invited to participate in a study exploring people's perspectives on how tangible interactions can be used to navigate virtual 3D spaces. The study is being conducted at the School of Information Technology and Electrical Engineering at the University of Queensland as a student thesis project in the Master of Interaction Design.

Why have I been invited to participate in this study?

For this stage of the study, we are seeking adults who are willing to share their perspectives on this area of technology development by being part of a prototype testing session and interview.

'What if I don't want to take part in this study, or if I want to withdraw later?'

Participation in this study is voluntary. It is completely up to you whether or not you participate. If you wish to withdraw from the study once it has started or decline to answer particular questions, you can do so at any time without having to give a reason.

'What does this study involve?'

If you agree to participate in this study, you will be asked to sign the Participant Consent Form.

This study involves testing of- and answering interview questions regarding a developed prototype in the space of Tangible User Interfaces to navigate virtual 3D worlds. The aim of this prototype is to answer whether a tangible user interface could be a viable alternative to navigate a virtual 3D world.

'Are there risks to me in taking part in this study?'

You will be asked to share information about your experiences and expectations of emerging and future technologies. You might find the discussion inconvenient or potentially emotionally upsetting. You can decline to answer any question that you do not wish to answer without having to give a reason.

'Will I benefit from the study?'

Participating in the study will not directly benefit you. This study aims to further knowledge and may improve how we design technology in the future.

'How will my confidentiality be protected?'

All the information provided by you in the study will be confidential. Any information you give us will be stored securely and only shared with people within the research team. Audio recorded interviews will be transcribed, removing all identifying information and then the audio files will be destroyed. Any published data will have information which identifies identity removed. We will store the data for up to 5 years.

'What happens with the results?'

After analysis, the grouped findings from all participants will be used to help design a system navigating a virtual 3D world. It will be written up for a student report. In any publication, information will be provided in such a way that you or your location cannot be identified. You can also receive a copy of the results if you like.

'What should I do if I want to discuss this study further before I decide?'

Please feel free to contact the main researcher at this e-mail with any questions regarding the study.

s.soerensen@uqconnect.edu.au

'Who should I contact if I have concerns about the conduct of this study?'

When you have read this information, you can discuss the study with the local researcher and ask any questions:

Sigurd Sæther Sørensen
0413 665 557

This study adheres to the Guidelines of the ethical review process of The University of Queensland and the National Statement on Ethical Conduct in Human Research

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Whilst you are free to discuss your participation in this study with project staff (contactable on 0413 665 557), if you would like to speak to an officer of the University not involved in the study, you may contact the Ethics Coordinators on +617 3365 3924 / +617 3443 1656 or humanethics@research.uq.edu.au

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Thank you for taking the time to consider this study