Getting comfortable in the zone with S3DComfortZone

by

Wallace Balaniuc

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Abstract

The ultimate goal of game developers is to produce content that engages and immerses their audience. Throughout history several technologies have been developed and utilized by game developers to increase engagement and immersion. One such technology is stereoscopic 3D (S3D) which creates the illusion of depth through a combination of monocular and binocular cues all of which are displayed using a flat two-dimensional image. A major hurdle of S3D is the feeling of nausea or discomfort when viewing S3D content such as 3D movies or wearing virtual reality headsets. Nausea can be caused by several factors but is predominantly influenced by the vergence-accommodation conflict which occurs when the eyes tilt inward to focus on the depth of the display but also attempt to process objects that are at a different depth position relative to the display, also called simulator sickness. The depths at which objects may be perceived comfortably varies depending on factors such as distance to display. With the wide variety of S3D technologies available it becomes imperative to understand the bounds of comfortable viewing across devices and technologies. The comfort zone refers to a volume of space, often surrounding a display, in which an object placed within the space should be seen comfortably by the user. This thesis presents two experiments that were designed and conducted to understand and elaborate on the previous works definition of the comfort zone. The first experiment examined the effects of a rich background versus a black background on comfort levels. The second experiment validated a comfort zone visualization tool.

This thesis hypothesizes that the comfort zone visualization tool would effectively illustrate the comfort zone and result in virtual objects being viewed more comfortably. Game designers would be able to develop content for several stereoscopic devices in tandem while having confidence that the virtual objects will be perceived comfortably. The results of these study 2 suggest that the comfort zone visualization tool is an accurate depiction of the comfort zone and is consistent with prior literature in its definition. They also demonstrate the accuracy of the tool across two distinct S3D devices (3DTV and HMD). Of particular interest is that the results show that the

device used to display S3D content also plays a major role in users comfort level. It is recommended that developers of S3D content be cognizant of the device parameters being utilized and realize the effects of distance to display on the comfort zone in order to tailor 3D content to multiple stereoscopic devices in tandem.

Chapter 1

Introduction

1.1 Motivation

Developing games and other media in 3D provides several challenges for designers. Challenges such as reducing simulator sickness and utilizing the S3D effect in the context of the game is still a novel issue to overcome. This challenge is heightened when developing for multiple stereoscopic 3D devices, each with their own unique construction, configuration and setup resulting in varying visual output despite identical virtual content. Providing confidence to game designers that their content will be perceived comfortably across multiple devices can allow designers to focus on other issues during development.

Game and media developers strive to produce immersive content for their audience. With new forms of media emerging, it becomes imperative to understand the nuances of the technology and its impact on user experience to enable developers to create immersive content. Many factors influence the user experience ranging from the display technology used to the content being displayed, to specific sequences such as objects moving towards the edge of a display creating a ghosting effect as shown in figure 1.1. These multi-tiered issues present great challenge to content creators that distract from developing content.

Figure 1.1: Ghosting effect on an in-game object. Notice the faint outline of the wolf object towards the right side of the screen. [1]

Stereoscopic 3D (S3D) is a pillar in the popularity behind virtual reality. Stereoscopic 3D content presents viewers with an image on a 2D display containing two slightly offset images that stimulates a sense of depth in the brain also know as stereopsis [2]. These 2 images on the 2D display are interpreted and fused by the brain to give the sense of depth. The ability to fuse two distinct images presented to each is called binocular vision when referring the human visual system [3]. Figure 1.1 shows a single image constructed from 2 separate images, each image intended for a single eye.

The inception of Virtual Reality (VR) can be traced back to Ivan Sutherland in 1964 with the invention of SketchPad [4]. Virtual reality devices have remained a niche product throughout the past 50 years due to high cost and low graphical fidelity. Devices throughout this period were utilized in academic and military research endeavors with little to no influence on main stream media. The first exposure of virtual reality to mainstream consumers was with the Nintendo Virtual Boy in 1995. The display utilized red-coloured LEDs and provided a low resolution display capable of rendering 2D sprites and low-quality 3D graphics [5]. The Virtual Boy

suffered from unfocused design specific to stereoscopic 3D [6]. An example include positioning 2D sprites on different depth layers as well as resizing the sprites to unify the sizes of all virtual objects. But the resulting objects were strenuous to view and often were unclear as to whether objects were in front of, or behind adjacent objects causing confusion in the players vision [5]. Several years passed without a successful commercial device capturing the mainstream. This changed drastically with the creation of the Oculus Rift in 2011 by Palmer Lucky. The Oculus Rift presented the first virtual reality device intended for mass market consumption and garnered significant popularity within the gaming community particularly with renown game developer John Carmack who presented his video game Doom 3 at the 2012 Electronic Entertainment Expo using the initial prototype of the Oculus Rift [7]. Since the announcement of the Oculus Rift, readily available mass-market virtual reality devices have become more prominent with the introduction of the HTC Vive, Google Cardboard, Playstation VR and several devices.

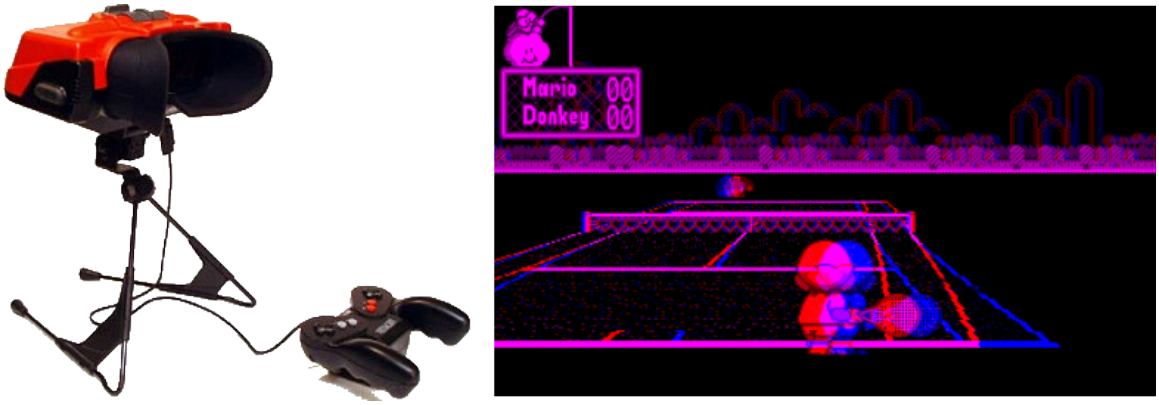

Figure 1.2: On the left the Virtual Boy head mounted display along with controller. On the right the game Mario's Tennis (1995) with in-game footage. [8]

Figure 1.3: The Oculus Rift development kit 2. [9]

With hardware making strides to mainstream media it is natural to see software follow closely behind in supporting virtual reality devices. Accessibility to low cost, high fidelity virtual reality devices has spurned the need for software to allow for content to be created for these devices. Amongst the first virtual reality supported software platforms were Unity3D and the Unreal Engine v4 game engine. Game engines such as those listed provide an accessible interface for state-of-the-art graphics and development tools for games as well as other digital content. Virtual reality support amongst these game engines come in the form of plugins that provide simple one-button solutions that simply enable virtual reality support without any guidance in proper design for the medium. These plugins allow the game engines to render content to supported virtual reality devices and lack any guidance or insight in proper design for the devices.

Combining the rise of VR-supported hardware with integration to commercial game engines creates a development pipeline that also extends beyond gaming. Industries such as training and serious games may benefit from increased understanding of S3D development and profit from a tools within the development pipeline that will increase their ability to make high quality experiences.

Given the rise of virtual reality devices in the past 50 years coupled with non-intuitive software support for prominent game engines, there is a clear gap in providing game designers with the proper information required to design content for virtual reality devices. Without the ability to have confidence in the work being created, content designers will falter in their creations resulting sub-par experiences for users and potentially hurting the appeal of virtual reality. Research into the human visual system has identified elements that affected users while interacting in virtual reality such as simulator sickness which became a major area in research. Average game developers do not have access to the latest research results with regard to virtual reality making it difficult to create effective content. There is a gap in the tool-chain at the disposal of game designer enabling them to make informed decisions on the development of virtual reality enabled games. It is imperative that the tools enable designers to understand how the content will impact user experience as well as provide instantaneous feedback on how content should be modified to maximize user experience.

User experience does not have an agreed upon definition amongst the scientific community and is often used in a variety of contexts [10]. Given the lack of a formal definition, there are agreed upon factors that influence the users experience such as immersion, presence, flow, and others. One important factor influencing user experience is presence, often described as the users feeling of "being there" inside of the virtual world [11]. While presence is often interchanged and confused with immersion however in this thesis I adopt a working definition by Slater et al [12] as presence being a psychological acceptance of a virtual world by the user whereas immersion focuses on removing real world sensations and replacing them with sensation related to the content being presented . It has previously been shown that an increase in presence will lead to an increase in user experience [13]. Several factors influence user experience with S3D content which include the visual appearance of the content displayed, realism of the content shown, comfort level of the user and others [14]. Game and media developers continuously strive to maximize the users experience within their products and enhancing a users sense of presence helps lead to that goal. Currently, developers are unaware of the fine difference between stereoscopic devices. While stereoscopic devices presents the same virtual content, differences in device parameters creates the possibility of visual disparity between devices. This creates the chance that objects are uncomfortably perceived in one device, yet comfortably perceived in another leading to possible difference in user experience across devices.

Designers currently do no have aids integrated into their development pipeline that informs them of the difference across devices.

Empowering content developers with information pertaining to the comfortable viewing zone provides them with more information regarding stereoscopic 3D device constraints allowing them to be better informed in making decisions with respect to their application and modify content to maximize comfort and as such increase user experience. Urvoy et al [15] states that comfort is a subjective feeling of unease that is influenced by many factors including distance to the virtual objects, display being used and specific content of the experience. A major influence on the comfort level of the user is related to distance the viewer is from the virtual objects. Virtual objects that appear too close to the user may cause the eyes to cross in order to properly fuse the two distinct images or not fuse the images at all. Virtual objects appearing too far may prevent the users eye from converging properly thus preventing any fusion at all [16]. Therefore a comfortable viewing area must be defined to define a volume of space in which virtual objects presented to a user will have optimal chance of being perceived comfortably.

The effects of the environment itself may also have a profound effect on depth perception among users. A major concern with regard to stereoscopic 3D is the phenomena of edge violations in which virtual objects appears in front of the display plane and are present only one of two eyes before appearing to the other. Spottiswoode [17] invented the floating window technique which utilizes are artificial border created within the virtual world itself to compensate for the edge violation as seen in figure 2.7 . Iterations of the floating window technique include a dynamically floating window with options to fine-tuning properties such as size and position of the window [18] and utilizing a floating window on mobile applications [19]. The floating window technique was found to bias users depth perception which may be a result of clutter within the virtual scene [20]. This leads to the question of how richness of a virtual scene impacts depth perception and more broadly the comfort of the user.

1.2 Stereoscopic 3D

Stereoscopic 3D was popularized in mainstream media through films in the 1950s. The 3D effect was produced by projecting two images, one red and one blue, onto a single screen which was then separated in the human eye with the help of red and blue lensed anaglyph glasses [21]. At the time, the 3D effect was used as a novelty as an attempt to attract individuals to the cinema but could not overcome a declining film industry as a whole [22]. More recent 3D applications within the film industry

can be traced back to James Cameron's film *Avatar* which reinvigorated the notion of 3D among the general populous [23]. Subsequent films added the 3D effect but were not successful among viewers who believed the effect did not add anything of value to the film. Unlike *Avatar*, these films were not created with stereoscopic 3D in mind and were not incorporated within the development of the film [24].

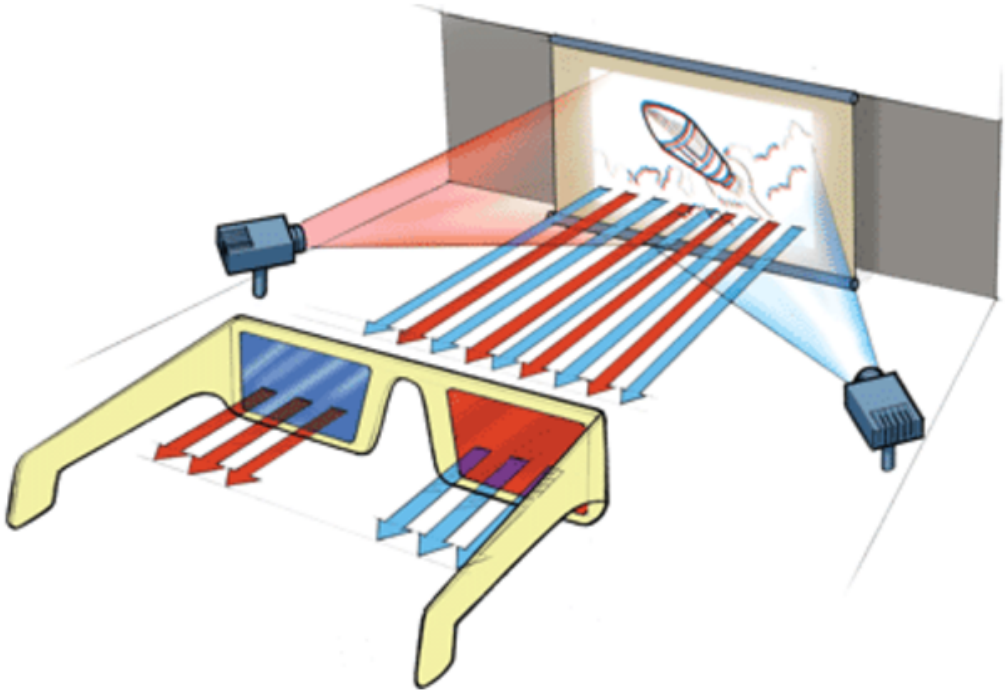

Figure 1.4: Anaglyphic 3D produced using two slightly offset images projected in red and blue. Viewer receives the intended image by filtering the corresponding coloured image out. [25]

Video games often share many parallels with the film industry and likewise have some history with stereoscopic 3D. The history of stereoscopic 3D in games often begins with the Nintendo Virtual Boy released in 1995. It represented the first mainstream device to support stereoscopic 3D. The Virtual Boy contained oscillating mirrors which would provide each eye with an array of lines which the player would focus on. Among several cited reasons for the failure of the Virtual Boy, the most common discussed among researchers and population was the discomfort caused by the posture needed to play the device as well as reports of motion sickness and eyestrain after prolong periods of use [26].

1.2.1 Issues with Stereoscopic 3D

One of the greatest factors with regard to stereoscopic 3D is known as simulator sickness. Simulator sickness is most commonly caused by the perception of motion by the eyes but no actual motion occurring causing a conflict within the brain called a visual-vestibular conflict [27]. In the context of digital media, simulator sickness is linked to conflicts in vergence distance and focal distance. In normal circumstances, the human eyes pivot slightly inwards to focus on an object with the vergence and focal distance being equal [2]. When presented with a stereo image, the distance to the display (focal distance) may not be equal to the distance of the object being presented in 3D (vergence distance) as shown in Figure 1.5 [28]. The sickness is often described as disturbing or nauseating [29].

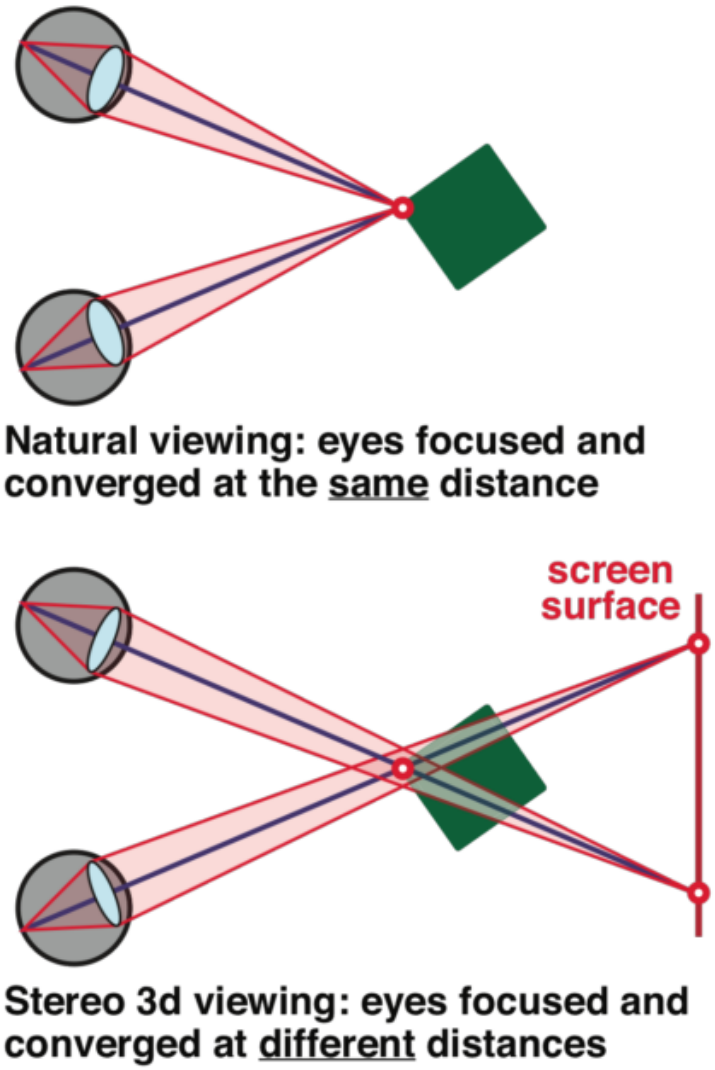

Figure 1.5: Conflict between vergence distance and focal distance [29]

1.3 User Experience

Kankainen [30] describes user experience as being personal and that the involvement with a product is based on skill, knowledge and previous usage of similar products. Desmet et al [31], [32] also defines user experience as an interaction with the product and the subsequent feelings and emotions from interacting with the product. Hassenzahl [33] described attributes of user experience as being enjoyable, being pleasurable and being joyful when using a product. Hassenzahl notes that experience of the user may be different than the intended experience created by the designer.

The notion of defining user experience for stereoscopic 3D content provides us interesting challenges to consider. Similar to the film industry, S3D was used objectively as a novelty for specific games. The impact stereoscopic 3D has on user experience can be both positive and negative. Tam et al [34] outlined several advantages including a preference to stereoscopic 3D when viewing a sequence of images, depth perception in 3D, and sharpness of stereoscopic sequences. Further advantages include animations containing depth information being perceived faster in 3D [35], as well as the user receiving greater spatial information and geometrical information of 3D objects [36]. As stated earlier, a large disadvantage to stereoscopic 3D is simulator sickness which has a negative effect on user experience. Among other disadvantages of stereoscopic 3D to user experience is that the stereo images are dependent on the display being used [37]. These difference between displays creates a problem where content created to maximize user experience for one display may suffer when presented on other displays. It is then necessary to bridge the gap and give developers the information it requires to ensure a consistent user experience across displays.

1.4 Purpose of this Work

This thesis explores the quantification of a stereoscopic 3D comfort zone for virtual reality and the creation of a visualization tool. Two separate studies were performed to confirm Chen's[38] mathematical model of the comfort zone and to validate the accuracy of a comfort zone visualization tool. The first study was a confirmatory study to investigate the mathematical model of the comfort zone defined by Chen et al [38]. This study also compares the comfort level of the user when an object is presented to them in an environmentally rich background versus a simple black background. This comparison is essential observing the effect of other ambient objects on the perceived comfort of the object being focused on and whether there is disparity between no background and a rich background. The second study evaluated the accuracy and

effectiveness of S3DComfortZone, a tool to visualize the comfort zone. The tool was used as an aid to develop a similar scene as study 1 but with modifications made to adjust for the comfort zone of a 3DTV as well as the Oculus Rift.

1.4.1 Hypothesis

It is hypothesized (H1) in this thesis that if identical objects are presented to the user in an environment with a rich background consisting of other contextual objects, there would be a difference in user comfort level compared to a simple black background. It is also hypothesized (H2) that given previous models of the comfort zone that a visualization tool of the comfort zone would accurately represent the comfort volume across multiple devices.

1.4.2 Thesis Structure

Following this section of the thesis, Chapter 2 provides a background and literature review of stereoscopic 3D. An overview of the human visual system, past literature into the zone of comfort and visual fatigue, as well as history of stereoscopic 3D in film, media and games is presented. Past and current design methodologies are discussed and an overview of the impact of presence and immersion within stereoscopic 3D is reviewed. Chapter 3 outlines study 1 confirming past models of the stereoscopic 3D comfort zone and testing hypothesis H1. Chapter 4 describes the creation of the S3DComfortZone tool. Chapter 5 presents study 2 which compares the accuracy of S3DComfortZone across a 3DTV and an Oculus Rift. Chapter 6 discusses the results and implications of this work and outlines future work. The overall result of this thesis is the foundation of a visualization tool for the comfort zone that was developed using past literature and tested in a controlled environment.

Chapter 2

Related Work

This chapter presents existing research in the area of stereoscopic 3D as well as current design practices utilized in implementing stereoscopic 3D content. First, an introduction to stereoscopy and the human visual system is provided. Second, current design techniques and methodologies utilized in video games and film for implementing 3D content. Third, user experience for 3D content. Finally an exploration of existing tools used by game designers and filmmakers when creating stereoscopic 3D content is provided.

2.1 Stereoscopy

Stereoscopy and the understanding of how humans visually perceive the world has been an active area of research since Wheatstone [39] invented the stereoscope . Ian Howard [2] describes stereoscopy or "stereoscopic vision" as the ability to perceive three dimensional structures in the world with either one eye, referred to as monocular, or two eyes, referred to as binocular. Objects throughout the world provide visual cues that supply information to individuals in determining that objects position, orientation and relationships to the world and other objects [29]. Monocular cues include object size[40], object occlusion [41], lighting information [22], aerial effects such as hazing [42] and focusing [2]. These aspects more specifically affect the ability to perceive depth. An object's perceived size has a bearing on depth due to object appearing smaller as it moves further away from the viewer [2]. Likewise, when one object occludes another object the natural conclusion would be that the former object is in front of the latter and thus being at a further depth. Lighting information such as the presence of shadows provide height cues and is often combined with occlusion to provide additional depth information [43]. Aerial information distorts light bouncing off distance objects which must travel through an increase in air and water molecules

causing the resulting image to become blurry and distorted [44]. Blurriness is also a by-product of an eye's ability to focus. This is commonly seen in photography using depth-of-field as objects in the foreground are often kept sharp versus objects in the background become blurry and creating a depth separation between the two visual planes [45]. Comparatively, binocular cues rely on disparities between the two images received by both eyes that is dependent on the vergence [29] and accommodation [46] of both eyes. Vergence is the movement of both eyes, typically inward, such that their independent sight lines will cross (or converge) at the object being focused on [47]. Accommodation refers to the eye altering the shape of its lens to maintain focus on the object being viewed [48].

Of particular interest to S3D developers is the relationship between vergence and accommodation as it plays a major factor in causing simulator sickness. The vergence distance refers to the distance between the eyes and the point in which their sight lines cross. The focal distance is the distance from the lens of the eyes to the point being focused on. Under normal circumstances both the vergence distance and focal distance are equal, producing a clear and focused image of the desired viewing target but also blurs objects in the viewers periphery [28]. The relationship between vergence and accommodation becomes noticeable with the inclusion of a 3D display as it often results in a conflict between the vergence distance and focal distance. The result of this conflict often leads to visual fatigue and simulator sickness from the viewer. This conflict arises as a result of the eyes natural tendency to focus on the display surface itself while the vergence distance can occur at distances not equal to the distance to the display. This is visualized in Figure 2.1 wherein panel (A) shows both the vergence and focal distance being equal resulting in the image seen in panel (C). With the inclusion of a display screen as seen in panel (B) the focal distance is not equal to the vergence distance resulting in the image seen in panel (D). Comparing panel (C) to panel (D) it becomes apparent that under normal circumstances the point of interest becomes focused with blurred peripheries versus the entire image being unnaturally in focus.

Psychological	Immersion	Brown and Cairns [49] describe features of immersion as relating to the concept of flow by noting parallels that both immersion and flow require attention and that the sensation of time can be manipulated or even lost when feeling immersed on in optimal flow state.
	Fun	Federoff et al [50] describe fun as a combination of user interface and game play. Game play that contains goals and challenge, and allows for mastery of tools to reach goals creates satisfaction in the activity. Federoff continues by discussing the notion of fantastical worlds meant to immerse players in the world which results in an enriching experience.
	Presence	Riva et al [51] state that *when we experience strong mediated presence, our experience is that the technology has become part of the self...*". They continues by stating that optimizing presence will improve the experience in interactive media.
	Involvement	Schild: "results related to attention and cognitive involvement indicate more direct and less thoughtful interactions with stereoscopic games, pointing towards a more natural experience through stereoscopy." [52]
	Engagement	McMahan [53] describes engagement as a near-obsessiveness state players reach with a game called *deep play*. Furthermore, engagement is labeled as a combination of immersion and nondiegetic levels of involvement that culminates into an increased sense of presence.
	Flow	Schild et al [52] described a mechanism in evaluating user experience in games but utilizing the Game Engagement Questionnaire. In the creation of the Game Engagement Questionnaire, Brockmyer et al [54] describe flow as the feeling of enjoyment that is a result of a balance between skill and challenge the completion of an activity.
Physiological	Interpupillary Distance	The interpupillary distance between the eyes results in each eye receiving two distinct images of what is being viewed. Lambooij [48] states that people with a smaller IPD perceive more depth than individuals with a large IPD.
	Monocular cues	Cues involving a single eye include the perceived size of the virtual object [40], occlusion of the object [41], lighting characteristics [22] of the environment and aerial effects such as hazing [42], [2].
	Binocular cues	Binocular cues are a result of both eyes working together to view an image through the coupling of vergence and accommodation [55]. Hoffman [55] states that an uncoupling of vergence and accommodation will lead to discomfort and fatigue for the viewer.

Table 2.1: Psychological and physiological factors that affect user experience

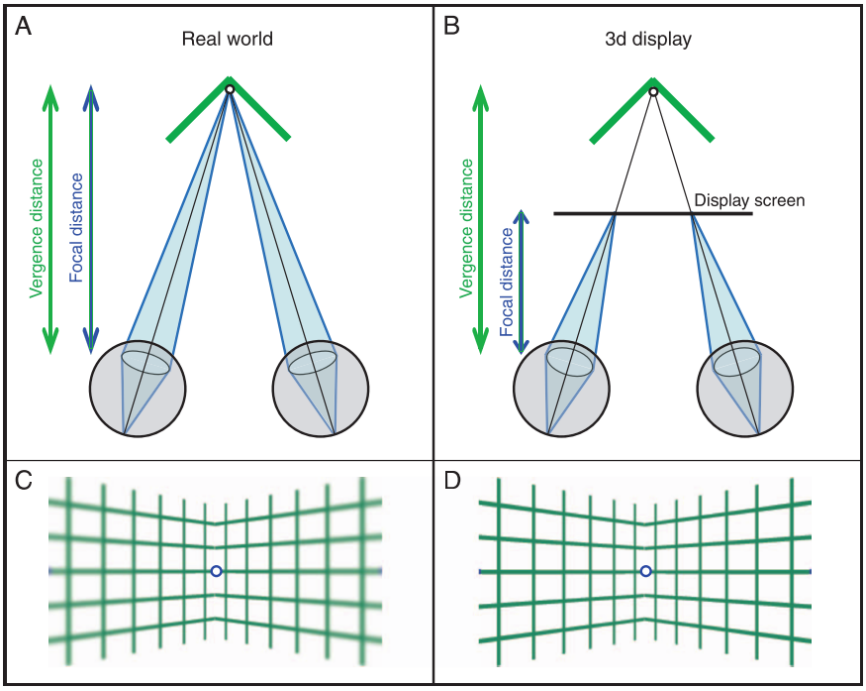

Figure 2.1: Vergence & focal distance disparity. [28]

Physiologically, one of the greatest factors that affect vergence and accommodation is the distance between the viewers eyes, called the interpupillary distance (IPD) [48]. The distance between eyes results in each individual eye receiving distinct images of the visual stimuli shifted parallel to the inter-pupil plane. This shift can be further exaggerated by maintaining the position of the eyes but move the point of focus away from the center of view creating a skewed offset [3].

2.1.1 Zone of Comfort & Visual Fatigue

Each of these factors contribute to the notion of a zone of comfort described as a region in which vergence and accommodation conflicts will not cause discomfort. The shape and size of the region is a function of the vergence and focal distance and that shape alters depending on these factors [56]. This defined zone ensures a reasonable level of comfort in viewing three dimensional objects without experiencing visual fatigue or visual discomfort. Visual fatigue is described as a decrease in the performance of the human vision system [16]. Figure 2.2 shows the geometry of the zone of comfort. The zone of comfort is confined between the near clip plane and the far clip plane as well as within what is viewable through the display. These planes represent an acceptable amount of positive and negative parallaxing that the human visual system can withstand [28]. The amount is dependent on factors such as distance from the display and physiological differences between individuals.

An equal distance between the vergence and accommodation points is referred to as *zero parallax*. A vergence distance greater than the accommodation distance is referred to as *positive parallax* and contrarily a vergence distance less than the accommodation distance is referred to as *negative parallax*. It should be noted that there is a potential for convergence of the eye to not occur resulting in *divergent parallax*. As individuals approach the zero parallax plane, according to the zone of comfort model presented by Chen et al [38], the distance from the zero parallax plane to the far clip plane and the near clip plane decreases. This would show the zone of comfort shrinking.

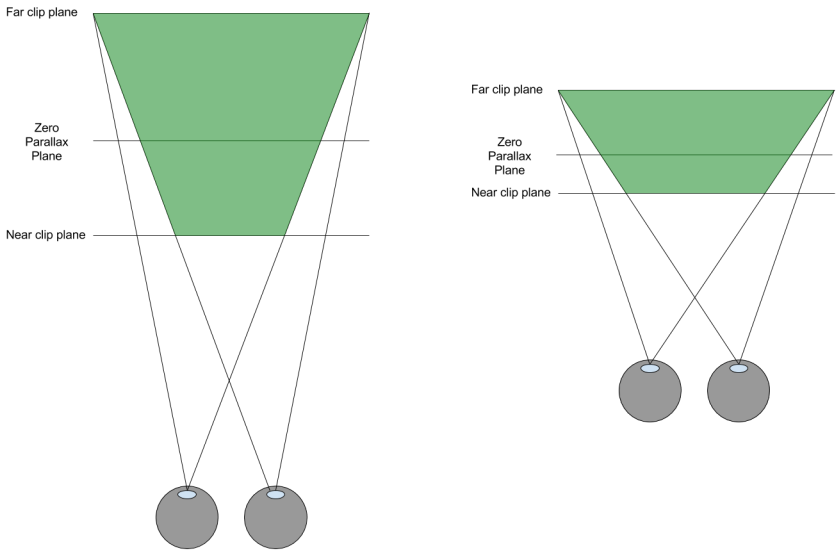

Figure 2.2: Illustration of the zone of comfort

The most common source of visual comfort arises from binocular asymmetry which is best described as a disparity between the left and right images of a stereo image [57]. Several differences between the stereo images can result in visual fatigue which include:

- Anomalies of binocular vision [58]
- Distortion between left and right eyes [59][58]
- Vergence-accommodation conflicts [60]
- Excessive binocular parallax [61]

Anomalies of binocular vision refer to the stereo images received by the eyes being significantly different in pattern matching, contours, lighting and contrast information resulting in binocular mixture, binocular rivalry and binocular luster. *Binocular mixture* occurs when a homogeneous image is received by one eye with the other eye receiving a complicated image. *Binocular rivalry* is a result of each eye acquiring dissimilar high contrasting images [62] [48]. Finally *binocular luster* is the result of the luminance or colour value of the two objects being different [58].

Distortion between the images received in each eye are produced when the angle caused by vergence induces incorrect vertical (*keystone distortion*) or horizontal (*depth plane curvature*) parallax [58]. The resulting image per eye would appear trapezoidal and have a great effect on visual discomfort [59]. The effect is visualized in Figure 2.3. Another common distortion present in stereoscopic 3D viewing is referred to as *crosstalk*. This occurs when an eye sees a part or all of an image intended for the other eye or vice versa [57]. The result is a faded image superimposed on the main view often referred to as "ghosting" [63]. Crosstalk levels between eyes should be kept at a 1% level or lower [64].

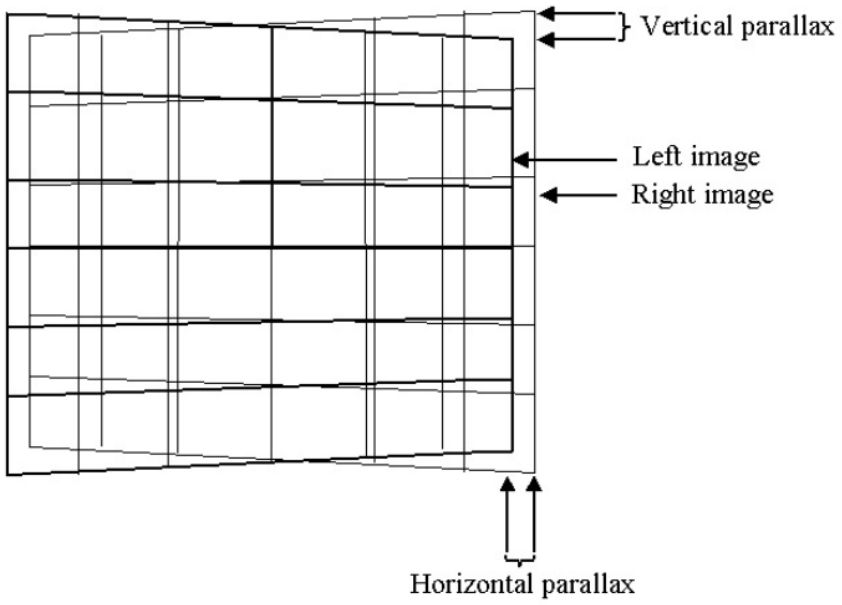

Figure 2.3: Keystone distortion and depth plane curvature. [58]

With the introduction of stereoscopic 3D displays, there is a decoupling effect between vergence and accommodation which has been theorized as a major factor in visual discomfort [16]. Under usual circumstances both vergence and accommodation work in tandem to produce a clear image but new displays automatically dictate

focal range of the eyes while manipulating the vergence distance. Vergence and accommodation conflicts arise from a mismatch between the vergence distance and focal distance.

Excessive binocular parallax occurs when the image viewed by the eyes differ substantially [61]. This phenomena also relates to rapid changes in parallax depths causing the eyes to quickly shift between varying depths. Continuous changes, such as an object moving from the foreground to the background, is generally tolerable as the shift is gradual [61].

2.1.2 Stereoscopic 3D in Film & Media

There has been a recent resurgence of interest surrounding 3D by the public and the introduction of consumer-grade VR. One large driving force behind this is the adoption of 3D within the film industry. Many films have been released within the past decade that utilized stereoscopic 3D including James Cameron's *Avatar*, Disney's *Toy Story 3* and Pixar's *Up*. Within traditional 2D viewing, the boundary of the object displayed on the screen were confined within a 2D display and changes of depth among these object did not alter the viewers perception. The vergence and focal distance are equal; ranging from the viewers eyes to the display. With the utilization of 3D in film, the depth and motion within the depth axis of objects become important and the idea of a comfortable viewing zone likewise becomes critical [65]. As shown earlier, a mismatch between the vergence and focal distance can result in eye strain and blurred vision which is understandably unwanted by the creators of the film [16].

The earliest device for entertainment that implemented the 3D visual effect was the *stereoscope* developed by Dr. Wheatstone in 1838 as seen in Figure 2.4 [66]. The device consisted of two 45° mirrors used to reflect two photographs of the same object taken at slightly offsetting angles. The reflection of the two photographs are then bounced into the viewers eyes which are positioned in front of guiding holes. The result is the fusion of both photographs into a single image appearing fully 3D [67]. From this point many iterations of dedicated stereoscopic devices were created for entertainment purposes but eventually lost it's appeal to films towards the beginning of the 20th century. Stereoscopic content became scarce until the 1950s when stereoscopic 3D was being utilized by many films as a novel addition to viewing films. Early 1950 films utilized anaglyph glasses which used colorized filters (red for left and cyan for right) for each lens to differentiate the image received by each eye as shown in Figure 2.5 [21]. This was replaced later in the 50s by the use of polarized 3D lenses that filtered natural light intended for each individual eye as shown in Figure

2.6. The 3D image was created by shining two projectors onto the screen with each projector displaying an image for one intended eye. While both methods achieved the desired S3D effect, both resulted in simulator sickness and eventually fell out of favour the public [23].

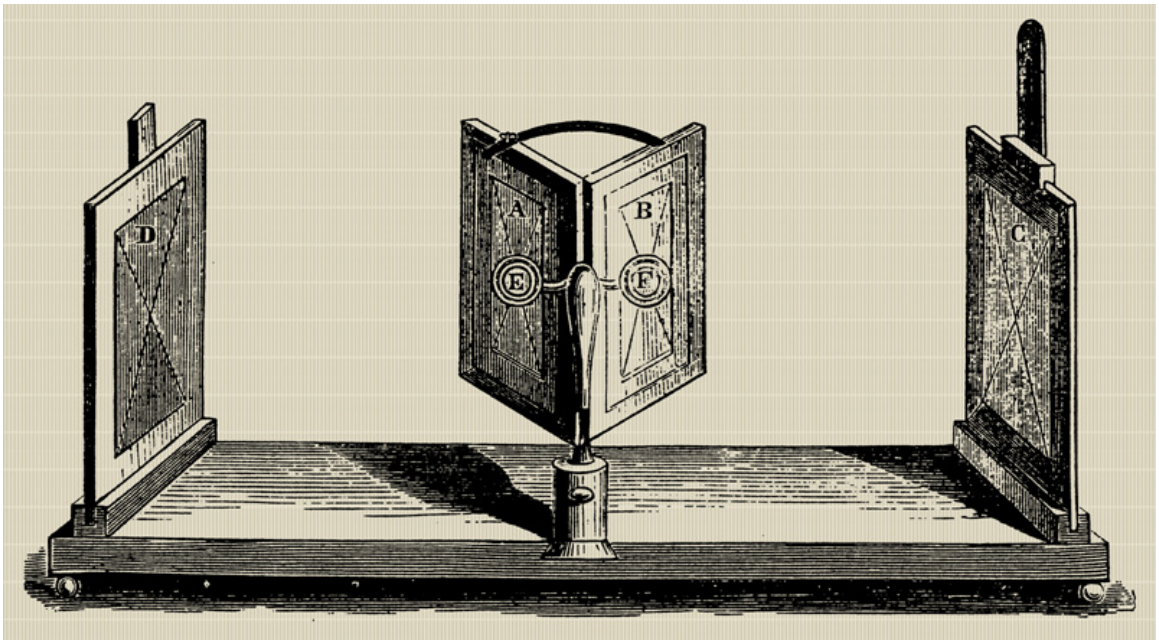

Figure 2.4: Dr. Wheatstone's Stereoscope. Illustrates binocular depth perception by reflecting 2 images located to the side of the viewer into the viewers eyes with angled mirrors [39]

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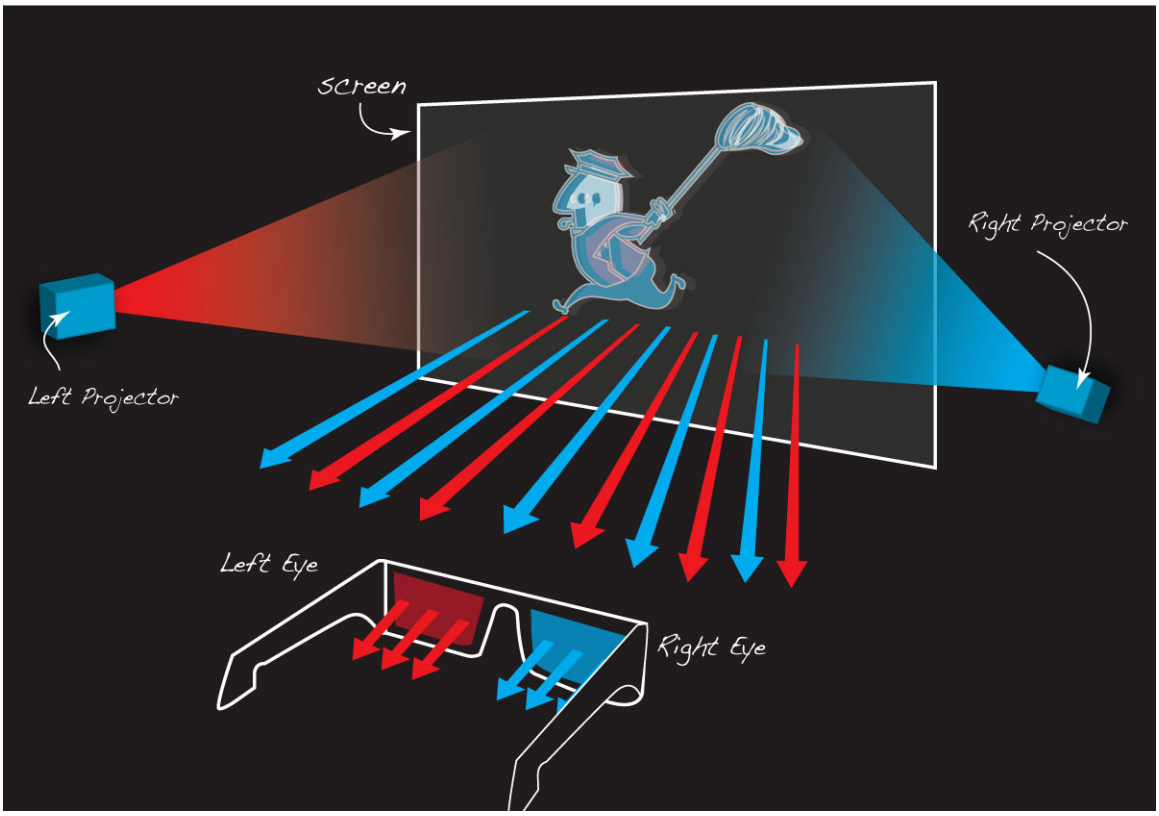

Figure 2.5: Illustration of anaglyphic glasses. This shows two projects each displaying a red and blue offsetting image onto a common display. One of the two lenses will filter out a specific colour with the other lens filtering out the other. In this example the left lens is filtering out the blue projection and the right lens is filtering out the red projection [68]

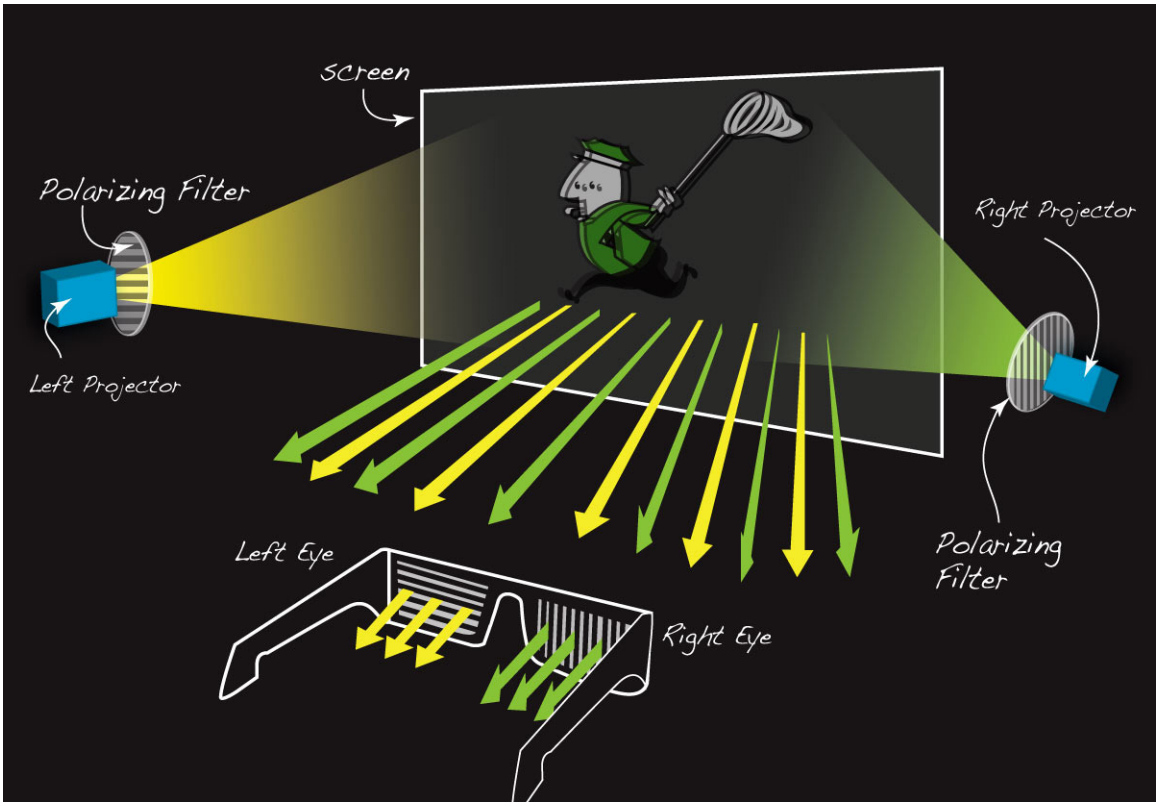

Figure 2.6: Illustration of polarized glasses. Similar to anaglyphic glasses, polaized glasses require two projector showing a slightly offset image onto a common display. Each projector is fitted with a polarization filter that is matd by one of the two lenses the user is wearing. The major difference versus the anaglyphic glasses is that the produced images are natural in colour and not skewed toward a tint of red or blue. [68]

Anaglyph and polarized glasses as shown in 2.5 and 2.6 are examples of *passive shutter* glasses. *Active shutter* glasses contain similar lenses as polarized glasses but are coupled with fast-acting shutters that alternates in blocking a single eye from viewing the image for a short period of time [69]. The alternating shutters are synchronized with a 3D capable device such as a television which subsequently alternated between two distinct images intended for each eye. Thus an image for the left eye will be displayed on the screen as well as the left shutter be open while the right is covered [70].

From its inception the 3D effect in the film industry has received resistance from creators and actors. Initial arguments surrounding 3D stemmed from the fact that the 3D effect was not spawned as a result of the artistic community but rather intrusively created through technology and science [17]. It was further argued that the 3D effect is a distraction and that it takes away from the narrative created from the film [23].

There have been several techniques utilized by film industry to try and combat the negative effects of stereoscopic 3D. A popular technique by creators is to view the boundaries of the screen similar to the boundaires of a window. The object displayed on the screen would appear similar to viewing the same object through a window [71]. A major issue with this technique is known as a *stereo window violation* where objects appear in front of the edge of the border but then become occluded as it moves towards the edge [29]. The object will be visible in one eye but not in the other causing a ghosting effect. Bob Whitehill, stereographer at Pixar, was quoted as saying "we want stereo 3D to be a window into a new world, not draw attention to itself" with regard to creation of films such as *Toy Story* and *Up*. A method developed to overcome this edge violation is known as the "floating window" technique [23]. This works by creating a another window that hovers in front of the screen with adjustable borders. This will result in the initial problem object to be occluded by the floating window eliminating the window violation [18].

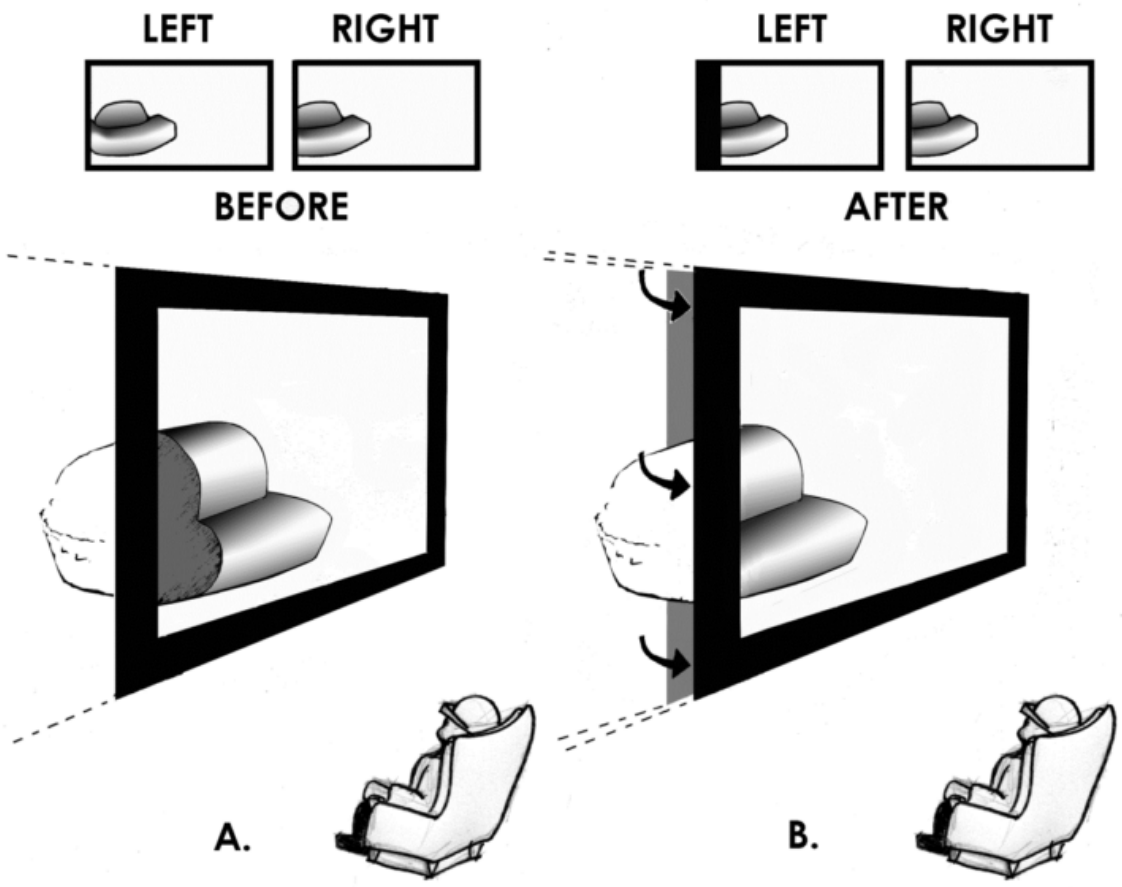

Figure 2.7: Floating Window Technique. The left image shows the the pictorial representation of a non-floating window implementation along with the subsequent image received by the left and right eye. In this scenario the object displayed is noticeably prominent in the left eye and displays additional geometry as opposed to the right causing a window violation and likely ghosting. The right images shows the implementation of a digital "floating window" in which a portion of the displayed object is occluded from the left eye thus producing a similar images as the right eye receives and preventing a window violation. [18]

An extension of the floating window was created by Gardner called the *dynamic floating window*. This extension allow for greater freedom of the borders with the floating window. Adjustment to individual border widths, heights, as well as rotational components can be achieved [18].

2.1.3 Stereoscopy in Games

Related to the implementation of stereoscopic 3D into film is the concept of implementing stereoscopic 3D content into video games. The issues present with presenting stereoscopic 3D content in video games are identical to those of film. Video game creators must be cognizant of the vergence-accommodation relationship, users sense

of visual fatigue and properly displaying content to not induce visual fatigue. One major difference between film and video games is the fact that the content being viewed is not in the control of a film director but rather the player of the game. Objects present within the game world can be displayed from a infinite number of angles and position which further emphasizes the issues presented with stereoscopic 3D.

With users controlling the camera directly, the zone of comfort stated earlier becomes increasingly important to understand and implement. The zone of comfort allows for the virtual object to be observed by viewers with minimal or no visual strain or visual fatigue. This area of this zone extends only a few centimeters behind and in front of the display [72]. Given this small area the final image displayed must be adjusted to conform to this zone in order to ensure comfortable viewing by the user. Image adjustments in film are controlled by the director who can position shots such that points of interest fall within the zone of comfort. This further illustrates the amount of control directors have in controlling what the audience will see. Comparatively, performing image adjustments in video games falls to the responsibility of game designers. Given that players are in control of the camera, algorithms must be utilized that scale the image such that objects fall in the zone of comfort. Several algorithms have been developed in an attempt to dynamically scale the image in order to conform to comfortable viewing parameters. Jones at al [46] developed a method of scaling in which the scene can be mapped to a desired depth range . Similarly, Holliman et al [73] showed a method of mapping the scene to a non-linear viewing range which allows for further customization and adherence to a defined comfortable viewing zone . As visualized in Figure 2.8, a near region and far region are defined and based on that the region of interest (ROI) is defined.

Similar work has also been produced by Chen et al [38], who has developed a mathematical models to quantify the distance to the near and far comfort planes based on the distance from the display. A value for both the near plane and far plane represent the distance from the user to the respective planes.

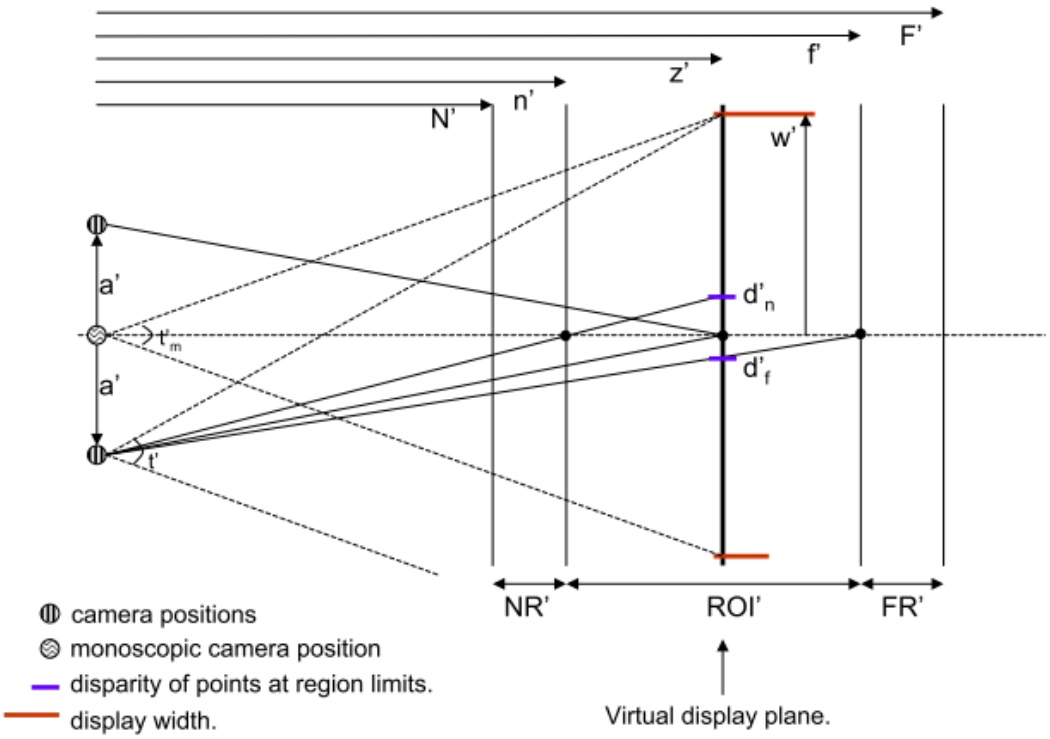

Figure 2.8: Scene geometry with near (NR), region of interest (ROI) and far (FR) regions defined [73].

A similar technique was used during the development of Sony's Killzone 3 [74]. Bickerstaff deconstructed the game into multiple depth areas as having a landscape that stretched into the distance, the players gun in the close foreground, and the remaining object between. The implementation was achieved by rendering the background landscape and foreground gun separately then compositing both images together. Without this step, Bickerstaff states that placing the gun in the comfortable viewing area would result in the remaining world appearing flat or conversely placing the background into the comfortable viewing range would lead to the gun to have excessive negative parallax and appear unnaturally in front of the display [74].

Given the number of techniques available to adjust and control the size and shape of the comfortable viewing zone, it is imperative to understand that there is no way of guaranteeing that the viewing experience will be comfortable in interactive games [75]. Other human factors have an effect on depth perception which influence the users viewing experience. This includes users interocular distance, their accommodation ability, pupil size, distance to the target, luminance of the target, and observation

time [75]. Schild et al [76] states that devices such as Nvidia 3D Vision and the Nintendo 3DS put the players in control of defining the comfortable viewing region by allowing them to adjust the interaxial distance of the two in-game cameras so that the view feels comfortable using a slider. Another method was created that presented users with two screens with identical content but with differing interaxial distances. Users were asked which of the two screens appeared more comfortable and adjustments were made to the images. Users were prompted again with the adjustments made and eventually lead to a desired setting. This indicates that a slider can be used to accurately tone the visual fidelity of the S3D image. [77].

2.2 Design

Creating a sense of depth for the user presents new challenges for designers when creating games. Stereoscopic 3D images provide more information pertaining to relative location, size, shape and orientation of objects in the environment which aid in depth estimation and object positioning within the virtual environment [36]. This additional information provides designers with new game mechanic challenges that can take advantage of the additional information without intruding on the stereoscopic effect [78]. Schild and Masuch [75] outline a catalog of design concepts associated with stereoscopic 3D games. They divide stereoscopic 3D game concepts into four categories: camera, game challenges and design ideas, game GUI and extreme S3D.

Cat.	S3D game design concepts	Perceptual considerations and possible benefits
Camera	Depth-promoting camera perspectives	Speed perception, better distance estimation, more immersive experience
	Camera interaxial adjustment	Hypostereo, hyperstereo, playing as big monsters or tiny creatures
	Non-linear depth mapping	Depth perception of both fore- and background, e.g. in racing games both track and cockpit
	Dynamic depth mapping	Maintaining stereovision comfortable and spectacular between perspectives/scene transitions
Game Challenges and Design Ideas	Depth-estimation tasks	Unbalancing depth cues e.g. texture gradient, lighting, shadows, transparency, or relative position can create optical problems, solvable through S3D
	Balancing towards easy tasks	High contrast, complex texture, bright colors, close depth ranges
	Balancing towards difficult tasks	Low contrast, simple homogeneously colored textures, far away depth ranges
	Memory tasks	No impact from S3D expected
	S3D game scenarios	Mapping real world stereo applications for gaming tasks: bullet casings, diamond reflections, etc.
	Depth-based level design	Possible impact on flow due to specifically designed variety of depth ranges in level design
Game GUI	Depth-positioning of context information and system control	Still unsolved, requires smart dynamic placement to reduce depth jumps and avoid depth cue conflicts
	Text-directed attention	Text can draw attention towards certain depth layers
Extreme S3D	Deliberate double-vision	Simulating gun-sights, image comparison tasks, simulation of drug effects
	Abusive gaming	Putting up physical strain on purpose to simulate sick characters and push towards finding a remedy

Figure 2.9: S3D game design concepts and related considerations [75]

The importance of creating depth becomes amplified when introducing the stereo 3D effect as it provides additional depth information about the game. One instance where the additional depth information due to stereo 3D was effective was in the game Uncharted 3: Drake's Deception. Schneider [79] describes the game's most effective moments as being ones with significant differences in depth between objects such as hanging off an airplane or looking down into an empty chasm. He further describes the game experience as "comparable to what you would get in a modern 3D Hollywood movie". A major concern that must be accounted for by game designers are sudden changes in camera positions results in abrupt shifts in depth cues [75]. Certain game genres inherently minimize this risk by maintaining a comfortable viewing zone surrounding a main character in action-adventure games or a vehicle as seen in racing

games. The common element of these genres are that the camera is situated behind and slightly above the point of interest, be it a character or car. Issues begin to arise when creating first person games where players are viewing the world directly through the eyes of the character being controlled.

Figure 2.10: Uncharted 3: Drake's Deception. Nathan Drake hanging off a ledge illustrating an example of beneficial stereo 3D effect. [79]

S3D design challenges for video games include consideration of the additional depth information present with stereoscopic 3D. The texture applied to the object, the lighting within the scene and the relative positioning with other objects in the scene become increasingly prominent with the additional depth information [75]. Hubona et al [36] demonstrated the importance of shadows in providing depth cue information of objects in space. Shadows also provide information related to the height of objects and their proximity to other object in its vicinity. Schild and Masuch [75] mention that tasks involving objects at close depths should be brightly textured and close to screen. Tasks involving objects located a far depths should be similarly coloured with darker shades [75]. Depth based tasks presented to the user become amplified when stereo 3D is being utilized.

The graphical user interface (GUI) in video games present a challenging obstacle to overcome when utilizing stereo 3D. Schild and Masuch [75] discuss that traditional GUI elements as well dialogue and subtitles are super-imposed in front of the objects shown on screen. This results in a visual conflict with contradicting depths between the GUI elements placed at a depth equal to the screen against objects at a depth behind the screen to a depth in front of the screen [75]. The natural expectation of the user would be that objects moving towards them would occlude other objects such as the GUI located at screen depth but is often not the case. Our physiological reaction to resolve the vergence-accommodation relationship would result in jumps between extreme depth cues creating discomfort. Players should not be subjected to rapid shifts in depth cues in order to maintain a comfortable view unless these shifts

occur at similar depths [74]. In a study outlining design techniques for information visualization, Schild and Masuch [75] compared the GUI of several games and their implementation of GUI with a stereo display. The first game being the racing game *Blur* which implements several 2D panels at varying depth which became difficult for users to scan across the monitor and perceive the information. The second game mentioned was the first-person shooter game Far Cry 2 which provided information to users through in-game objects rather than superimposed 2D panels. The result was favourable as the depth of the elements were similar to each other and the transition between the first person view and the in-game objects was comfortable. The final example provided was the third-person shooter Dead Space 2. With the camera being over the shoulder of the protagonist there may be risk of sudden depth changes between the player the environment. This is mitigated through the use of a laser pointing from the players gun which provides users a method of gradually transitioning between depths reducing fatigue on the eyes. The game also displays important information such as health and ammunition directly onto game models similar to Far Cry 2.

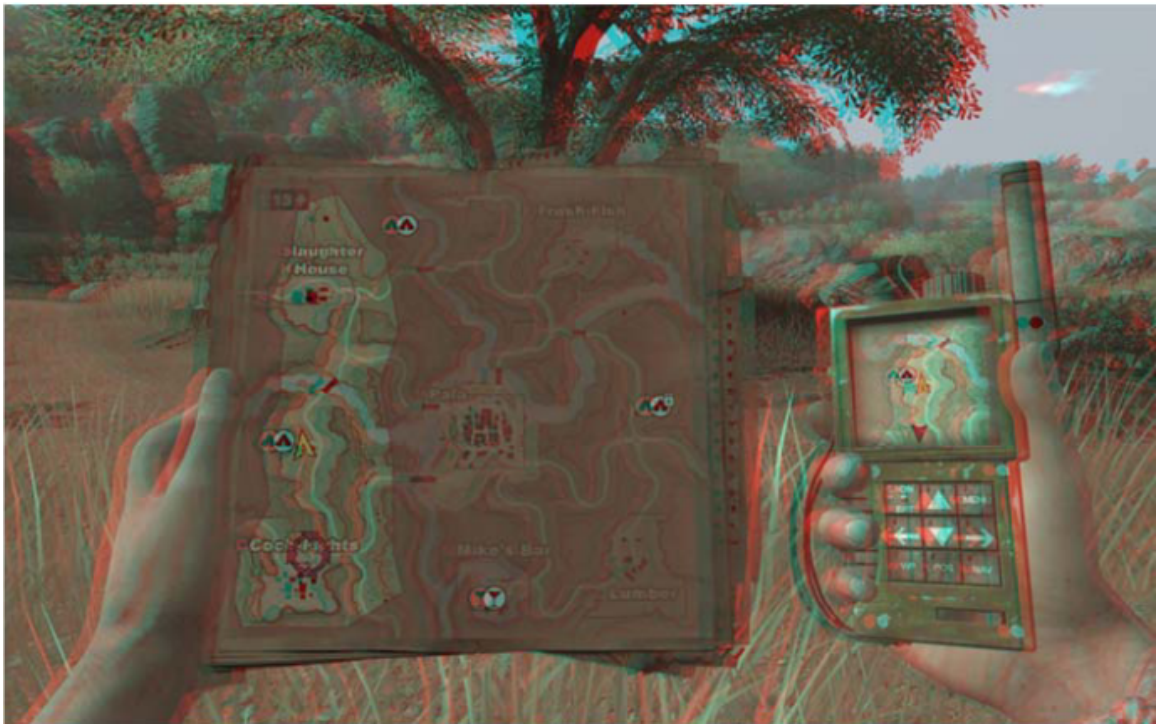

Figure 2.11: Screenshot of Far Cry 2 and their use of in game objects for information visualization shown in an anaglyphic 3D format [5].

The final category explains how to utilize the extremes of stereopic 3D in games. This refers to controlling the negative physiological reaction to improperly implemented stereopic 3D and using that reaction to enhance an effect. For example simulating a reaction to a drug can be accomplished by generating blurred vision enhancing the effect felt by the user [75]. This illustrates an example of abusive game design in which negative effects are reflected towards the user [80]. Abusive game design takes advantage of the personal experience created between users and playing video games and exploits this notion. Wilson and Sicart explain that *rather than give players what they "want" or what they supposedly "need", abusive game designers give players something idiosyncratic, weird, and confrontational* [80].

While the design of the game itself is critical, the importance of how users interact with the game cannot be overlooked. Traditional input methods were strictly two dimensional as seen with the use of a mouse or joystick. With the introduction of depth information through the use of stereoscopic 3D, the importance of 3D input becomes apparent. Early attempts at 3D input were achieved by utilizing 2D input methods such as the mouse in combination with other input commands or in conjunction with particular system modes [81]. An early example of this type of input is shown by Chen et al [82] through their implementation of a "virtual track ball" which allowed objects to be rotated around any 3D axis with the 2D input of a mouse. A more novel approach to interaction in 3D virtual environments is to provide users with replicas of the virtual object in real space. This is evident in current games with the use of a physical steering wheel for racing games or with physical guitars for the game Rock Band [83]. Most recent endeavors into 3D input revolves around spatial tracking of the user's motion or a particular gesture used to control elements in 3D. Oikonomidis et al [84] showed how the Microsoft Kinect can be used to track hand articulation through the use of its depth camera. Other mid-air handwriting recognition techniques utilized the Leap Motion in which users were able to point a finger and perform handwriting gestures as if they were using the finger as a writing tool [85].

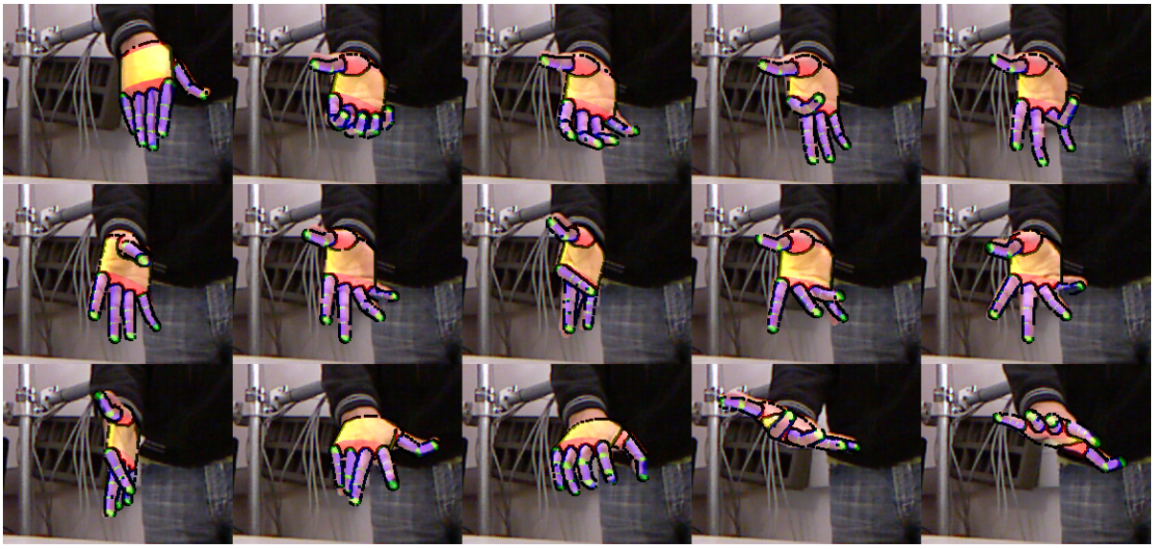

Figure 2.12: Microsoft Kinect used to track hand articulations [84]

2.3 User Experience

User experience, as defined by Nielsen and Norman, encompasses all aspects of the end-user's interaction with the company, its service and its product [86]. User experience is often mistaken for quality assurance which focuses on maintaining a technically stable experience for the user by minimizing system slow-downs and bugs [87].

It has been shown that stereoscopic 3D can have both a positive and negative affect on the user [52]. It has been shown that sequences of images are preferred in stereoscopic format than non-stereoscopic if the image does not contain noticeable artifacts [34]. As mentioned earlier, stereoscopic 3D provides more information regarding the relative size and position of an object in space which can provide a positive impact on user experience [36]. In contrast, visual fatigue resulting in blurred images, eye strain or headache negatively impacts user experience [52].

Specific tasks such as driving can become easier with the increased depth information presented in games [13]. Zerebecki et al showed that content designed specifically to take advantage of stereoscopic 3D can result in enjoyable experiences [88].

Past literature outlines numerous factors that affect user experience in games and in stereoscopic 3D applications. This thesis touches upon several factors but by no means is it a representation of all possible factors. Takatalo et al categorizes past literatures work on factors that influence user experience into *user experience for stereo displays* and *user experience for games*.

When discussing user experience it is important to understand the concept of immersion and presence. This thesis uses the definition of immersion and presence out-

lined by Mestre[89] which states that immersion is technology-related and objective and presence is a psychological, perceptual and cognitive consequence of immersion. In simple terms, immersion refers to the technology used to replace the users senses and presence is the belief the user has in being present within the virtual world.

2.3.1 Immersion & Presence

Immersion and presence are often substituted with each other in research but an important distinction exists between both. For the purposes of this literature, *immersion* is defined as the technical aspect of replacing human senses with senses controlled by that of a virtual environment [89]. Examples of this includes replacing users vision with a head-mounted display (HMD) or providing tactile feedback of the virtual environment through a haptic device. *Presence* revolves around the user psychologically accepting and being a participant within the virtual environment presented to them. In literature this is often referred to as the users feeling of "being there" [11]. The major distinction is that immersion relates to the technology used to control the users senses verses presence which relates to the users psyche.

The notion of presence extends well before the advent of virtual environments and technology. Early accounts of presence can be seen through the work of P.T. Barnum and Aristotle [90]. P.T. Barnum is famous for his showmanship and for his use of the circus environment to entertain and captivate audiences. Much of Barnum's work and ideologies in making the audience an active member in the show can be seen in modern day theme parks [90]. At its core, Barnum challenged audiences perception of reality by presenting objects in extraordinary ways. Aristotle similarly challenges users sense of reality but approaches the audience passively though the user of poetry and storytelling. This allows the audience members to form their own reality based on a small amount of subtle cues [90]. Both approaches attempt to achieve the same result; an audience with a different sense of reality.

It is important to be able quantify and qualify presence in order to understand what mechanisms affect a users level of presence. Current methods of measuring presence in research is broken down into three categories: subjective, behavioural and physiological [91].

Subjective measures of presence is the most widely used form of measurement due to presence being a subjective sensation [92]. Subjective measures are performed with the administration of post-experience questionnaires all of which rely on the user answering questions related to what they just experienced. There are several questionnaires utilized for the purpose of measure presence which include:

- The Witmer-Singer presence questionnaire [93]
- The Slater-Usoh-Steed questionnaire [12]
- The ITC-Sense of Presence Inventory [94]
- The Temple Presence Inventory [95]

Questionnaires are often preferred as they are easy to administer as well easy to evaluate [91]. A major issue cited with questionnaire and measuring presence is the user takes the questionnaire after their experience and is relying on memory which creates uncertainty [89]. A questionnaire is unable to measure the fluctuation in the users level of presence in real time [91]. The results of questionnaires in measuring presence can be skewed based on the participants prior experience [96].

Behavioural measures of presence are based off the perceived natural unconscious responses triggered by an environment [91]. Freeman et al [97] studied postural responses as a way of measuring presence. Users were asked to view a video of a rally car taken from the hood of the car. Changes in the posture as a result of swaying were corroborated with subjective measures of presence. Insko [98] developed another study where users could move towards the edge of a 20-foot drop in a virtual environment wherein reality they would move wards a physical edge represented by a piece of plywood, or no physical edge. Behavioural responses were measured between both setups such as taking baby steps, leaning away from the drop and testing the drop with the extension of a foot. The results showed an increase in behavioural reactions and thus presence with the physical edge [98].

Figure 2.13: Virtual Environment used to induce a behavioural response. [98]

Figure 2.14: Virtual Environment used to induce a behavioural response. [98]

Another example comes from the work of Nordahl and Korsgaard [99] who used distraction as a measure of presence. They believed the notion that a users level of presence is equal to the amount of distraction required to remove them from the experience. The first of two studies looked at visual distraction and the second looked at haptic distraction to measure presence. In the visual distraction test, users played a first person shooter game under with varying difficulty levels in an attempt to induce different stress levels within the player. Simultaneously a circle at the periphery of the users vision would constantly increase and users must push a button when their attention shifted to the circle. It was found that medium difficulty averaged the largest circle [99]. The result was linked to Csikszentmihalyi's [100] flow theory which has been shown within the context games. The notion of flow theory in games can be extended beyond simple entertainment and provides value in other areas such as education, military and corporate environments [101]. Haptic distraction was tested by applying vibrations to palm of users hands while watching a film. Results did not show significance [99].

Figure 2.15: Circle on the periphery used as a visual distraction to measure presence. [99]

Behavioural measures are prone to experimenter bias in evaluating whether a behaviour has been performed. Actions performed by the participants may be falsely interpreted by experimenters or the actions may not as a result of changes to the experimental condition.

Physiological measures have also been used in trying to measure users level of presence. A *change in heart rate* is measured with an electrocardiogram and is affected by a number of facts including stress, fear, anxiety, emotions, etc [91]. It has been shown that positive emotions cause an increase in heart rate and negative emotions cause a decrease [102]. *Skin conductance* as well as *skin temperature* can also be used to indicate a reaction based on a stimuli. Wiederhold et al [103] showed a correlation between heart rate and skin conductance to subjective presence rating. Physiological measures have the advantage of being more objective and sensitive to time when used. Disadvantages of using physiological are that several stimuli can cause physiological reactions and linking the change to presence can be difficult [91]. Physiological measures also require equipment attached to the user body which can create an unnatural environment.

2.4 Tools

An arsenal of robust, accurate and efficient tools in any profession is vital to accomplish a job. Developments of stereoscopic 3D content are no different in their reliance of effective tools. There are a number of tools and aids that are available to film makers and game developers that aid them in implementing stereoscopic 3D in their films and games [104], [105].

Many tools for 3D film also exist and share many similarities between film editing and game development. Film editing tools such as Adobe Premiere, Corel VideoStudio, MAGIX Movie Edit Pro all have built-in functionality to produce a 3D film. Adobe Premiere offers the tools necessary to convert a simple 2D film into a 3D anaglyphic film with their built-in tool chain [106]. Corel VideoStudio has a built-in video exporter that automatically converts an edited video into a 3D format for DVD, Blu-ray, advanced video code HD, and Windows media video [107] MAGIX Movie Edit Pro offers support for capturing 3D video with a 3D camera and offering editing capabilities of a 3D video [108]. Film editing allows the director to manipulate the video produced after the fact allowing for frame-by-frame manipulation of objects in the scene and lighting details. While these tools are effective at editing 3D film, a major hurdle game developers face is the removal of camera control from the hands of the director. In film, the camera is controlled by the camera operator at the direction of the director who can make positional and rotational adjustments that will optimize the 3D video output. Video games provide a unique challenge in implementing 3D because the camera is often controlled directly by the player which presents the possibility of a virtual scene being viewed in an infinite number of positions and rotations. Furthermore, video games will often take cinematic cues from film and combine full interactive control by the player with predetermined camera movement based on triggers within the game.

The most popular method of applying stereoscopic 3D to games is done in post-production by video card manufacturers including Nvidia and AMD. New releases of video games will often be accompanied by drivers days prior to the release of the game in order to prepare and optimize computers for the games. Stereoscopic 3D on personal computers (PC) can be implemented with supporting displays and video cards. Similarly, video game consoles must also contain supporting video cards and must be connected to proper displays but given the hardware configuration for a console remain relatively fixed throughout its life cycle. An example of a 3D console include the Playstation 3 which required active shutter glasses to view the content.

The Nintendo 3DS is another example of a dedicated 3D vidoe game console. It provided users with a physical slider to increase or decrease the 3D effect being shown. The 3DS was also unique in that it was an autostereoscopic display eliminating the need for glasses or other hardware to view the content.

Another tool available in creating stereoscopic 3D content is the nVidia's VRWorks toolset. The suite of tools interface with known game engines including Unity3D from Unity and the Unreal Engine from Epic Games and has been available since 2017. VRWorks provides specialized tools for game developer such as optimized stereo rendering, resolution adjustments per render pass and support for multi-GPU rendering. NVidia also provides a software development kit (SDK) which provides a development enhancements such as GPU scheduling plug-and-play improvements for VR headsets as well as improvement to audio and video capture and production. Finally improvements to nVidia's PhysX physics engine allow for detection of motion controllers and haptic devices.

Specific stereo 3D tools have slowly begun to appear within the development life cycle. Many commercial game engines such Unity and Unreal offer support for 3D-capable devices such as 3D TVs and the Oculus Rift. These tools are often geared towards one particular hardware configuration such as the Oculus Rift but lack support for other possible configurations. Furthermore, many of these tools are often presented as a simple button to "turn on" 3D. This automated functionality removes control in the hands of the developer who can tailor the content for their specific needs.

Given prior literature, there shows an opportunity to continue investigation into the comfort zone and the tools used to create stereoscopic 3D content. Past research has formally defined a model for the comfort zone and has related its effect to user experience. This thesis explores the validity of the comfort zone model presented as well as the creation of a visualization tool of the comfort zone intended for video game developers.

Chapter 3

Study 1 - Quantitatively Defining the Zone of Comfort

It is essential for developers who are building content using stereoscopic 3D to understand the boundaries and parameters affecting user experience while designing their games. When creating games it is essential to make design decisions for the intention of maximizing user experience for the end product. As noted in section 2.1.1, the zone of comfort represents a volumetric area which maximizes the chance for humans to perceive displayed objects correctly using stereoscopic 3D. It is necessary to provide information regarding the zone of comfort to developers of stereoscopic 3D content in order to empower them to position important information within the zone of comfort. Furthermore, the importance of other visual cues present in a typical video game scene may alter the zone of comfort. It is thus necessary to compare a visually stale zone of comfort to that with a complex environment containing several visual cues.

The objective of this Study was to quantify the theoretical comfort zone defined by Chen et al [38] from past literature. The focus of this Study was to confirm three subzones within the zone of comfort through experimentation using a 3D object that would appear at defined points on the users view. The subzones are defined as the following:

- *Object is clearly visible with no discomfort*
- *Object is visible with some discomfort*
- *Object is visible with discomfort*

3.1 Background

The comfortable viewing zone represents a volume of space in which binocular fusion is possible and potential blurring is minimized resulting in an image that is comfortable to view. Chen et al [38] describes two mathematical models, shown in Figure 3.1 used to define near clip plane and far clip plane of the comfort zone based on the viewing distance (V) of the subject as well as a depth of focus (DoF) of +0.2 diopter to -0.2 diopter relative to viewing distance [109] The diopter value of 0.2 was selected based on the work of Yano et al [60] which indicated visual fatigue being clearly induced when presented outside the bounds.

$$Z_f = d - \frac{1}{\frac{1}{d} + 0.2}, Z_b = \begin{cases} \frac{1}{\frac{1}{d} - 0.2} - d, & \text{if } d < 5 \\ \infty, & \text{if } d \geq 5 \end{cases}$$

Figure 3.1: Zone of comfort formula

Within the context of video games a defined comfort zone would provide a level of confidence for game designers of virtual content that any object positioned within the volume of space would maximize the chances being seen comfortably. Applying the mathematical model defined by Chen et a [38] across multiple devices viewed at varying distance would result in differing front and back depth planes used to define the boundary as dictated by the mathematical model in Figure 3.1. An individual sitting 1m from the display will yield a Zf value of 0.167m and a Zb value of 0.25m creating a near and far plane values relative to the user at 0.833m (near) to 1.25m (far). Contrasted with an individual sitting 2m from a display will yield a Zf value of 0.57m and a Zb value of 1.33m creating a near and far place values relative to the user at 1.43m (near) and 3.33m (far).

Given the variety of displays available for development it becomes increasingly important to confirm the mathematical model of the comfort zone as a starting point.

3.2 Method

The Study required participants to view an object at different positions under two conditions: 1) solid black background and 2) within a typical video game environment. All participants wore polarized glasses for both conditions. Conditions were counter-balanced by randomizing both the position in which the object would spawn and

whether the environment was black or based on a typical video game. The experiment was created using version 5.3.1 of the Unity game engine. The object displayed to every participant was a T-pose character model named *Ethan* taken from the "standard assets for Unity" package available for free on the Unity asset store. This character was selected as it represented a typical character within a video game.

Head tracking was also performed using six OptiTrack Flex 3 infrared trackers. Participants were asked to wear a baseball cap that contained three infrared markers used by the trackers. A fixed marker was placed at the front of the seating area in order to provide a baseline distance between the seating location and the display being used. This was to measure variation in users head distance from the display throughout the session and ensure that changes to head position and subsequent to the comfort zone were within reasonable limits.

Participants were first asked to complete a general demographic questionnaire in order to gain knowledge on their experience with stereoscopic 3D and video games. After completing the questionnaire, all participants underwent the randot stereotest in order to check for stereoscopic 3D acuity. If they were unable to successfully complete the task, the participant was thanked for their time and asked to leave. All remaining participants conducted the 15 minute experiment.

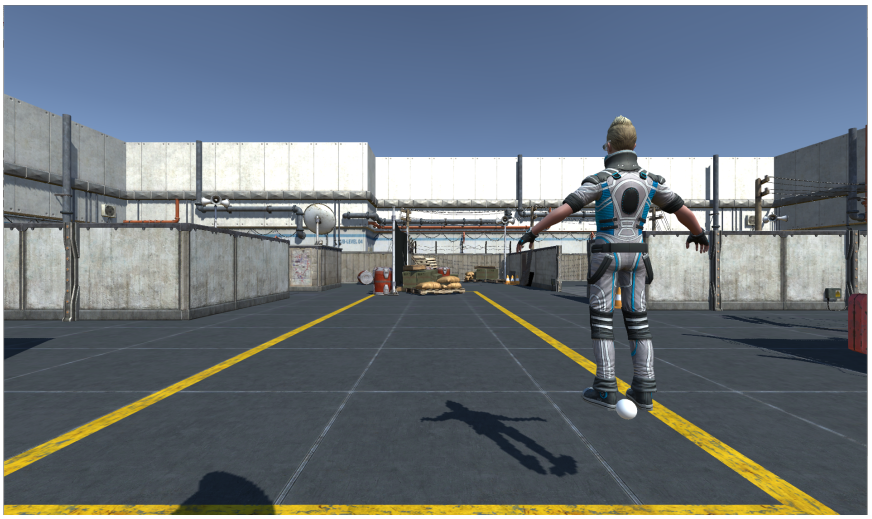

Figure 3.2: Study with game scene

Figure 3.3: Study with no game scene

3.2.1 Participants

A total of 27 participants were used in the Study with 19 males and 8 females. Participants were predominantly undergraduate students selected from the Game Development and Entrepreneurship program at the University of Ontario Institute of Technology (UOIT). Three other participant data sets were excluded due to interruption during the experiment. Nineteen participants were between 18 - 24 years of age, seven were between 24 - 35 years of age and one was between 35 - 44 years of age.

3.2.2 Setup

The experiment was conducted at the game experimental lab at University of Ontario Institute of Technology. The lab is approximately 15 ft x 20 ft x 10 ft and contains a leather couch, television, and workstation connected to the television. The television is the LG 55LW5700-UE 55 inch 1080p, 120Hz, LED 3D TV. The room was kept illuminated before and after performing the experiment and all non-essential equipment remained off to minimize noise and visual distraction. During the experiment all room lights were turned off. Participants were given a minute to adjust their eyes to the darkness. Participants were seating approximately 8ft from the television which falls within the recommended boundaries of 2m - 7m (6.5ft - 22.9ft) outlined by the television's user manual. Image settings were kept set as follows:

- Aspect Ratio: **16:9**
- Picture Mode: **Normal**

- AV Mode: **Off**

All participants wore LG Cinema 3D glasses for the duration of the experiment.

The room also contained six OptiTrack Flex 3 infrared trackers interconnected with an RCA sync cable. Each tracker is also connected via USB to a single USB HUB which is then connected to workstation. The software used to interface and monitor the head tracking was version 1.5 of the Motive unified optical tracking software offered by OptiTrack. Participants were asked to wear a baseball cap that contained 3 retro-reflective balls used by the infrared trackers to track positions.

Participants viewed 64 total instances of the Ethan model. 32 instances were shown with a black background and 32 were shown within a game environment.

Figure 3.4: Experimental setup of Study 1. Distance from the couch to the television was approximately 8 feet with 6 mounted infrared tracking cameras surrounding the area used for head tracking

3.2.3 Hypothesis

The results shown by Stanfield et al [20] when implementing a floating window solution show the ability to manipulate a viewers depth perception of virtual objects to be perceived as closer or further away than its actual placement in the virtual world. It is argued that the presence of virtual objects protruding out of the screen represents points of reference in judging the depth of virtual objects. It is then important to isolate and Study changes between rich environments against simple environments and view any changes to the users sense of comfort. It was predicted that participants would show that with the presence of a game environment the comfortable viewing zone would skew further away from the camera as compared to a completely black background.

This experiment was also conducted to confirm the past work in defining the boundaries of the zone of comfort as described in section 2.1.1. Chen et al [38] outlines a mathematical formula shown previously in Figure 3.1. This model defines the far plane (left) and back plane (right) positions given a distance to the zero parallax plane. The distance provided by the model is a distance relative to the zero parallax plane. Participants were situated approximately 2.4m from the display which resulted in a near plane of 0.77m and far plane of 4.4m from the zero parallax display. The characters spawning pattern was then set to extend beyond the far plane and near plane 50% so that the maximum depths the character would spawn is +6.6m beyond the zero parallax plane and +1.4m in front of the zero parallax plane. A graphical representation of the expected comfort zone can be seen in Figure 3.6.

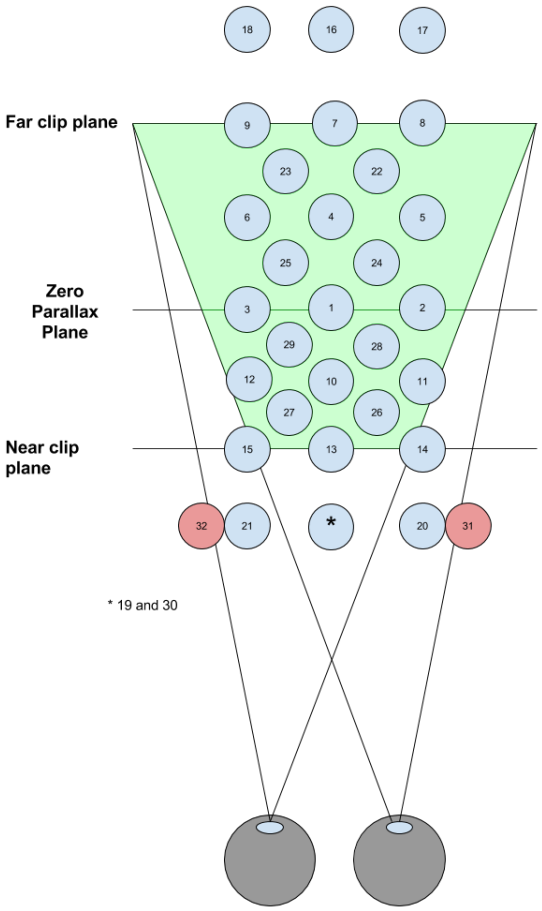

Figure 3.5: Spawning positions for Study 1. Area shading in green represents the expected comfort zone.

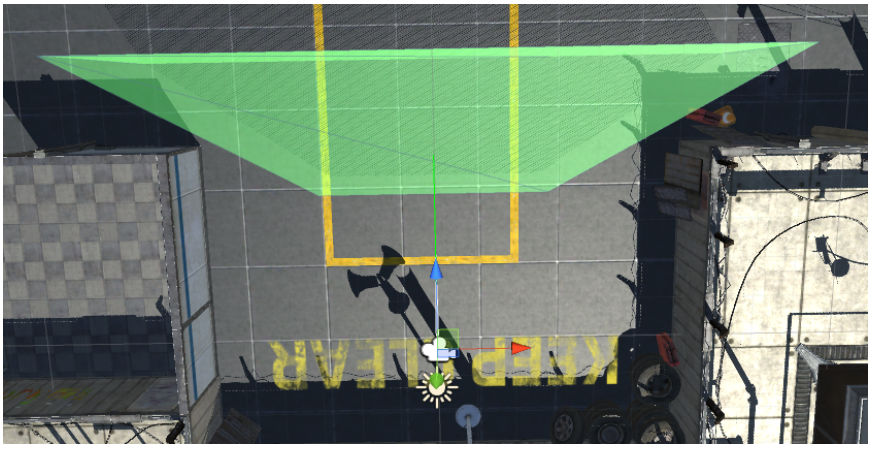

Figure 3.6: Graphical representation of the expected comfort zone within the game scene used.

3.3 Results

3.3.1 Participant Experience with S3D and Video Games

The demographics questionnaire asked participants a series of questions related to their experience in using stereoscopic 3D as well as the importance of several factors contributing to stereoscopic 3D including comfort and sense of depth. The questionnaire also asked the users about their experience with video games. Finally participants were asked of their experience with playing video games in 3D. They were also asked basic information about their age and gender.

Participants were asked to rate their experience with stereoscopic 3D on a seven point Likert scale with 1 being *not experienced* and 7 being *very experienced*. Participants were then asked what forms of media have they experienced stereoscopic 3D with options including *movies, television, video gamnes, stand-alone demo, head-mounted display, Google cardboard, none, and other*. These selections were not mutually exclusive. Participants were then asked to rate the importance of *comfort, objects popping out, and depth* with respect to stereoscopic 3D on a seven point likert scale with 1 being *not important* and 7 being *very important*. They were then asked to rate their level of experience with video games on a seven point likert scale followed by the number of hours a week the participant plays video games, concluding with level of experience playing video games in 3D on a seven point likert scale.

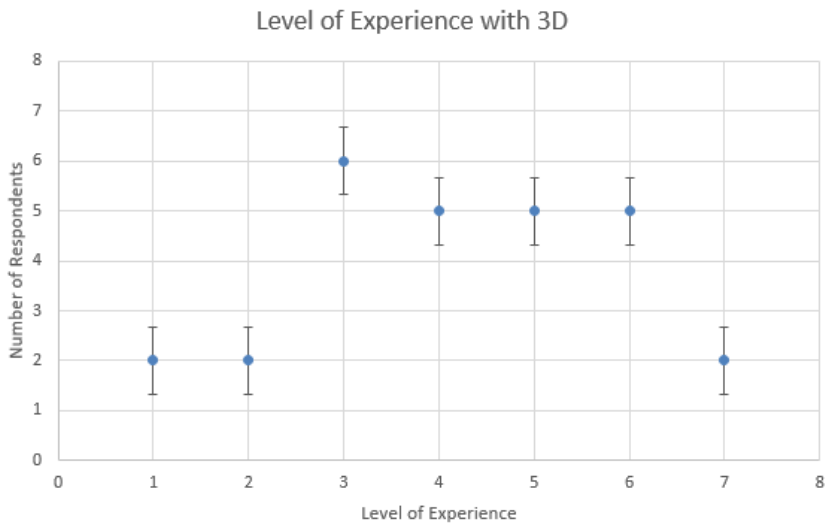

Figure 3.7: Participants experience level with stereoscopic 3D content on a 7-point Likert scale

Participants did not indicate high levels of experience with stereoscopic 3D; with a mean of 4.19. All 27 participants indicated experience with 3D in movies followed by 19 participants experience 3D in video games and 18 with a head-mounted display. Participants incidcated high levels of importance with regard to comfort in 3D with a mean of 6.19 as well as the importance of depth with a mean of 6.04. There was also moderate importance indicated for the perception of objects popping out of the display with a mean of 4.93. The participants were highly experienced with playing video games with a mean score of 6.11. The average amount of time playing video games per week among the 27 participants was 12.3 hours. Finally participants showed moderate to low levels of experience in playing video games in 3D with a mean rating of 3.15.

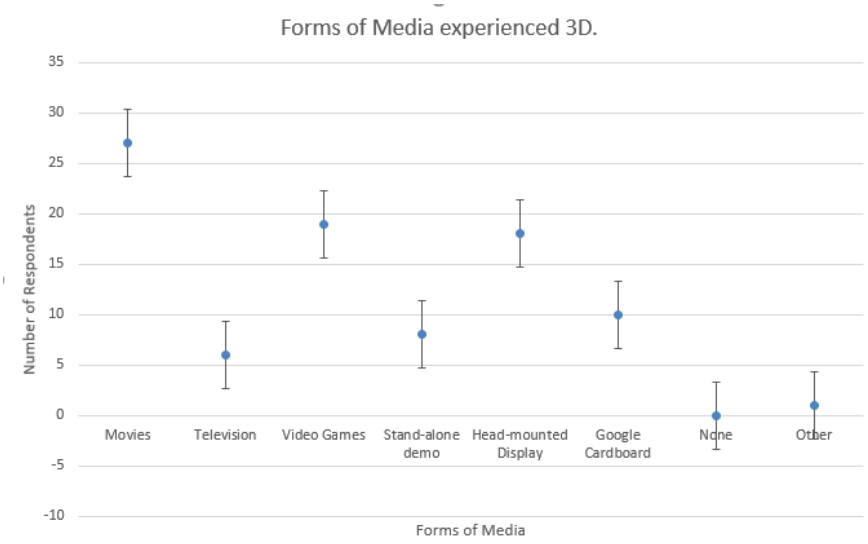

Figure 3.8: Forms of media experiences by participants. Note participants were able to select more than one.

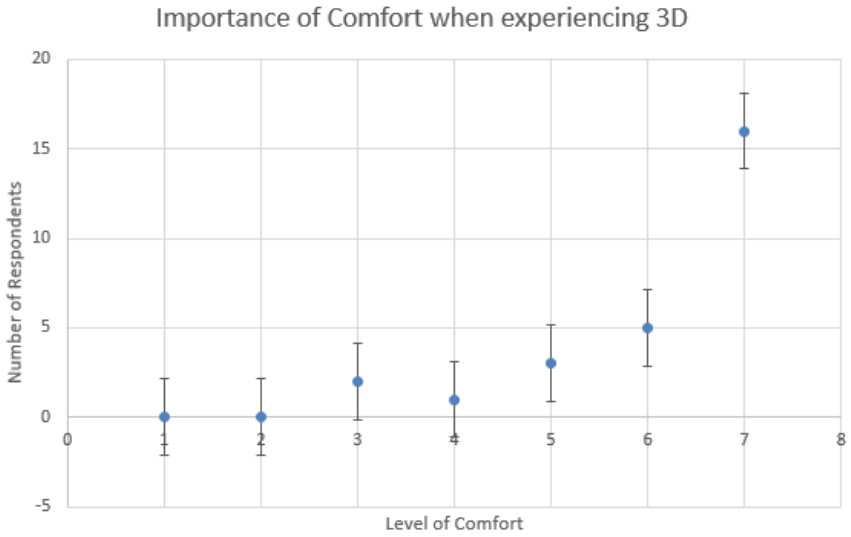

Figure 3.9: 7-point Likert scale indicated the importance of comfort among the participants.

3.3.2 Experimental Analysis

The independent variables were the positions the T-pose character could locate and whether the use was presented with a rich game background or a black background. The dependent variable was the self-reported comfort levels as indicated by the participant after each trial.

A Pearson's R test was conducted to measure correlation between a black background and a game background. The results show a statistically significant positive correlation between a black background and game background ($r = 0.395$, $p < 0.05$). This result indicated a moderate positive relationship between both backgrounds.

Black BG						
		L	M	R		AVG
farUncomfort		1.55556	1.62963	1.65385		1.61301
farComfort		1.55556	1.59259	1.59259		1.58025
midFarFar		1.51852		1.48148		1.5
midFar		1.51852	1.42308	1.25926		1.40028
midFarNear		1.57692		1.59259		1.58476
zero parallax		1.38462	1.42308	1.5		1.4359
midNearFar		1.46154		1.48148		1.47151
midNear		1.25926	1.25926	1.37037		1.2963
midNearNear		1.53846		1.59259		1.56553
nearComfort		1.44444	1.53846	1.33333		1.43875
nearUncomfort		1.55556	1.85185	1.51852		1.64198
	AVG	1.48809	1.53114	1.48873		

Game BG						
						AVG
farUncomfort		1.53846	1.62963	1.59259		1.58689
farComfort		1.51852	1.44444	1.62963		1.53086
midFarFar		1.51852		1.48148		1.5
midFar		1.59259	1.59259	1.48148		1.55556
midFarNear		1.38462		1.62963		1.50712
zero parallax		1.37037	1.51852	1.48148		1.45679
midNearFar		1.26923		1.48148		1.37536
midNear		1.51852	1.30769	1.7037		1.50997
midNearNear		1.55556		1.2963		1.42593
nearComfort		1.66667	1.55556	1.55556		1.59259
nearUncomfort		1.51852	1.74074	1.7037		1.65432
	AVG	1.4956	1.54131	1.54882		

Figure 3.10: Visualization of comfort levels for each of the 32 positions. Left shows the black background results and right shows the rich game background results.

A paired sample t-test was conducted to compare the 32 comfort indications with a black background against the 32 comfort indications with a game background. The result showed no significant difference in comfort levels between the black background ($M = 1.516$, $SD = 0.134$) and the game background ($M = 1.549$, $SD = 0.140$) for $t(27)=1.287$ and $p=0.207$. This result suggests the difference between a black background and a game background does not significantly alter the comfort zone. The distribution of comfort values are shown in Figure 3.11 and individual means for each spawn position are shown in Figure 3.12 and Figure 3.13. Overall mean values per position is shown in 3.10.

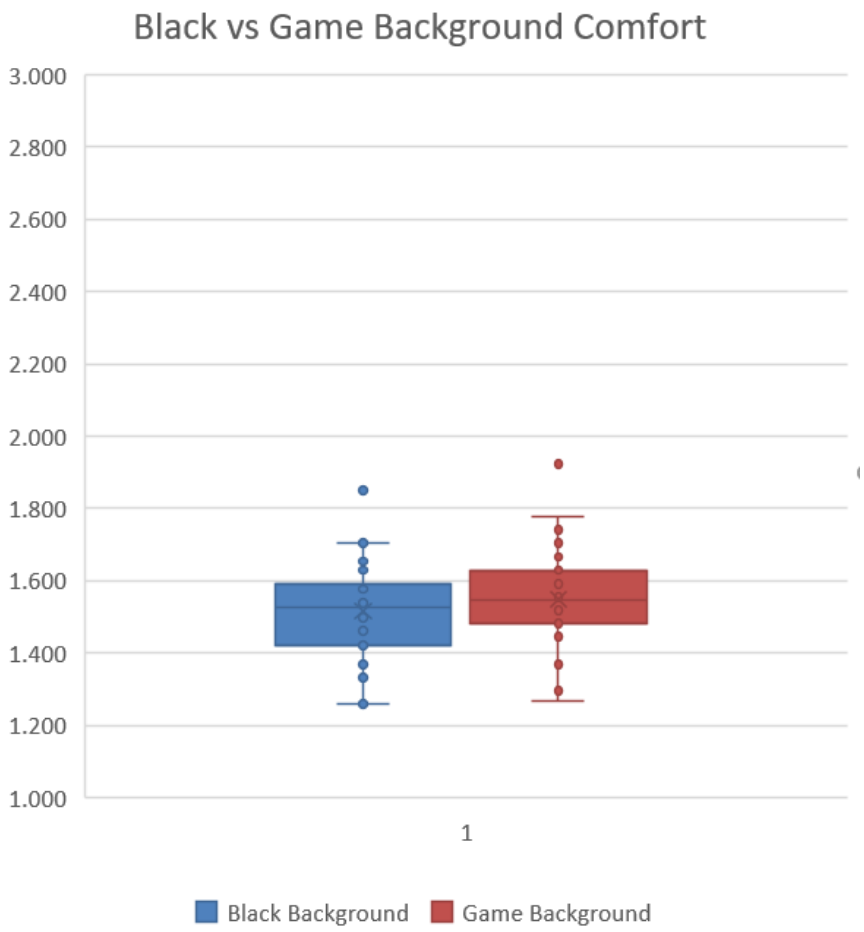

Figure 3.11: Box and whisker plot showing distribution of comfort values for black background and game background. A value of 1 represents "no discomfort", 2 represents "slight discomfort" and 3 represents "much discomfort These values were mapping taken directly from the 3-point Likert value taken during the experiment.

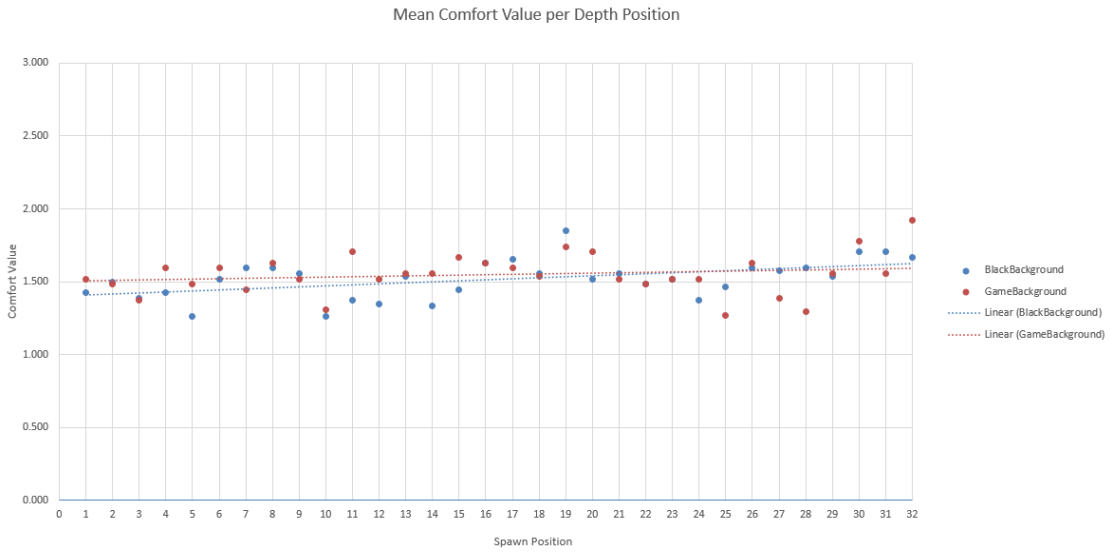

Figure 3.12: Plot graph showing a comparison of mean comfort value for each depth position. Blue represent the black background and red represent the game background

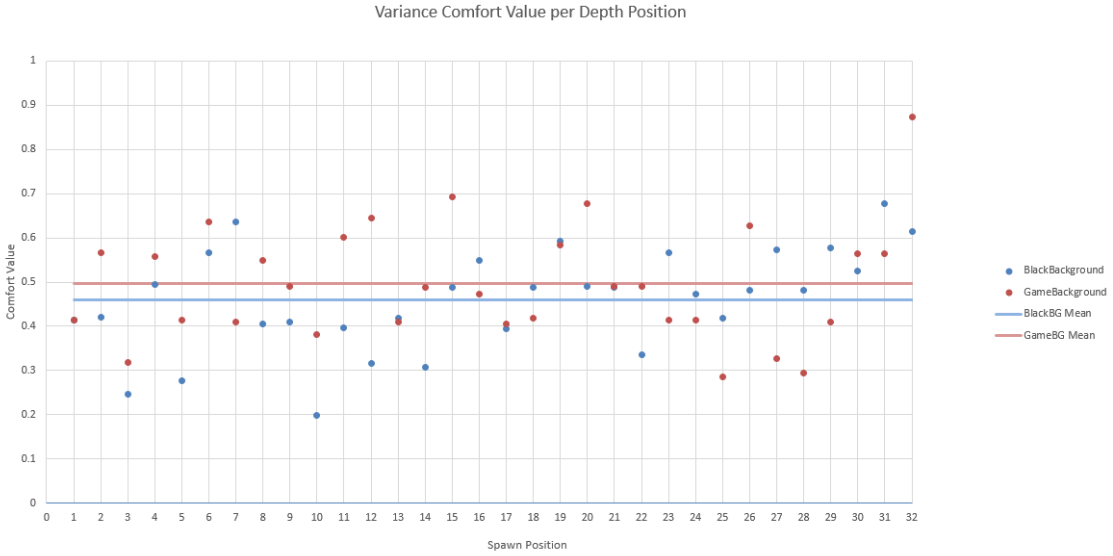

Figure 3.13: Plot graph showing a comparison of variance of comfort value for each depth position. Blue represent the black background and red represent the game background. Light red and light blue represent the mean variance values of black background and game background respectively.

Head-tracking data measured the position of the participants head at the end of each trial for a total of 64 positions for each participant. The average distance away from the 3DTV was 1.913m (or 6.276 feet) with a standard deviation of 0.235 and a variance of 0.055. The lowest average distance from the 3DTV was 1.492m away and

the highest average distance was 2.267m. The distribution of head position is show in Figure 3.14

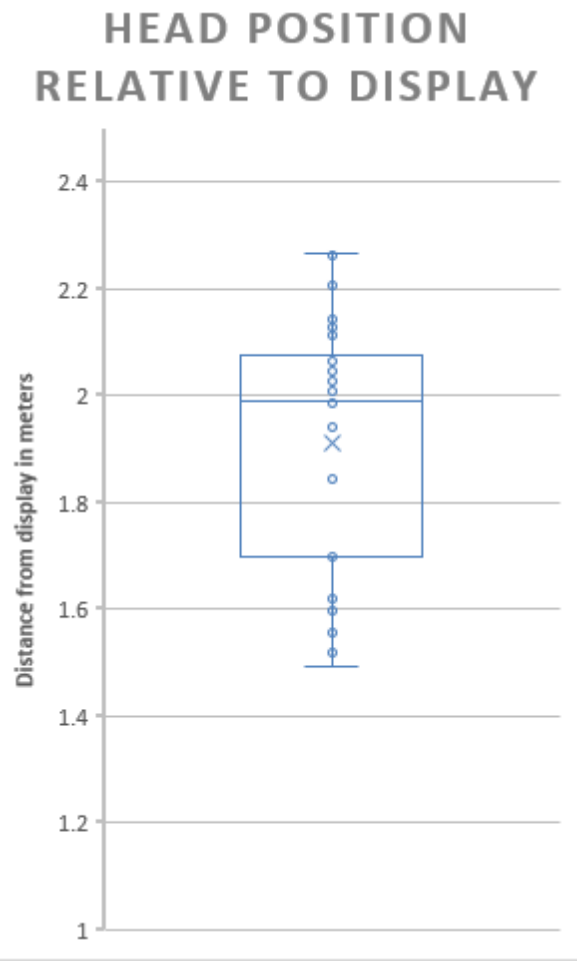

Figure 3.14: Box and whisker plot showing distribution of head position relative to the 3DTV.

The head-tracking data also shows several instances of participants shifting theirs head position over the course of the experiment. For instance it can be observed that some participants began the experiment leaning forwards and over the course of the session slowly leaned back and vice versa. The range in Figure 3.14 shows a range between 2.3m (HP1) and 1.5m (HP2) from the display results in a difference of 80cm. Taking these values HP1 would produce a comfortable zone volume ranging from 1.153m to 2.141m and HP2 would range from 1.575m to 4.255m. As users lean forward towards the display, the volume decreases in size and moves slightly towards the user and as the user leans back away from the display the volume increases in

size and moves slightly away. Of note, the furthest and closest spawned characters remained outside of the comfort zone volume despite the shift in comfort zone size.

3.3.3 Free-Form Comments

Following the experiment, participants were asked two questions as prompts to comment on their experiences. The first question was *did you notice a difference in your ability to see the 3D character when the background was black vs when the background was a game scene? Explain.* A total of 23 participants indicated in their response that a difference was noticed between the two backgrounds whereas four did not. Some examples of responses from participants that noticed a change include:

> P02 - "Yes. the characters appeared to pop out more when there was a scene in the background. i think this is because i had to focus my eyes on the character to separate the background."
>
> P23 - "Yes. the amount of 3d objects during a full scene made the entire scene collectively harder to look at."
>
> P17 - "It was easier to see on the game scene. The seemed to blur more on plain black."

Some examples of responses from participants that did not notice a change include:

> P21 - "The background changed? i was so concentrated on the character that i didnt realize."
>
> P09 - "I did not really notice the difference between the two, but it felt ever so slightly easier to see the movement of the actors on the black background."

The second question asked *do you have a preference in seeing 3D objects with a rich background or an empty background?.* Results show slightly less favoritism among participants with eight stating a preference for a black background, seventeen stating a preference for a game background and two citing context as the deciding factor.

Some comments expressing favour towards a game background include

> P02 - "I prefer the rich background because it gives a more prominent feeling of depth."
>
> P12 - "It would be nice to integrate 3d objects with a rich background, but if there are other cues that will distract me then it becomes hard to enjoy the 3d. i would prefer rich environments with balanced 3d"

3.4 Discussion

The results of this Study contradict the initial proposed hypothesis. It was stated in the hypothesis that the zone of comfort would be shifted away from the participant when objects were presented with a rich game background. With additional visual data providing cues to the user, it was shown by Stanfield et al [20] that providing additional visual cues changed the depth perception of the user. Given the increase in cues available with a rich game background, it was hypothesized that the comfort zone would be pushed away from the user. Based on the analysis it shows a moderate positive correlation between a rich background versus no background at all, but no statistically significant change based on the experimental setup. While no significance was shown between both experimental conditions this does not preclude the possibility of objects at particular depths affecting the comfort level of participants when viewing other objects at other depths. One possible explanation for the lack of significant change may be due to the construction of the game scene itself not providing enough depth cues to affect the comfort zone. A scene containing a controllable amount of identical depth cues in front of and behind the display could isolate the effect objects in a scene have on the position of the comfort zone. Another possibility is that the introduction of a game scene only minimally alters the shape of the comfort zone. Several additional factors include the time spent on the scene itself, which limited users to a short, fixed period of time or given that the scene was static, movement-based queues were not available to the user. Future work can be performed to conclusively determine whether other objects within the players field of view has significant impact on the shape of the comfort zone.

The results of this Study suggest the mathematical model defined by [38] does define the comfort zone based on the comfortable values recorded by the participants. The objects placed within the comfort zone defined by the model were viewed comfortably as suggested by Figure 3.11. Insufficient samples outside the comfort zone factors in the inability to conclusively define the bounds of the volume based on the model. This also provides an explanation for the non-significant hypothesis stated before. Furthermore, the definition of the zone of comfort from literature does not directly incorporate other objects within its mathematical model.

3.4.1 Free-form Comment Discussion

As mentioned in section 3.2 a total of 23 of 27 participants noticed a difference in their ability to perceive the 3D character with a game background and a black background.

Among the participants that noticed a change, there were varying reasons suggested for their differences. Many participants noted that the inclusion of a game scene aided in their ability to determine depth. This is consistent with work done by [42] that shows the inclusion of other monocular and stereo cues in a 3D scene increases the accuracy of depth estimation. Other participants noted that the 3D character against a black screen allowed them to focus only on the character and felt as if viewing the content was easier as reflected in comments such as:

> "Yes I felt there was less eye straining on the black screen when the characters were in different positions than when they were in the game scene."

> "I found my eyes strained less against the black background in comparison to the scene, as the models were easier to look at with the contrasting black backdrop."

This may be due to the game scene not being optimized for stereo 3D viewing and causing visual conflicts with participants. The game scene itself was comprised of a combination of military and industrial objects such as crates, oil drums, and supply crates, all of which were within the field of view of the camera. Each of these objects were placed at varying depths which may have conflicted with the participants ability to clearly perceive the character in a rich game scene.

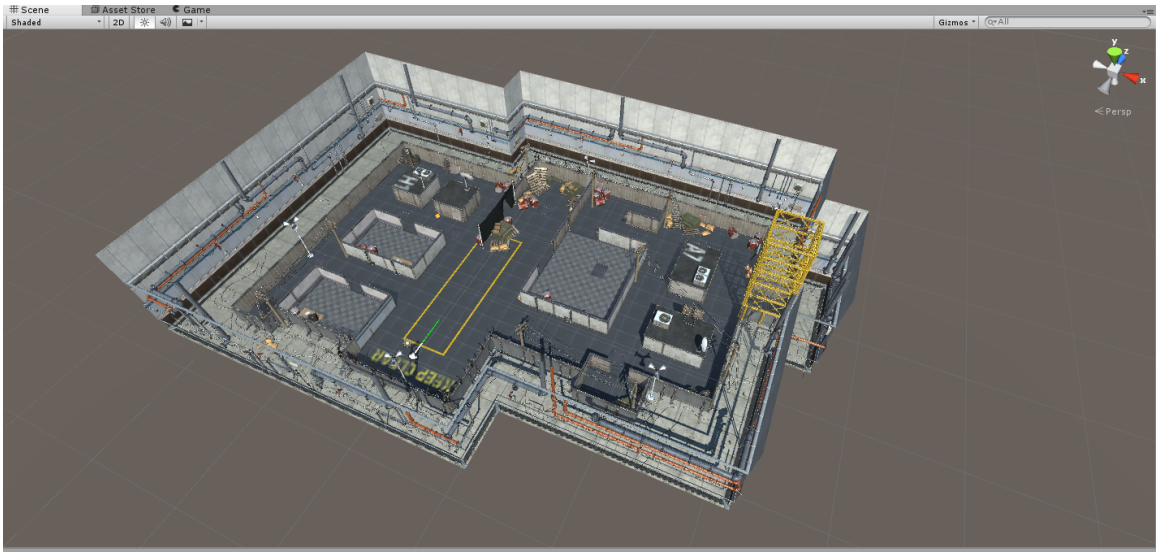

Figure 3.15: Overview of the game scene used in Study 1 available through the Unity asset store.

The data suggests that the comfort zone defined by [109] may accurately define some form of a comfort zone. The data retrieved within this study does suggest all

objects placed within the comfort zone are viewed as comfortable but a lack of objects outside the boundary limit the conclusiveness of the zone. Anecdotal evidence from Study 1 suggests that degradation of the comfort zone may begin at the border of the volume but this remains unclear and requires further testing.

Chapter 4

S3DComfortZone

Displaying the comfortable viewing zone will provide designers of 3D content with the necessary information in positioning virtual objects to maximize comfort. The previous study applied quantitative values to a comfort zone based on the physical layout of the experimental setup. The results of Study 1 confirmed the hypothesized comfort zone described in previous literature.

It then becomes imperative to formalize the visualization of the zone of comfort based on varying technological setups. Several devices exist which present their own unique physical constraints such as the aforementioned 3DTV used in Chapter 3 to head-mounted displays and beyond. The noticeable difference is the distance between the users eyes and the display for each technology. It has been stated in Chapter 2 that changes in distance between display and user has significant effects on the geometry of the zone of comfort. Further variation can be observed with simple changes such as altering the distance a user sits from a 3D TV.

4.1 Motivation

Initial motivation to develop the presented S3DComfortZone (S3DCZ) tool stems from the idea of developing the same piece of content for multiple devices and configurations. This already presents challenges in a non-stereo setting. Given the nature of stereoscopic 3D application and its ability to induce simulator sickness and visual fatigue it is important to maximize comfort at all times. Providing designers with the ability to visualize the comfort zone of a variety of outputs together can maximize development efficiency of stereo 3D content.

S3DComfortZone was built using the Unity game engine and written in Unity's variation of JavaScript. This tool was also developed using the FOV2GO toolkit created by the MxR Lab as USC [110] also written in JavaScript. S3DComfortZone

acts as an overlay to the existing FOV2GO toolkit and provides a visualization of the zone of comfort.

The colorized camera frustum is based on the defined bounds outlined in past literature and validated through the study described in Chapter 3. The validation of past literature through the study allows for S3DComfortZone to expand its functionality to additional configurations. S3DComfortZone is applied by attaching the provided script components to a game camera containing FOV2GO.

S3DComfortZone can be enabled under the standard Unity configuration in which the editor window displays the content being built from camera within the scene. The editor camera overlooks the content and can pivot in an arcball manner. From this view, S3DComfortZone is visible when the editor camera overlooks a game camera with the tool attached to it. The frustum of the game camera will be colorized based on the volume gradient. Objects within the editor window will not be highlighted. An example is shown in figure 4.1.

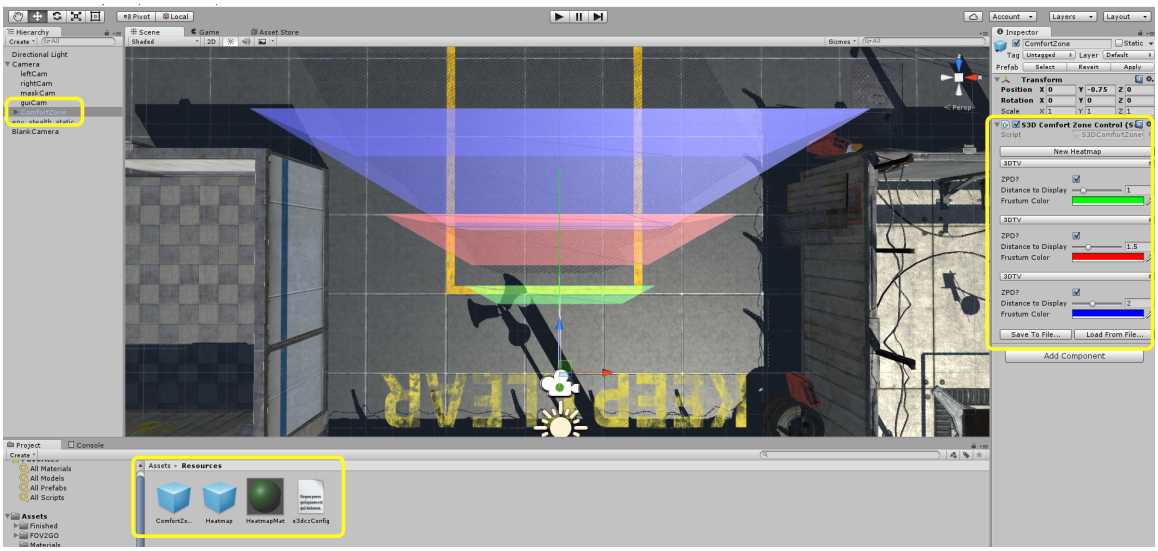

Figure 4.1: S3DComfortZone visualizing three separate comfort zones (green, red and blue) in the Unity Game Engine. The colour of the viewing frustum maps with the distance of 1m (green), 1.5m (red), 2m (blue). The changes to the tool are shown on the far right in the Unity inspector window. The S3DComfortZone tool attached to the FOV2GO camera is shown on the far left. Assets used to in attaching the tool to the camera are shown at the bottom.

Current tools allow for executable version of the project to be built for various technologies but does not optimize the content for the particular medium. For example developing content for a 3DTV creates unique challenges compared to developing content for the Oculus Rift. In terms of accurately and comfortably displaying objects

in 3D, the greatest discrepancy between the 3DTV and Oculus Rift is the distance the user sits from the display. The head-mounted display of the Oculus Rift sits directly on the face of the user whereas a 3DTV may have considerable distance between itself and the user. Distance to display is a key factor in determining the bounds of a comfort zone. Visualizing both zones in unison will allow developers to position objects of importance such that it is optimized for multiple outputs and eliminate the need for revisions in the future.

4.2 Application

S3DComfortZone is a development tool geared towards developers of 3D content using the Unity 3D game engine. It allows developers to place objects of interest to maximize the likelihood of comfortable viewing by the user. Furthermore, S3DComfortZone will provide options for various technological outputs. This allows developers to overlay multiple comfort zones based on the model provided through past literature mentioned in chapter 2. This will allow developers to streamline the development timeline by building content for multiple 3D displays in parallel and ensure an accurate visualization of the comfort zones.

Based on the comfort zone model defined by Chen et al [38], figure 4.2 shows a scenario in which a game object is positioned at a fixed point within the virtual world with the only modification being the distance from the display by the user. The boundaries of comfort zone for both instances utilize Chen's mathematical model. The illustration shows the game object positioned outside the zone of comfort at a distance of 2m from the display whereas at a distance of 2.5m from the display, the object would be considered in the comfort zone. With the only change being distance from display, the result is a potentially significant change to the size of the perceived comfort zone.

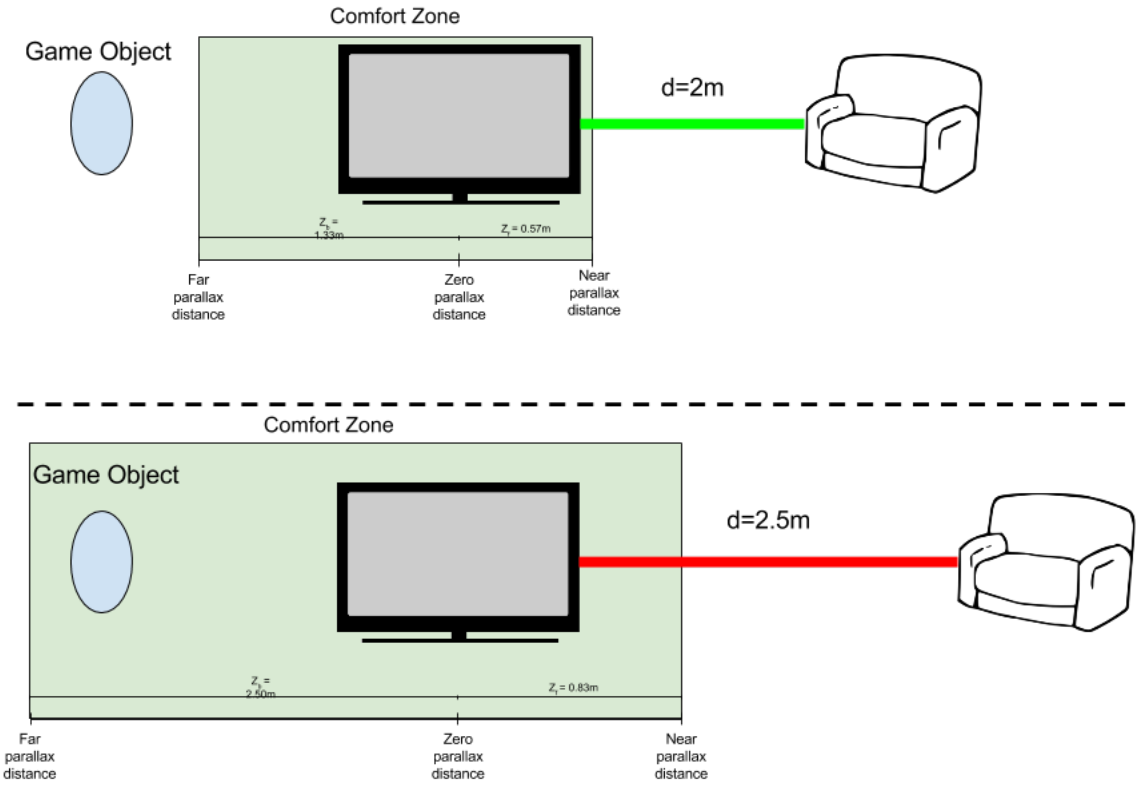

Figure 4.2: 2D visualization of the comfort zone and the effect of distance to display on the size of the comfort zone. The top image illustrates the size of the comfort zone when seated 2m from the display. The bottom image illustrates the size of the comfort zone when seated 2.5m from the display. Note that the only modification to this is the distance from display. The center of the display and position of the game object remain fixed.

4.3 Implementation

S3DComfortZone is built on top of FOV2GO and provides developers with a visualization of the zone of comfort. It is comprised out of a series of scripts written in C# working on conjunction with FOV2GO which is written in JavaScript.

S3DComfortZone is a prefabricated object within Unity that can be attached as a child object to the main camera which also contains the functionality of FOV2GO. Users are able to generate new visualization volumes of the comfort zone and apply settings based on the output used. Each comfort zone volume remains persistent during the session and can also be saved directly to a file. An example of tool interaction is shown in figure 4.3.

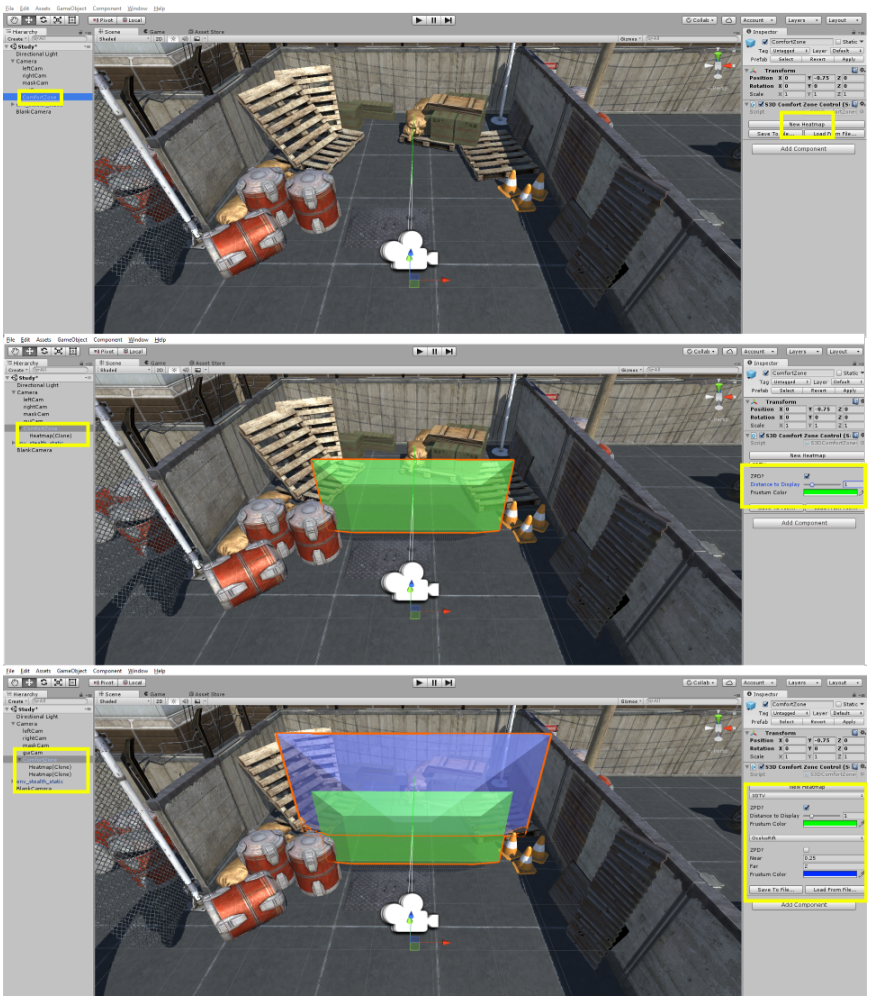

Figure 4.3: Creating a comfort zone visualization in S3DComfortZone. The image shows the ComfortZone prefabrication attached to the camera object in Unity (top). The "New Heatmap" button produces an empty visualization. Selecting the ZPD (zero-parallax distance) reveals a slider representing distance in meters (middle). ZPD deselected displays near and far plane values that can be set to correspond with the near and far comfort planes (bottom).

Each volume can be defined either through a zero parallax distance or by defining a near and far comfort distance manually. Given a zero parallax distance, the near and far comfort distances are calculated using formulas defined by Chen et al. [109]. Given a calculated or known near and far comfort zones, the vertices of the volume are calculated using the camera objects field of view and its aspect ratio. From the calculation four vertices of the near plan and four vertices of the far plane are determined. Each of these vertices are then used to construct the mesh of the visualized volume.

Chapter 5

Study 2 - Validation of S3DComfortZone Tool

It is essential to validate the S3DComfortZone tool in its ability to accurately relay comfort information. Validation of the tool will provide confidence to the developer that objects placed in the visualized comfort zone will be comfortable to view by the user. This will also ensure that content created for different display outputs will display the visualization information correctly. It is imperative that S3DComfortZone reflect accurate information as well as provide extensibility options to accommodate future technologies and output devices. A study was conducted to test the validity of S3DComfortZone. The objective of the study was to compare the users level of comfort between unmodified and modified game scenes for two displays as well as to compare the consistency between both unmodified scenes. Modifications to the scene were made using S3DComfortZone and the results of this study are used in determining the validity of the tool as a visualization of the zone of comfort.

5.1 Hypothesis

It was predicted that S3DComfortZone would accurately visualize the zone of comfort based on the output used and allow for objects outside of the zone to be placed inside and yielding better comfort for the user. In other words, the zone of comfort would be accurate in placing key objects in a position to be seen comfortably by the user.

5.2 Method

Similar to the study conducted in Chapter 3, the study required participants to view an object at different positions. In this case, the independent variable was modifications to the position of the objects based on the visualized feedback given

by S3DComfortZone. The unmodified position contained locations ranging in various depths from the camera. Positions were purposefully selected to try and induce uncomfortable viewing such as very close to the camera and very far from the camera. Modifications to the positions were performed as a percentage of distance towards or away from the camera. For instance the furthest point away from the camera in the unmodified scene was moved towards the camera such that the object was positioned on the edge of the visualized comfort zone. This shift was then applied to all other points in the scene such that each point was within the comfort zone indicated by S3DComfortZone but also maintained the same relative distance to all other points.

All participants wore LG Cinema 3D glasses for the trials associated with the 3DTV. When undergoing the trials involving the head mounted display, participants were asked to sit in a chair located next to the television. The chair remained in the same location for all participants and for all trials involving the head-mounted display. For consistency the unmodified scene used with the 3DTV output will remain identical for the head-mounted display output. This is necessary to ensure that the changes conducted on the scene for both displays are accurate. The only change for this comes from building the game scene into compatible formats to be displayed by each device. The spawn positions remain unaltered.

Prior to trials, participants underwent the randot stereotest to measure stereo acuity. If stereo acuity was satisfactory the participants continued with the experiment. All participants satisfied stereo acuity. Upon completion of the randot stereotest the inter-pupillary distance was taken for each participant using a digital caliper and recorded. Once measured, the participant were then asked to complete a demographics questionnaire.

Participants viewed a total of 4 scenes, 2 with the 3DTV and 2 with the head-mounted display. Within these scenes participants observed characters shifting the various points of depth within the scene. This occurred a total of 30 times per scene or 120 times in total. For each position, participant were asked to indicate their level of comfort using an XBOX controller and selecting 1 of 3 buttons associated with a comfort level. The green "A" button indicated a perceived normal comfort, the yellow "Y" button indicated a perceived slight discomfort and the red "B" button indicated a perceived discomfort.

After completion of each trial, participants were given the Game Engagement Questionnaire to complete. The purpose of issuing the questionnaire was to observe any possible changes in engagement level between trials as well as between output devices.

5.2.1 Participants

A total of 28 participants were used with 22 being males and 6 being females. Participants were predominantly selected from the Game Development and Entrepreneurship Program at the University of Ontario Institute of Technology but recruitment was not limited within the university. A total of twenty participants were between the ages of 18 - 24, six were betweeen the ages of 25 - 34, one participant was between the ages of 35 - 44 and one over 55.

5.2.2 Setup

The experiment was once again conducted at the game experimental lab at University of Ontario Institute of Technology. The room setup remains consistent from the study described in chapter 3. The television used was the LG 55LW5700-UE 55 inch 1080p, 120Hz, LED 3D TV. When viewing the modified and unmodified 3DTV scenes, the room was kept dark for the duration of the experiment but turned on before and after performing the task. The head-mounted display used was the Oculus Rift Development Kit 2 with each eyes containing a resolution of 960x1080 running at 60hz. The head-mounted display was connected to a workstation in the lab via a USB 2.0 cable. Furthermore, head rotation was recorded using the gyroscope within the device itself.

When viewing the modified and unmodified head-mounted display the lights were also turned off for consistency and to eliminate any possible light leaking into the sides of the device. Participants were seated approximately 8 feet from the television which falls within the recommended boundaries of 2m - 7m (6.5ft - 22.9ft) outlined by the television's user manual. Image settings were kept set as follows:

- Aspect Ratio: **16:9**
- Picture Mode: **Normal**
- AV Mode: **Off**

Once all trials were completed participants filled out a post-study free form comments in order to provides context on preferences with regard to output devices.

5.3 Results

5.3.1 Participant Experience with Stereoscopic 3D

The demographics questionnaire indicated a broad spectrum in terms of the participants level of experience in using stereoscopic 3D. On a 7-point Likert scale 5

participants indicated a level of experience of three, five, six and seven. Four participants indiciated a level of experience of two while two participants indicated a level of experience of one and four. Participants were asked which forms of media they have experienced in 3D with the results displayed in figure 5.1.

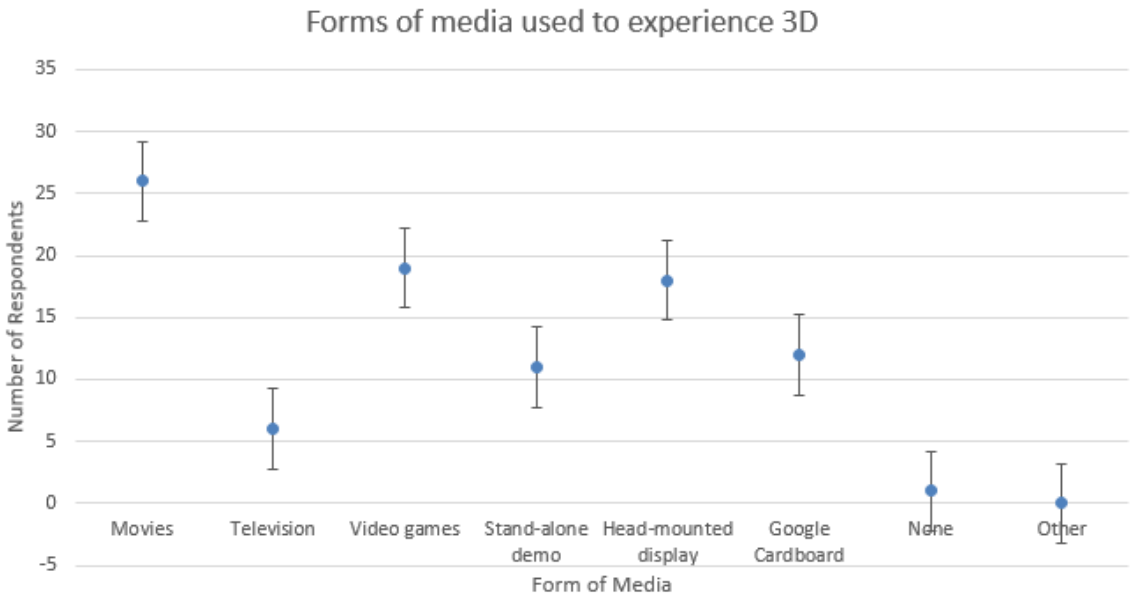

Figure 5.1: Participant results of forms of media used to experience 3D

Each participant was asked how important comfort was when experiencing 3D. Results showed that 27 of 28 participants rated comfort as 5 or higher on a 7-point Likert scale which suggests comfort being a key factor when experiencing 3D. When asked the importance of objects "popping out" of the screen 23 of 28 participants indicated 5 or greater on the 7-point scale. Furthermore when asked the importance of "depth" when experiencing 3D 24 of 28 indicated a score of 6 and higher on the 7-point scale. Finally when asked their level of experience playing video games 15 of 28 indicated a experience level of 7.

Figure 5.2: Participant results of experience playing video games

On average participants played 12 hours of video games per week with the highest number of hours being 30 and the lowest being 0.

Participants were asked to also indicate their level of experience playing video games in 3D.

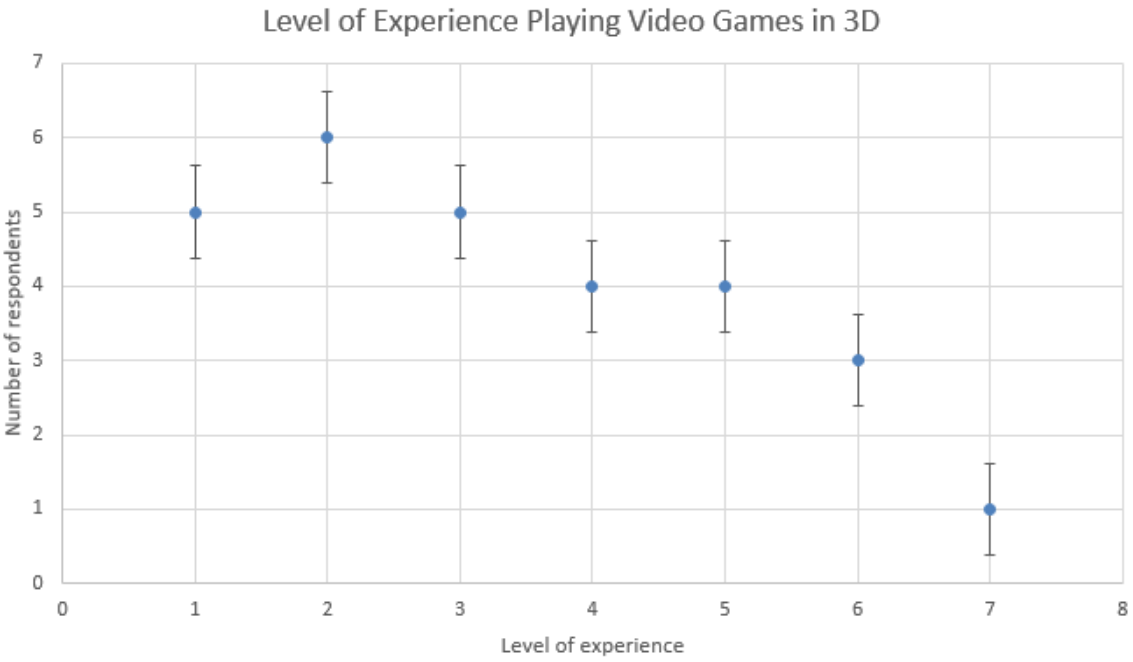

Figure 5.3: Participant results of experience playing video games in 3D

5.3.2 Game-Engagement Questionnaire

Each participant was asked to complete the Game Engagement Questionnaire following each of the 4 conditions. Therefore a total of 112 (28 participants x 4 conditions) were administered. In accordance with the development of the questionnaire, a GEQ score was calculated for each participant based on a value of -1 for the answer "no", 0 for "maybe" and 1 for "yes" [54]. A paired samples t-test performed between the following GEQ scores for the 3DTV show in 5.4.

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Overall_U	-8.1786	28	6.24828	1.18081
	Overall_M	-7.2857	28	6.88991	1.30207
Pair 2	Absorption_U	-3.1429	28	1.89960	.35899
	Absorption_M	-3.1071	28	1.95011	.36854
Pair 3	Flow_U	-3.8214	28	3.28919	.62160
	Flow_M	-3.5000	28	3.39389	.64139
Pair 4	Presence_U	-1.1429	28	1.95721	.36988
	Presence_M	-.7500	28	2.18793	.41348
Pair 5	Immersion_U	-.1071	28	.78595	.14853
	Immersion_M	.0714	28	.81325	.15369

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	Overall_U & Overall_M	28	.893	.000
Pair 2	Absorption_U & Absorption_M	28	.676	.000
Pair 3	Flow_U & Flow_M	28	.901	.000
Pair 4	Presence_U & Presence_M	28	.787	.000
Pair 5	Immersion_U & Immersion_M	28	.650	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	Overall_U - Overall_M	-.89286	3.10721	.58721	-2.09771	.31199	-1.521	27	.140
Pair 2	Absorption_U - Absorption_M	-.03571	1.55116	.29314	-.63719	.56576	-.122	27	.904
Pair 3	Flow_U - Flow_M	-.32143	1.49204	.28197	-.89998	.25713	-1.140	27	.264
Pair 4	Presence_U - Presence_M	-.39286	1.37003	.25891	-.92410	.13839	-1.517	27	.141
Pair 5	Immersion_U - Immersion_M	-.17857	.66964	.12655	-.43823	.08109	-1.411	27	.170

Figure 5.4: Paired samples t-test performed on the GEQ scores for the 3DTV across the unmodified (indicated with the postfix "_U") and modified (indicated with the postfix "_M") scenes. Values are categorized as overall, absorption, flow, presence and immersion.

A paired samples t-test was also performed between the following GEQ scores for the Oculus Rift shown in 5.5

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Overall_U	-8.1786	28	6.24828	1.18081
	Overall_M	-7.2857	28	6.88991	1.30207
Pair 2	Absorption_U	-3.1429	28	1.89960	.35899
	Absorption_M	-3.1071	28	1.95011	.36854
Pair 3	Flow_U	-3.8214	28	3.28919	.62160
	Flow_M	-3.5000	28	3.39389	.64139
Pair 4	Presence_U	-1.1429	28	1.95721	.36988
	Presence_M	-.7500	28	2.18793	.41348
Pair 5	Immersion_U	.3214	28	.72283	.13660
	Immersion_M	.1071	28	.78595	.14853

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	Overall_U & Overall_M	28	.893	.000
Pair 2	Absorption_U & Absorption_M	28	.676	.000
Pair 3	Flow_U & Flow_M	28	.901	.000
Pair 4	Presence_U & Presence_M	28	.787	.000
Pair 5	Immersion_U & Immersion_M	28	.524	.004

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	Overall_U - Overall_M	-.89286	3.10721	.58721	-2.09771	.31199	-1.521	27	.140
Pair 2	Absorption_U - Absorption_M	-.03571	1.55116	.29314	-.63719	.56576	-.122	27	.904
Pair 3	Flow_U - Flow_M	-.32143	1.49204	.28197	-.89998	.25713	-1.140	27	.264
Pair 4	Presence_U - Presence_M	-.39286	1.37003	.25891	-.92410	.13839	-1.517	27	.141
Pair 5	Immersion_U - Immersion_M	.21429	.73822	.13951	-.07197	.50054	1.536	27	.136

Figure 5.5: Paired samples t-test performed on the GEQ scores for the Oculus Rift across the unmodified (indicated with the postfix "_U") and modified (indicated with the postfix "_M") scenes. Values are categorized as overall, absorption, flow, presence and immersion.

The results of Figure 5.4 and Figure 5.5 indicate that between the unmodified and modified scenes for each device there is no significant difference in overall GEQ score. Deeper analysis of the GEQ based on the subcategories defined by [54] were also performed. Each of the subcategories (*absorption, flow, presence and immersion*) did not show significance.

The results further echo the notion that any difference in engagement between the unmodified and modified scenes for both output devices is likely due to chance.

Similarly, each individual subcategory was likewise analyzed with a paired sample t-test. Results in Figure 5.6 indicated that *absorption, flow and immersion* were significant between the unmodified scene of the 3DTV and the Oculus Rift. The results also showed that *presence* was not significant between both devices.

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Overall_U_3DTV	-8.1786	28	6.24828	1.18081
	Overall_U_HMD	-5.1429	28	8.02641	1.51685
Pair 2	Absorption_U_3DTV	-3.1429	28	1.89960	.35899
	Absorption_U_HMD	-1.9643	28	2.34887	.44389
Pair 3	Flow_U_3DTV	-3.8214	28	3.28919	.62160
	Flow_U_HMD	-2.7143	28	3.91443	.73976
Pair 4	Presence_U_3DTV	-1.1429	28	1.95721	.36988
	Presence_U_HMD	-.7857	28	2.40920	.45530
Pair 5	Immersion_U_3DTV	-.1071	28	.78595	.14853
	Immersion_U_HMD	.3214	28	.72283	.13660

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	Overall_U_3DTV & Overall_U_HMD	28	.722	.000
Pair 2	Absorption_U_3DTV & Absorption_U_HMD	28	.200	.307
Pair 3	Flow_U_3DTV & Flow_U_HMD	28	.813	.000
Pair 4	Presence_U_3DTV & Presence_U_HMD	28	.753	.000
Pair 5	Immersion_U_3DTV & Immersion_U_HMD	28	.389	.041

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	Overall_U_3DTV - Overall_U_HMD	-3.03571	5.56765	1.05219	-5.19462	-.87681	-2.885	27	.008
Pair 2	Absorption_U_3DTV - Absorption_U_HMD	-1.17857	2.70875	.51190	-2.22891	-.12823	-2.302	27	.029
Pair 3	Flow_U_3DTV - Flow_U_HMD	-1.10714	2.28261	.43137	-1.99225	-.22204	-2.567	27	.016
Pair 4	Presence_U_3DTV - Presence_U_HMD	-.35714	1.59198	.30086	-.97445	.26016	-1.187	27	.246
Pair 5	Immersion_U_3DTV - Immersion_U_HMD	-.42857	.83571	.15793	-.75263	-.10452	-2.714	27	.011

Figure 5.6: Paired samples t-test performed on the GEQ scores for the unmodified (indicated with "_U") scenes of the 3DTV versus the unmodified scene of the Oculus Rift. The term "HMD" refers to the Oculus Rift (or "head-mounted display"). Values are categorized as overall, absorption, flow, presence and immersion.

5.3.3 Study data

Participants were asked to rate their level of comfort using an Xbox 360 controller. A total of 4 possible answers could be provided: **comfortable**, **less comfortable**, **not comfortable**, and **no answer**. As part of the analysis of the data the three answers were converted into a 3-point scale with comfort being 1, less comfortable being 2 and not comfortable being 3. In the event no answer was given that entry was omitted in the calculation of the final mean.

Figure 5.7 shows the mean comfort values for each depth position presented. The first two columns represent the mean values for the unmodified 3DTV scene (3DTV

U) and the modified 3DTV scene (3DTV M). The second column shows the mean values for the unmodified Oculus Rift scene (VR U) and the modified scene (VR M). The depth positions of each value (0 throught 29) are shown in figure 5.8.

AVG					
	3DTV_U	3DTV_M		VR_U	VR_M
0	1.076923	1.142857		1.148148	1.074074
1	1.25	1.214286		1.222222	1.285714
2	1.074074	1.25		1.185185	1.214286
3	1.25	1.232143		1.142857	1.142857
4	1.321429	1.25		1.25	1.142857
5	1.178571	1.236364		1.185185	1.071429
6	1.392857	1.309091		1.392857	1.357143
7	1.464286	1.428571		1.357143	1.321429
8	1.571429	1.446429		1.464286	1.25
9	1.518519	1.472727		1.37037	1.178571
10	1.464286	1.436364		1.392857	1.464286
11	1.296296	1.410714		1.357143	1.357143
12	1.857143	1.553571		1.714286	1.321429
13	1.571429	1.660714		1.703704	1.464286
14	1.821429	1.696429		1.75	1.428571
15	2.178571	1.875		1.785714	1.571429
16	2.259259	1.981818		1.851852	1.642857
17	2.071429	1.944444		2.037037	1.535714
18	1.178571	1.574074		1.071429	1.428571
19	1.076923	1.127273		1.178571	1.607143
20	1.178571	1.054545		1.148148	1.392857
21	1.25	1.036364		1.071429	1.178571
22	1.214286	1.142857		1.142857	1.178571
23	1.185185	1.178571		1.035714	1.392857
24	1.777778	1.178571		1.714286	1.892857
25	1.607143	1.214286		1.607143	1.678571
26	1.714286	1.267857		1.642857	1.607143
27	1.821429	1.357143		1.642857	1.851852
28	1.714286	1.339286		1.535714	1.571429
29	1.777778	1.290909		1.62963	1.642857
AVG	1.503805	1.376775		1.424383	1.408245

Figure 5.7: Mean comfort scores for four conditions

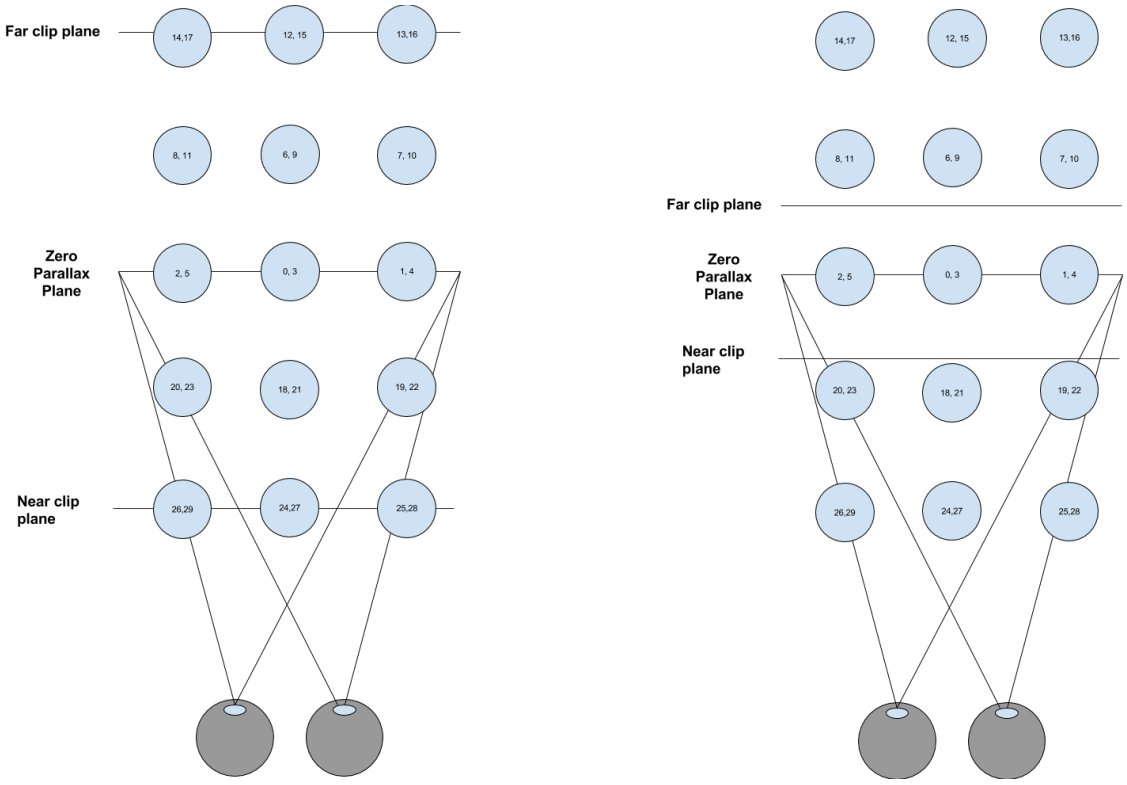

Figure 5.8: Positions of the spawned character relative to the user for the modified scenes (left) and unmodified scenes (right). Note that in the modified scenes all spawn points fall within the comfort zone visualized by S3DComfortZone.

Each of the four data sets were tested for normality using the Kolmogorov-Smirnoff test with the results shown in the Appendix followed subsequently by Q-Q plots of each data set.

A paired-samples t-test were performed between the data sets of the 3DTV unmodified and 3DTV modified, VR unmodified and VR modified and 3DTV unmodified and VR unmodified. Furthermore each set of data was used in a Pearson Correlation test.

5.4 Discussion

The independent variables of this study were the positions of the T-pose model across the unmodified and modified scenes for the two displays. The dependent variable was the self-reported comfort levels given by participants after every trial.

The results of the t-test performed on the participants overall GEQ scores indicate no significance between the unmodified and modified scenes for a 3DTV as well as for the Oculus Rift. This suggests that any change in the level of engagement by the participants between both conditions were not caused by changes to the spawning

pattern of the character being presented to the participants. Furthermore, each of the subcategories within the GEQ did not show any significance.

Contrary to the previous study, the results of the paired sample t-test performed on the overall GEQ scores between the unmodified 3DTV scene and the unmodified Oculus Rift scene **did** indicate significance. This suggests that the users level of engagement significantly differs between output devices. Further testing on the subcategories within the GEQ shows significance for *absorption, flow, and immersion* but no significance for *presence*. Presence, as defined by Brockmyer et al, is a combination of being in a normal state of consciousness as well as have the experience of being inside a virtual environment [54]. The non-significant result may stem from the primitive nature of the experiment not providing enough stimuli to strengthen their sense of presence [111].

This study presented participants with four conditions with each condition consisting of 30 trials. The participant's comfort level was recorded for each trial. To mitigate any potential learned affect, a balanced latin square design was implemented. A minimum of 27 participants were required based on the results of a power analysis performed using G*Power 3.1.9.2 provided by Universität Düsseldorf. A goal of 28 participants was set in order to complete seven full iterations of the balanced latin square design.

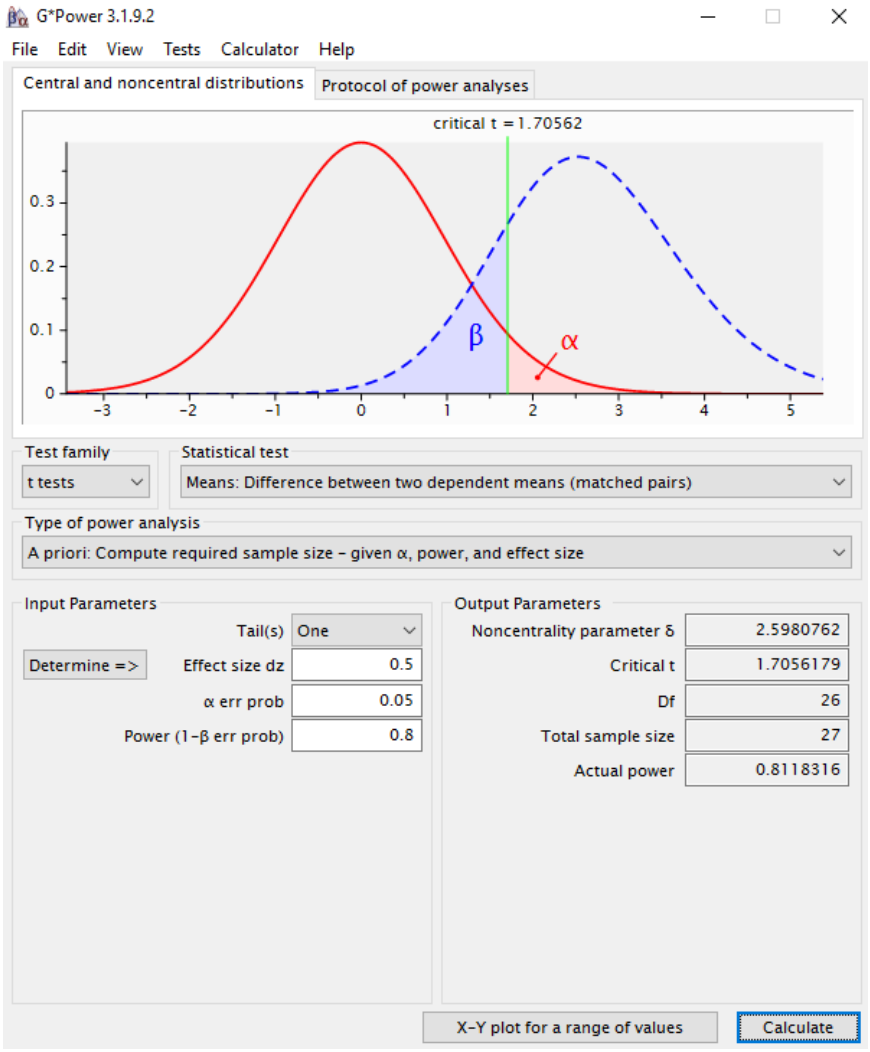

Figure 5.9: Power Analysis using G*Power [112]

The results of this study suggest S3DComfortZone can be effectively used to visualize the comfort zone. The output of the paired sample t-test show significance between the unmodified (M=1.50, SD=0.34) scene and modified (M=1.37, SD=0.25) scene presented with the 3DTV $t(29)=3.130$, $p=0.004$. This suggests that the changes in the spawning locations of the characters presented in the modified scene are likely more comfortable experience than the unmodified scene as predicted by the hypothesis.

The results of the t-test performed on the unmodified (M=1.42, SD=0.28) and modified (M=1.41, SD=0.22) scenes on the Oculus Rift did not show significance $t(29)=0.407$, $p=0.68$. This result suggests that any changes in the users perceived level of comfort was not a result of the changes to the spawning pattern presented for the Oculus Rift.

The output of the paired sample t-test between the unmodified 3DTV scene (M=1.50, SD=0.34) and the unmodified scenes presented on the Oculus Rift (M=1.42, SD=0.28) did show significance $t(29)=3.529$, $p=0.01$. The cause of the change in comfort may be a result of the device itself as indicated by the participants response in the post-study free form comments. When asked which device was more comfortable, a total of 53.6% preferred the 3DTV while 46.4% preferred the Oculus Rift. Several participants expressed concern over the Oculus Rifts visual fidelity and its effect on their comfort. Responses included:

- P3: "The characters were easier on the yes. After a while with the Oculus Rift my eyes felt fatigue"
- P7: "The Oculus Rift felt like there was uneeded motion while moving and had overall little more discomfort than the 3DTV. The 3DTV I was aware of my surroundings and everything felt fixed and stable, thus lowering the amount of discomfort I felt"
- P9: "Resolution in the occulus was low enough that it caused additional strain to my eyes. Based on this, I had a better time with the tv"
- P10: "Overall it was much more comfortable on my eyes and I was able to see the entire surrounding which helped make it a more enjoyable experience and more comfortable as well."
- P12: "I had more points of reference when I was using the 3DTV meaning I could look away and ground myself if I started to feel any discomfort. The oculus doesn't allow for that, or allow me to track where my body is in reference to what I see on screen."
- P15: "Not having to move my head to fully focus on the ball was more comfortable."

These comments may suggest that the resolution of the Oculus Rift plays a primary role in the comfort of participants. This is unique given that no mention of resolution or blurriness was given by the participants with regard to the 3DTV.

Chapter 6

Conclusion

As the market for more immersive experiences continues to grow it becomes increasingly important for designers to understand the constrains of new technologies and how to design for it. Specifically when designing for stereoscopic 3D reducing the likelihood of simulator sickness or fatigue presents a distinct challenge for designers. It has become imperative that designers are given knowledge and tools, based on science, that allows them to maximize user experience while immersed. Research into stereoscopic 3D, as well as more broadly into virtual reality, has identified several factors that influence user experience within an immersive environment. This thesis focused on the aspect of user comfort within the virtual environment and across various mediums.

The first study outlined in Chapter 3 investigated the mathematical definition of the zone of comfort as outlined by past research. Furthermore the study hypothesized that a change in the users level of comfort would occur when presented with a fully rich game environment compared to a simple black background. Participants were presented with a series of characters located at different depths and asked to self-evaluate their level of comfort in viewing that character as either comfortable, slightly uncomfortable or uncomfortable. The characters spawning position were randomized as well as the presence of a rich game background or a simple black background. The result was consistent with the defined zone of comfort outlined by [109] but the study showed no significant difference between the presence of a rich game background and a simple background with respect to comfort.

Upon completion of the first study, the S3DComfortZone tool was developed to visualize the comfort zone to developers using the Unity game engine. The tool visualizes the zone of comfort based on the mathematical definition developed by [109] and confirmed in study 1. The tool overlays a sliced frustum over the existing

main camera frustum which displays the comfortable zone. Users are able to supply a distance to the zero parallax plane or simply define the far and near planes of the zone.

The second study in Chapter 5 investigated the legitimacy of S3DComfortZone accuracy in visualizing the comfort zone. A total of four scenes were created with the aid of S3DComfortZone with the intention of displaying two of the scenes on a 3DTV and the other two scenes on the Oculus Rift. Each scene was created to display a randomized spawning pattern, similar to Study 1. One scene on each device had identical spacing for the spawning pattern and the other two scenes were modified to accommodate each devices unique comfort zone. The results indicate a significant change in the unmodified to modified scene for the 3DTV but no significance in the unmodified to modified scene for the Oculus Rift. Participants were also asked to complete the Game Engagement Questionnaire after each trial. Results show no significance between the unmodified and modified scenes for each device but did show significance between the unmodified scenes for each device. The hypothesized accuracy of S3DComfortZone was confirmed for a 3DTV.

Study 1 laid the foundation for the creation of the S3DComfortZone. The outcomes of the comfort levels showed the mathematical model developed Chen et al [38] to be an accurate representation of the comfort zone. The model provided a basis for visualizing the comfort zone in S3DComfortZone. The tool was then validated in Study 2 by modifying a purposefully-built uncomfortable game scene to fix the characteristics of the 3DTV and Oculus Rift comfort zones.

Further investigation into the Oculus Rift is warranted as many participants expressed concern over the resolution or blurriness of the device. The accuracy of S3DComfortZone may have been affected by the visual fidelity provided by the device whereas the region itself may have been visualized accurately within the tool. A study could be created that exposes users to content that fits the S3DComfortZone model with only graphical fidelity altered between blurry and crisp. It is also imperative to further investigate additional immersive technologies and its comfort zones to further enforce the usage of S3DComfortZone.

6.1 Contributions

This thesis explores the benefits and accuracies in developing a visualization tool for the zone of comfort that aids developers of immersive technologies. The first study confirmed prior research in mathematically defining the zone of comfort as well as showing no statistical difference between a game rich environment and simple black

background on a 3DTV in terms of comfort. S3DComfort zone was then developed as a tool for designers using the Unity Game Engine to visualize the comfort zone for different output devices. Finally the second study confirmed S3DComfortZone as accurately visualizing the comfort zone for the 3DTV. The overall result of this work provides the basis for an accurate visualization tool that can be utilized by game designers and other media creators. As modifications to virtual reality devices emerge coupled with innovative S3D technologies being created, S3DComfortZone provides a foundation in delivering content to those devices and maximizes the likelihood of viewing the content comfortably. Furthermore, a single unifying tool such as S3DComfortZone provides a single interface for multiple configurations of S3D devices. S3DComfortZone represents the first interactive comfort zone tool intended for game development and stereoscopic 3D content development. Not only will this provide developers with accuracy in terms of comfort but also visualizes common volumes of space between multiple devices. Developers can then tailor their content to fit the comfort zone of multiple devices in a single development project.

6.2 Limitations and Future Work

Further research must be put into understanding the influences behind the comfort zone. Study 1 would benefit from a revisit by ensuring the t-pose character is positioned an equal number inside and out of the comfort zone. Study 2 did not show significance in the changes made between the unmodified and modified study but comments recorded by participants afterwards showed complaints about the devices visual fidelity. Continued iterations on the device itself should improve visual fidelity and revisiting the study would be beneficial.

It is also important to further understand the impact of multiple cues on the comfort zone. Combining cues such as visual cues and audio cues in a 3D environment could impact the accuracy of depth perception of objects which may have a positive effect on the comfort zone. Contrarily a mis-match in cues providing conflicting information relating to objects in a 3D environment may negatively impact the comfort zone. Iteration on S3DComfortZone may be able to address many cues occurring parallel and accurately visualize changes based on multiple cues.

Similarly, extending the functionality of S3DComfortZone to visualize the comfort zone in a dynamic environment would be beneficial for developers. User interaction would becomes increasingly important to control in order to maximize the comfort of key objects within the context of a game. Objects such as treasures, enemies or areas

that are important in a gaming context would benefit from being positioned within in the comfort zone through manipulation of the users interaction with the game.

S3DComfortZone presents a raw foundation to visualize the zone of comfort. Continued iteration on the tool itself as well as testing for usability from professional and non-professional developers would be beneficial. Usability testing of the tool would ensure optimal usage. While the device used to display S3D content plays a major factor in determining the comfort of the content being viewed, it is not alone in influencing user comfort. Other sensory inputs, such as auditory, haptic, olfactory, play vital roles in user experience. Future work in determining the link between other sensory inputs and comfort can expand the capabilities of S3DComfortZone and result in a more accurate application given more data. Often ignored with respect to user experience is the environment information surrounding the user. Aspects such as ambient temperature, lighting conditions, external sounds as well as the physiological state of the user may all have affect on comfort. Isolating each potential influence on comfort and viewing varying intensities of each influence on comfort will provide additional data to S3DComfortZone.

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Appendix

This section contains raw information used to supplement the information and data presented throughout the thesis. Several piece of information to follow are references at various points within the thesis but also several are simply supplemental and not directly referenced.

Demographics Questionnaire

*Required

1. **Please indicate your age** *
   Mark only one oval.
   - ◯ 18 - 24
   - ◯ 25 - 34
   - ◯ 35 - 44
   - ◯ 45 - 54
   - ◯ 55+

2. **Please indicate your identified gender** *
   Mark only one oval.
   - ◯ Male
   - ◯ Female

3. **Indicate your level of experience with stereoscopic 3D** *
   Mark only one oval.

	1	2	3	4	5	6	7	
Not experienced	◯	◯	◯	◯	◯	◯	◯	Very experienced

4. **What forms of media have you experienced 3D? Select all that apply** *
   Tick all that apply.
   - ☐ Movies
   - ☐ Television
   - ☐ Video Games
   - ☐ Stand-alone demo
   - ☐ Head-mounted Display (Oculus Rift, HTC Vive)
   - ☐ Google Cardboard
   - ☐ None
   - ☐ Other: _____

Game Engagement Questionnaire

1. **My thoughts go fast**
   Mark only one oval.
   - ◯ Yes
   - ◯ Maybe
   - ◯ No

2. **I feel spaced out**
   Mark only one oval.
   - ◯ Yes
   - ◯ Maybe
   - ◯ No

3. **Things seem to happen automatically**
   Mark only one oval.
   - ◯ Yes
   - ◯ Maybe
   - ◯ No

4. **I really get into the game**
   Mark only one oval.
   - ◯ Yes
   - ◯ Maybe
   - ◯ No

5. **I feel like I just can't stop playing**
   Mark only one oval.
   - ◯ Yes
   - ◯ Maybe
   - ◯ No

Post-Study Free Form Comments

1. **Did you notice a difference in your ability to see the 3D character when the background was black vs when the background was a game scene? Explain.**

2. **Do you have a preference in seeing 3D object with a rich background or an empty background?**

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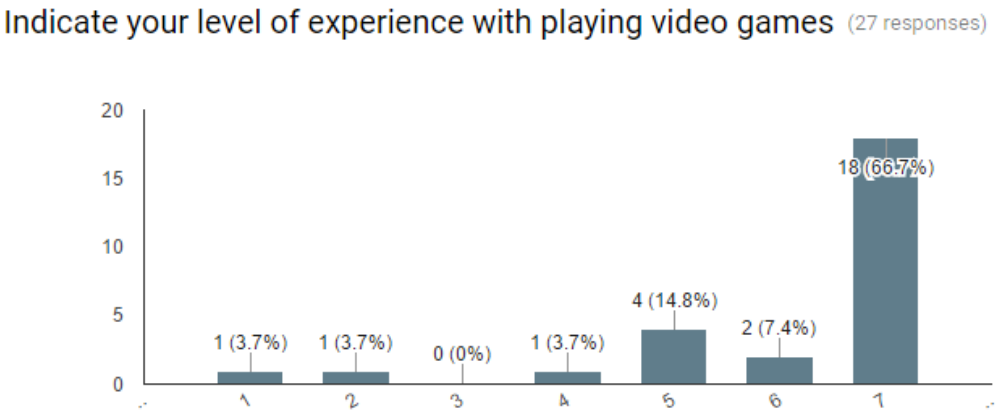

Figure 6.1: Study 1 - Experience playing video games questionnaire result

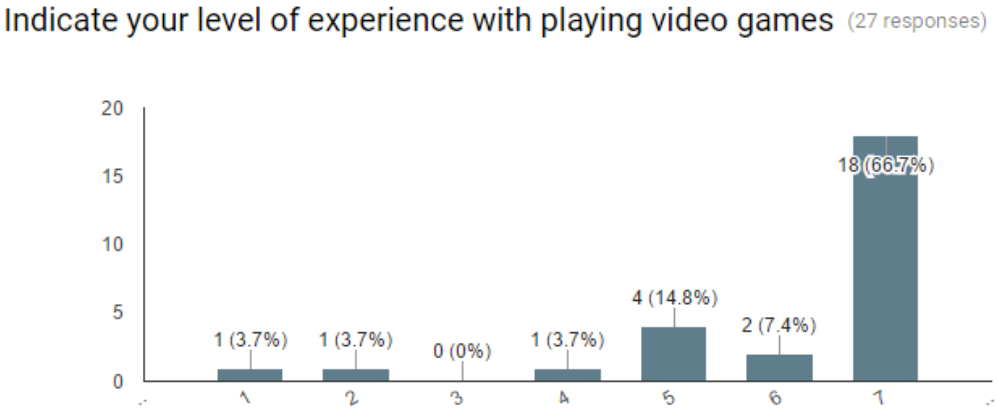

Figure 6.2: Study 1 - Experience playing video games questionnaire result

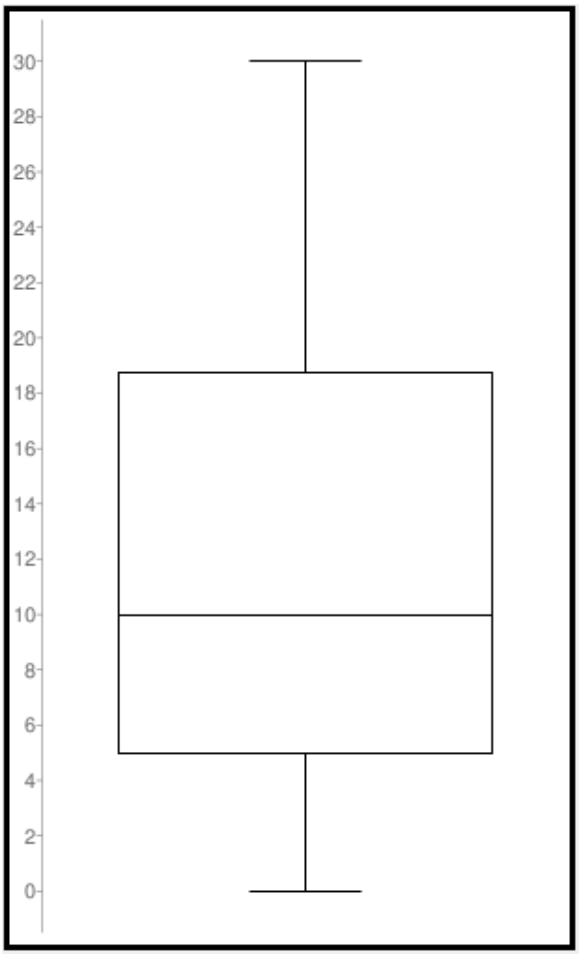

Figure 6.3: Box plot of the average number of hours playing video games

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	-8.178571	28	6.2482802	1.1808140
	TV_3D_M	-7.285714	28	6.8899129	1.3020711
Pair 2	VR_U	-5.142857	28	8.0264114	1.5168492
	VR_M	-4.964286	28	7.8480106	1.4831346

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	TV_3D_U & TV_3D_M	28	.893	.000
Pair 2	VR_U & VR_M	28	.902	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - TV_3D_M	-.8928571	3.1072113	.5872077	-2.0977079	.3119936	-1.521	27	.140
Pair 2	VR_U - VR_M	-.1785714	3.5177178	.6647862	-1.5426000	1.1854571	-.269	27	.790

Figure 6.4: Study 2 - Overall Game Engagement Questionnaire (GEQ) results

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	-3.142857	28	1.8995962	.3589899
	TV_3D_M	-3.107143	28	1.9501051	.3685352
Pair 2	VR_U	-1.964286	28	2.3488712	.4438949
	VR_M	-1.785714	28	2.4245220	.4581916

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	TV_3D_U & TV_3D_M	28	.676	.000
Pair 2	VR_U & VR_M	28	.649	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - TV_3D_M	-.0357143	1.5511559	.2931409	-.6371898	.5657612	-.122	27	.904
Pair 2	VR_U - VR_M	-.1785714	2.0009918	.3781519	-.9544751	.5973322	-.472	27	.641

Figure 6.5: Study 2 - Absorption Game Engagement Questionnaire (GEQ) results

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	-3.821429	28	3.2891919	.6215988
	TV_3D_M	-3.500000	28	3.3938943	.6413857
Pair 2	VR_U	-2.714286	28	3.9144286	.7397575
	VR_M	-2.571429	28	3.9667934	.7496535

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	TV_3D_U & TV_3D_M	28	.901	.000
Pair 2	VR_U & VR_M	28	.882	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - TV_3D_M	-.3214286	1.4920424	.2819695	-.8999822	.2571251	-1.140	27	.264
Pair 2	VR_U - VR_M	-.1428571	1.9189944	.3626559	-.8869655	.6012512	-.394	27	.697

Figure 6.6: Study 2 - Flow Game Engagement Questionnaire (GEQ) results

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	-1.142857	28	1.9572143	.3698787
	TV_3D_M	-.750000	28	2.1879299	.4134799
Pair 2	VR_U	-.785714	28	2.4091975	.4552955
	VR_M	-.714286	28	2.0880106	.3945969

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	TV_3D_U & TV_3D_M	28	.787	.000
Pair 2	VR_U & VR_M	28	.738	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - TV_3D_M	-.3928571	1.3700307	.2589115	-.9240996	.1383853	-1.517	27	.141
Pair 2	VR_U - VR_M	-.0714286	1.6539195	.3125614	-.7127516	.5698945	-.229	27	.821

Figure 6.7: Study 2 - Presence Game Engagement Questionnaire (GEQ) results

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	-.107143	28	.7859547	.1485315
	TV_3D_M	.071429	28	.8132501	.1536898
Pair 2	VR_U	.321429	28	.7228325	.1366025
	VR_M	.107143	28	.7859547	.1485315

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	TV_3D_U & TV_3D_M	28	.650	.000
Pair 2	VR_U & VR_M	28	.524	.004

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - TV_3D_M	-.1785714	.6696362	.1265494	-.4382293	.0810864	-1.411	27	.170
Pair 2	VR_U - VR_M	.2142857	.7382232	.1395111	-.0719674	.5005388	1.536	27	.136

Figure 6.8: Study 2 - Immersion Game Engagement Questionnaire (GEQ) results

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	-8.178571	28	6.2482802	1.1808140
	VR_U	-5.142857	28	8.0264114	1.5168492

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	TV_3D_U & VR_U	28	.722	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - VR_U	-3.0357143	5.5676456	1.0521861	-5.1946219	-.8768067	-2.885	27	.008

Figure 6.9: Study 2 - Overall GEQ score between the unmodified scenes presented with the 3DTV versus the Oculus Rift

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	-3.142857	28	1.8995962	.3589899
	VR_U	-1.964286	28	2.3488712	.4438949

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	TV_3D_U & VR_U	28	.200	.307

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - VR_U	-1.1785714	2.7087454	.5119048	-2.2289132	-.1282296	-2.302	27	.029

Figure 6.10: Study 2 - Absorption GEQ score between the unmodified scenes presented with the 3DTV versus the Oculus Rift

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	-3.821429	28	3.2891919	.6215988
	VR_U	-2.714286	28	3.9144286	.7397575

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	TV_3D_U & VR_U	28	.813	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - VR_U	-1.1071429	2.2826120	.4313731	-1.9922474	-.2220383	-2.567	27	.016

Figure 6.11: Study 2 - Flow GEQ score between the unmodified scenes presented with the 3DTV versus the Oculus Rift

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	-1.142857	28	1.9572143	.3698787
	VR_U	-.785714	28	2.4091975	.4552955

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	TV_3D_U & VR_U	28	.753	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - VR_U	-.3571429	1.5919772	.3008554	-.9744472	.2601615	-1.187	27	.246

Figure 6.12: Study 2 - Presence GEQ score between the unmodified scenes presented with the 3DTV versus the Oculus Rift

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	-.107143	28	.7859547	.1485315
	VR_U	.321429	28	.7228325	.1366025

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	TV_3D_U & VR_U	28	.389	.041

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - VR_U	-.4285714	.8357109	.1579345	-.7526263	-.1045166	-2.714	27	.011

Figure 6.13: Study 2 - Immersion GEQ score between the unmodified scenes presented with the 3DTV versus the Oculus Rift

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TV_3D_U	1.503805	30	.3358162	.0613114
	TV_3D_M	1.376775	30	.2513509	.0458902
Pair 2	VR_U	1.424383	30	.2752533	.0502541
	VR_M	1.408245	30	.2191839	.0400173
Pair 3	TV_3D_U	1.503805	30	.3358162	.0613114
	VR_U	1.424383	30	.2752533	.0502541

Figure 6.14: Study 2 - Comfort level paired sample test results

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	TV_3D_U - TV_3D_M	.1270302	.2223047	.0405871	.0440202	.2100401	3.130	29	.004
Pair 2	VR_U - VR_M	.0161376	.2171948	.0396542	-.0649643	.0972394	.407	29	.687
Pair 3	TV_3D_U - VR_U	.0794227	.1232772	.0225072	.0333903	.1254552	3.529	29	.001

Figure 6.15: Study 2 - Comfort level paired sample test

Correlations

		TV_3D_U	TV_3D_M
TV_3D_U	Pearson Correlation	1	.750**
	Sig. (2-tailed)		.000
	N	30	30
TV_3D_M	Pearson Correlation	.750**	1
	Sig. (2-tailed)	.000	
	N	30	30

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 6.16: Study 2 - 3DTV Person's Correlation test

Correlations

		VR_U	VR_M
VR_U	Pearson Correlation	1	.635**
	Sig. (2-tailed)		.000
	N	30	30
VR_M	Pearson Correlation	.635**	1
	Sig. (2-tailed)	.000	
	N	30	30

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 6.17: Study 2 -Oculus Rift Person's Correlation test

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
TV_3D_U	.142	30	.127	.929	30	.046
TV_3D_M	.139	30	.141	.903	30	.010
VR_U	.141	30	.133	.935	30	.068
VR_M	.086	30	.200*	.964	30	.393

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Figure 6.18: Study 2 - Test for Normality showing non-significance

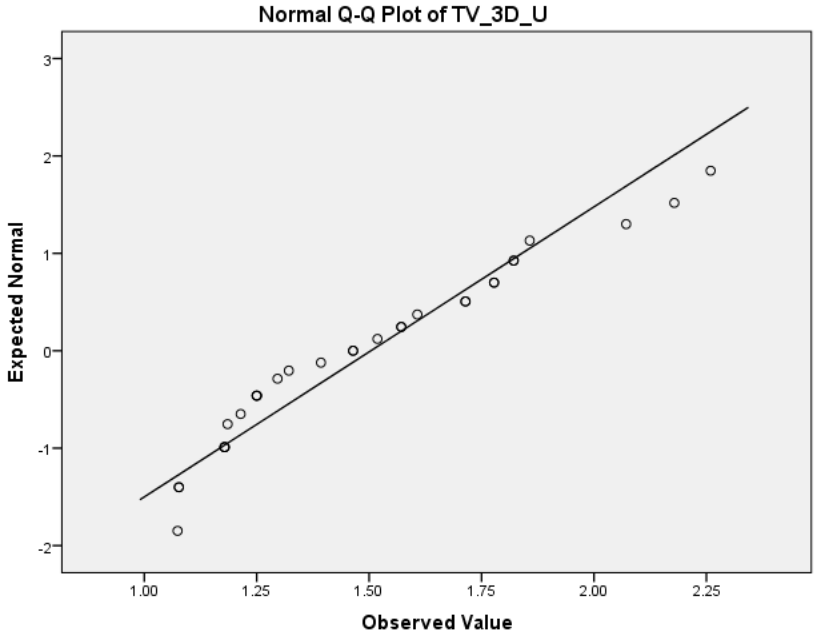

Figure 6.19: Study 2 - Q-Q Plot of the 3DTV unmodified scene

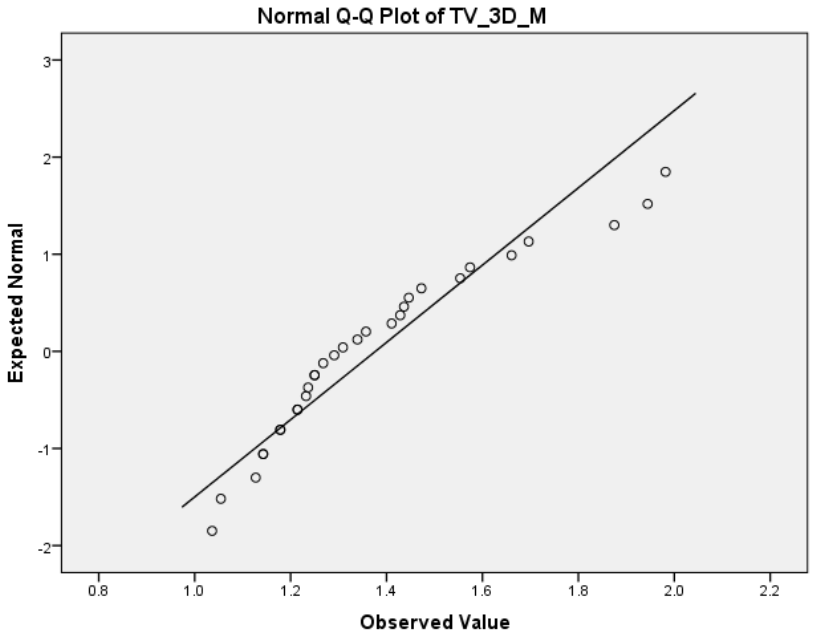

Figure 6.20: Study 2 - Q-Q Plot of the 3DTV modified scene

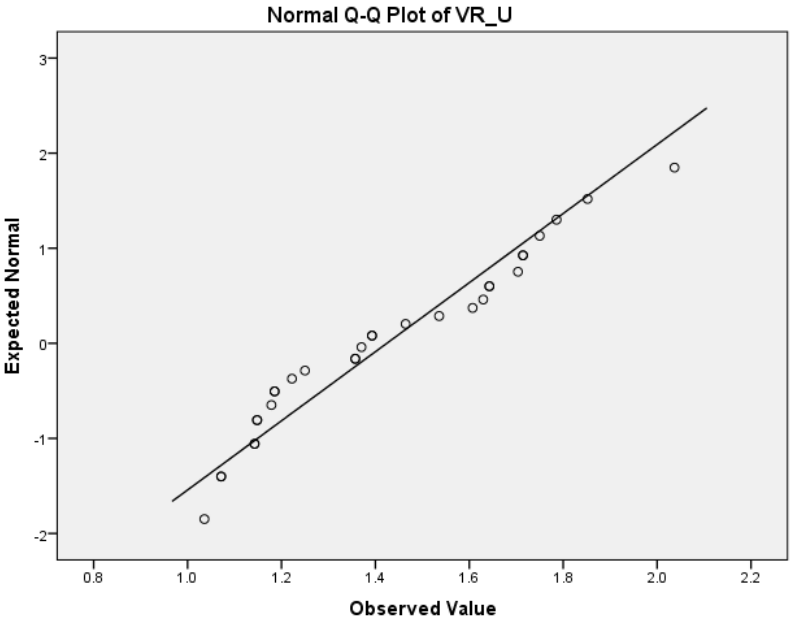

Figure 6.21: Study 2 - Q-Q Plot of the Oculus Rift unmodified scene

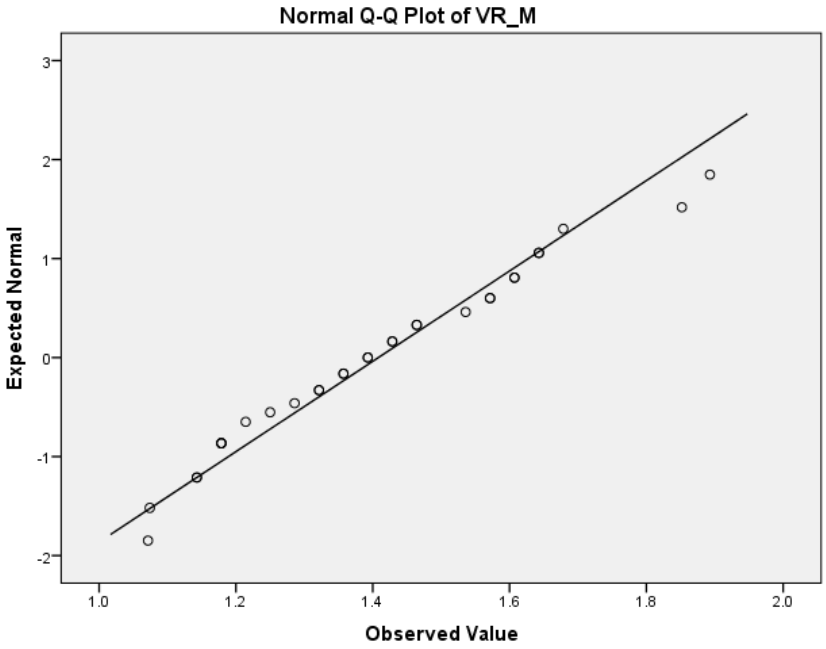

Figure 6.22: Study 2 - Q-Q Plot of the Oculus Rift modified scene