

Rendering and Perception of Depth Cues on a Multi-Focal Plane Stereo Display

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Master of Philosophy in Advanced Computer Science*

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Declaration

I Nicholas G. Timmons of Downing College, being a candidate for the M.Phil in Advanced Computer Science, hereby declare that this report and the work described in it are my own work, unaided except as may be specified below, and that the report does not contain material that has already been used to any substantial extent for a comparable purpose.

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Abstract

This is the abstract. Write a summary of the whole thing. Make sure it fits in one page.

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Chapter 1

Introduction

This research has been performed to fulfil the requirements of the MPhil Advanced Computer Science course.

It is research into the effects of introducing focal depth cues to rendered scenes through the presence of multiple focal planes on the accuracy of depth perception.

This is attempted with the construction of a custom stereoscopic multi-focal 3D display and development of software to configure and drive it.

One of the aims of this display is to counter the vergence-accommodation problem to reduce its impact on the perceived depth of the images being shown.

This is of particular interest to the study of VR(virtual reality) and 3D vision which in current commercial implementations present the user with a single focal depth which are in conflict with the convergence and binocular disparity cues of the image being shown.

Add some of the results and interesting things of the work here

This report includes a background of current techniques being used for VR and a short overview of similar methods using multi-focal planes.

There is then a breakdown of the requirements and techniques implemented in software and hardware for this multi-focal display with details of how they have been configured to achieve our results.

We also detail our experimental methods and results before summarising our findings and discuss future work which could take our research further.

Chapter 2

Background

Stereo displays such as those used for showing 3D movies and in HMD (head mounted displays), are in use in many commercial products and have seen significant improvement over the past decade [ref](#) but still have some large technical and usability problems related to rendering techniques which could restrict the wide-scale appeal of the products [17] and do not yet successfully mimic all the visual cues that the visual cortex processes when viewing objects in the real world.

When considering the comfort of the user the results of many psychometric and usability studies have suggested that the current implementations of binocular disparity through stereo rendering can lead to problems and discomfort for the users, sometimes known as “Simulation Sickness” [3]. These symptoms include distortion of perceived depth [10], visual fatigue [4], diplopia (commonly known as double vision) [6] and can even cause a temporary degradation in the oculomotor response. [7].

There are many factors contributing to cause these conditions varying from low quality images, such as the high persistence in the early Oculus Rift displays [24], or incorrect intraocular distances or having no comfortable point to allow the eyes to rest. A major cause that is often mentioned is the discrepancy between accommodation and vergence when using these displays

with a fixed real focal distance. In this context accommodation refers to the focusing of the eye on objects at different distances and vergence is the motion of eyes rotating to bring the convergence point of the optical axis to intersect at the distance of the object. These oculomotor actions are coupled and work together when looking at an object in the real world but cannot function correctly when decoupled due to being shown objects with stereo correspondence at one depth and vergence correspondence at another - which is the general case for objects shown on standard stereo head mounted displays (See Figure 2.3 and 2.2).

Past research has suggested [10] that the breaking of the link between accommodation and vergence cues can lead to a decreased perception of depth, which will affect how the user understands the space they are looking at and could have an adverse effect on the perceived realism of the space as the scale may appear inconsistent with what the user is accustomed to. This is of particular importance to artificial reality environments where the virtual environment is mixed with the real world. In this situation the depth cues from the display would have to match with those from the real world in order to maintain consistency and not induce the conflict.

2.1 Realism

In the context of this research we are considering realism to consist of many separate visual cues. In a perfectly realistic scene the user would not be able to tell the difference between looking a scene in the real world and one that is rendered as the cues would all match.

To achieve this, we would want a high quality rendering of a scene with correct lighting and reflectance within the full colour and intensity range that the human eye can perceive as well as being seen as 3D to the user through correct visual and depth cues.

Within the limited scope of this project we will not be able to develop all of those features but will be focused on improving the realism of a rendered

scene through the use of more sophisticated depth cues to measure whether that improves how real the scene appears to the user when compared to a scene which is lacking such cues.

2.2 Focal Length

As we will be discussing multi-focal displays it is important to clarify what the focal length is. In this context the focal length is the measure of the distance to the point that an optical system converges. The unit for Focal Length is the Dioptre which is measured as the reciprocal of the distance in meters to the convergence point.

$$X_{\text{Dioptries}} = \frac{1}{\text{Distance}_{\text{Meters}}} \quad (2.1)$$

2.3 Depth Cues

The human visual system has many cues for determining depth. Some that are visible in two dimensional displays (Table. 2.1) and some that are only possible with stereo or multi-focal displays (Table. 2.2). To attain maximum realism in the images shown the visuals would have to be delivering all of these cues [25].

For most people 'Binocular Disparity' is a very important depth cue [ref] which is relatively easy to replicate with two screens and as such is the cue that is most well represented by consumer 3D products at the moment, however conflicts with other cues can cause detrimental effects to the visual cortex's ability to form a single image and extract the depth like it would when viewing the real world. Patterns such as repeating identical vertical bars are particularly problematic for finding stereoscopic matches without other cues and this can lead to visual strain and fatigue.

Perspective	Objects further away from the eye appear smaller.
Known Sizes	We can judge relative depths of objects from known sizes. For example, if an image shows a football and a house as the same size we assume the house is further away.
High Frequency Detail	We assume when we can see more small details that the object is closer.
Occlusion	An object that occludes another is closer than the object it is occluding.
Lighting	The human visual system is accustomed to seeing objects under different lighting conditions and can therefore reason the position of objects in a scene by the lighting and shadowing between them. It is also able to judge distance by the slight dimming of objects in the distance due to atmospheric scattering.
Relative motion	An object closer to the camera appears to move across the view faster than one further away.

Table 2.1: Depth cues in two dimensional images.

Binocular disparity	The difference in the apparent position of objects under projection caused by the interocular distance between the two eyes. (<i>Stereo Only</i>)
Accommodation	The changing of the focal length of the lens in the eye to focus the view on an object at a particular depth. (<i>Muti-Focal Only</i>)
Convergence	Bringing the two images from each eye to overlap more coherently and face a specific point at a particular depth through rotation towards and away from the interocular midpoint.

Table 2.2: Depth cues in stereoscopic and/or multi-focal images.

2.4 Standard Stereo VR Implementations

The current standard for VR in a number of commercial hardware implementations consists of a head mounted display with the screen split vertically to

display a separate image of the scene for each eye and a lens to distort the image to increase the amount of the screen that is visible and to reduce the “Screen Door Effect” [19] caused by the low pixel density and visible lines between them. The software is then implemented using intraocular distances of the screen in the display with an appropriate field of view and a standard Off-Axis parallel projection for each eye (See Section 5.1.1).

The correctly calibrated projection of the same scene for the two separate views gives a feeling of depth and “realism” through the user picking up on stereo-correspondences from the disparity in the two images and perceiving them as a single object at an expected distance.

Since the screen that is being used is a fixed short distance from the users eyes at all times the user is always focusing at a fixed focal distance which is different than the identified distance for the motion and stereo correspondences that are being shown in the scene.

This triggers the Vergence-Accommodation conflict from a conflict in visual depth cues. There are examples of trying to use simulated Depth of Field blur in early VR and large screen 3D for very near objects to try and simulate one of the missing visual cues but this was found to induce ”Simulation Sickness” and is it now strongly advised against [26].

There is currently a push in 3D technologies to try and increase the frame rate of applications that are using these techniques beyond the normal high bar of 60 frames per second. This has been seen as a way to reduce the discomfort some users feel from uneven or clunky motion caused by low or varying frame-rates [22]. As resolutions and visual quality increases, making it harder to achieve, this is becoming a particularly important area to consider when developing for these technologies.

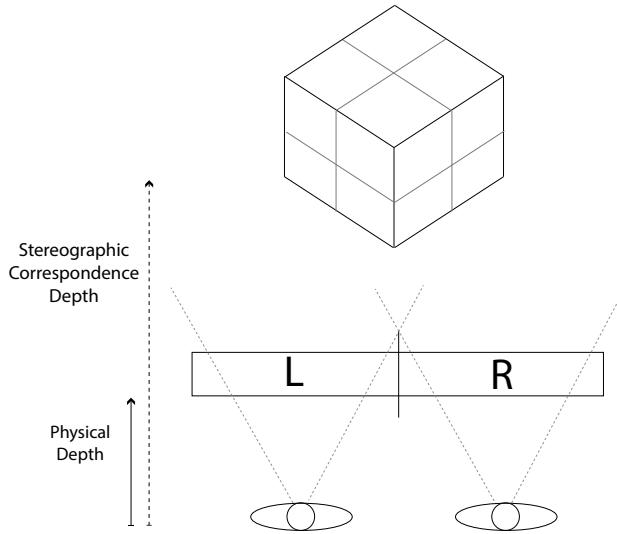


Figure 2.1: Basic comparison of the stereo and accommodation depths in a mismatched situation, such as a head mounted display.

2.5 Vergence-Accommodation Conflict

The Vergence-Accommodation conflict is a source of discomfort and disorientation for a lot of users of stereo displays [12]. It is caused by a mismatch of the focal depth and convergence depth cues. It is a problem which originates from trying to simulate depths of objects which have a different focal depth in software leading to correct stereoscopic disparity between eyes but an incorrect focal depth for those objects. This is particularly a problem for standard stereo displays due to the use of a single focal depth because of the fixed display panel position.

This conflict can cause eye strain, headaches and dizziness in some users and is strongly associated with “simulation sickness” [26].

While this conflict does have some effect on the comfort of the user [17], in the area we are looking at we are more interested in the effect this has on how the users perceives the distances to objects in the world when this conflict is reduced.

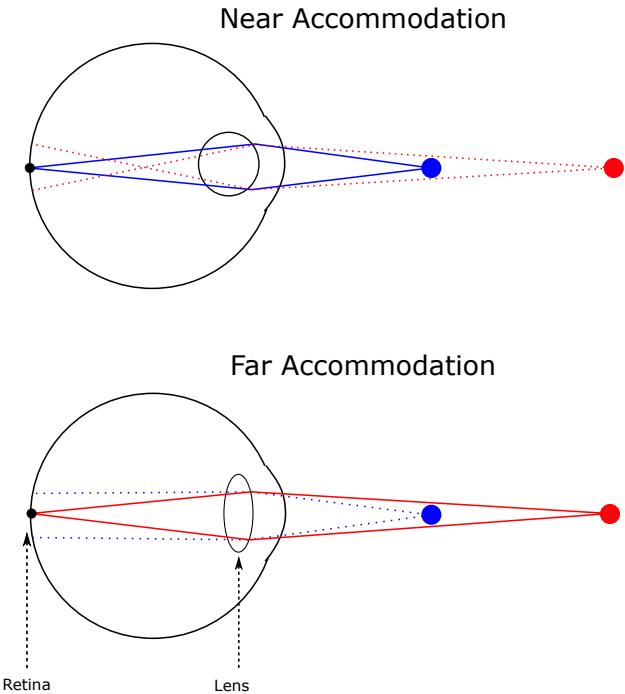


Figure 2.2: This diagram shows the basic physics behind the effect accommodation has to bring near and far objects in and out of focus by converging light towards the retina.

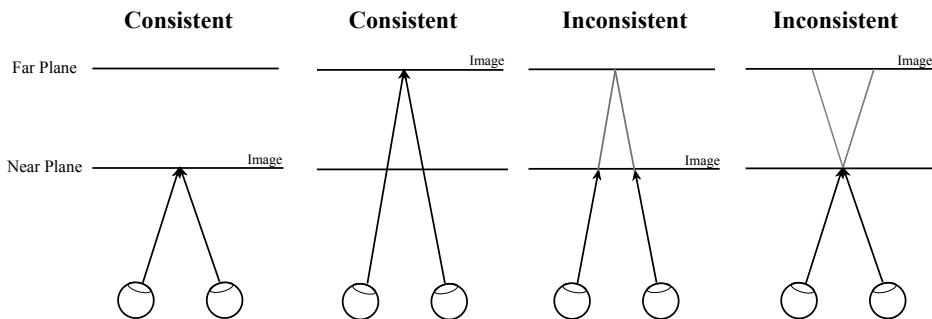


Figure 2.3: This is an illustration showing the different configurations which can cause a vergence-accommodation conflict. Any of the combinations which show a mismatch between the image depth and the convergence point can cause discomfort for the user.

It appears that when these visual cues are mismatched the users ability to judge the distance to objects becomes limited, vision can become less clear and the speed at which stereoscopic correspondences are matched is

decreased. These symptoms can all interfere with the stereoscopic technique as it reduces the ability of the user to create an internal model of the scene correctly.

If the user is unable to judge the depth and position of objects clearly in the scene then it would not be comparable to the real-world and therefore, not realistic.

One of the main aims of using multi-focal cues is that it will reduce the confusion of depths and allow it to be properly processed the same as any real-world scene.

Chapter 3

Related Work

3.1 Multi-focal viewing

Multi-focal displays aim to simulate real world light ray angles to provide correct depth cues to the user. It is an area that has been investigated for over a decade but has recently became much more popular with the rise of VR as a viable platform due to the problems the single focal displays which they use cause.

The idea for multi-focal viewing is to use multiple displays, or sections of displays [13] and a series of lenses, mirrors and beam-splitters to combine images at different depths into a single image for the user to see. The different distances to the screens will then give the user different focal points to focus on that will behave like real screens at those distances.

Through clipping the viewed images to have only the sections at the correct depths displayed on each screen you can effectively create scenes with discrete visible focal depths.

These screens were used to investigate the comfort and physical reactions of the human eye when viewing simple scenes [8] and found to increase the comfort of the user and reduce the negative effects of single focal plane stereo

rendering solutions.

A downside to this method is that it is very sensitive to calibration and the images need to match perfectly to create the illusion of a single image, see Figure 2.1. This means that displays have to be invariant to user motion and match the physical position and separation of the users eyes at all time to avoid unwanted parallax between the two planes.

Alternative more complex methods have been suggested such as a lenticular display setup [18], however, like many autostereoscopic methods, this method suffers from crosstalk which you do not get in more straight forward designs. Other alternative designs include methods which make use of the active stereo techniques to limit the number of screens [14] but this has its own implications on the frame rate and how active a scene can be as well as restricting the user to wearing special glasses which can be a problem for users who already wear corrective lenses.

For less complex display models, it is possible to avoid the eye tracking by using fixed depths and designing to accommodate different eye positions - which can be quite varied among a population.

There was a study carried out by the US Army which investigated the intraocular distance of its members and gives some very good data on the topic [2]. They showed a mean distance of 6.47cm for men and 6.23cm for women, see Table 3.1. Using this data work has been carried out to support many users with varying intraocular distances with adjustable hardware [15]. There was a more in depth analysis of the mean intraocular distances which took a more widespread look at the general population, including children [9] which are not represented in the US Army study. The general results within adults fell in line with what we see from the US Army work. As we are testing on adults we will be using the data for adults only to configure our display.

The downside to this type of method is that the user is required to maintain a calibrated head position through out to keep the effect working. To prevent the movement of the user causing problems some very *interesting* solutions

have been used in research such as bite-bars to bite down on to prevent the users head from moving [8]. However, these are a little impractical for a study covering multiple users which will need to support multiple distances and intraocular distances.

	Male	Female
Mean	6.47cm	6.23cm
Min	5.20cm	5.20cm
Max	7.80cm	7.60cm

Table 3.1: Interocular distances from the US Army data [2]

3.2 Depth Perception

There have been a number of papers investigating the effect of stereo displays on perceived depth. One such study performed an investigation into the effect of different fields of view when using a stereo setup and how that changes our interpretation of the depth which points to the conclusion that relative scale and rate of change of scale is important in our perception of depth.

In one experiment [21] were able to show that a user in the correct configuration could correctly navigate to a specific position in the scene, where as a user who was not calibrated would have difficulty due to “minification”.

This shows the ability to accurately determine the depth and position of objects is affected by depth cues, whether they are from stereo correspondences, projection or otherwise. Which gives us reason to believe that the accuracy and depth perception can be improved by the introduction of further depth cues. Particularly, focal length was shown as a way to determine the depth of objects from separate images static scenes under varying levels of focus [1].

Chapter 4

Hardware

The goal of this implementation is to create a display which we will be able to use to investigate the relative perceived realism of the scene through the effectiveness of depth perception when given the extra focal depth cue compared to standard stereoscopic rendering and allow it to be easily configurable for more specific tests in the future.

4.1 Display Requirements

The display is designed to allow us to investigate perceived realism for this work but also to be configurable for to support future work beyond this project.

This project requires that the display supports four high resolution, good quality displays which are able to be viewed at configurable focal distances in a stereo setup that allows the user to view only two screens per eye and support a wide range of users. This is to allow the testing of combinations of zero disparity, stereoscopic and multi-focal scenes.

To support male and female users it would be ideal that the displays were configurable to support both adult male and female average intraocular distances.

4.2 Display Design

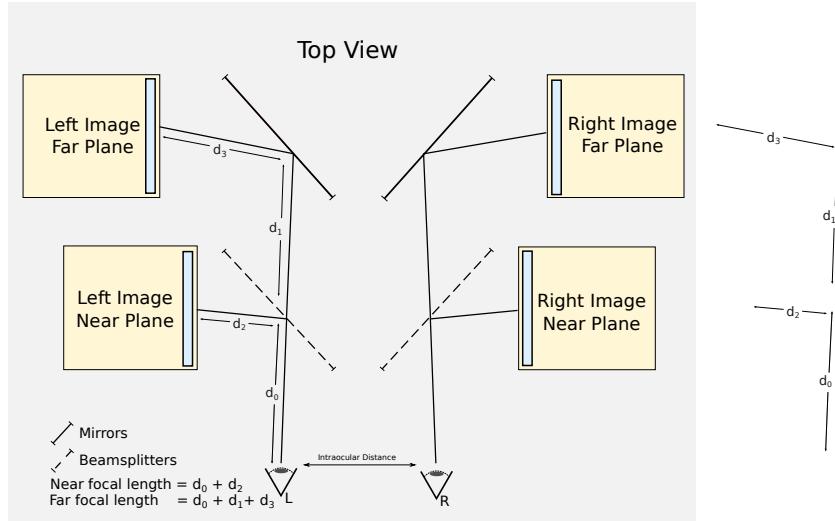


Figure 4.1: A high level view of the concept layout to achieve the stereo multi-focal images.

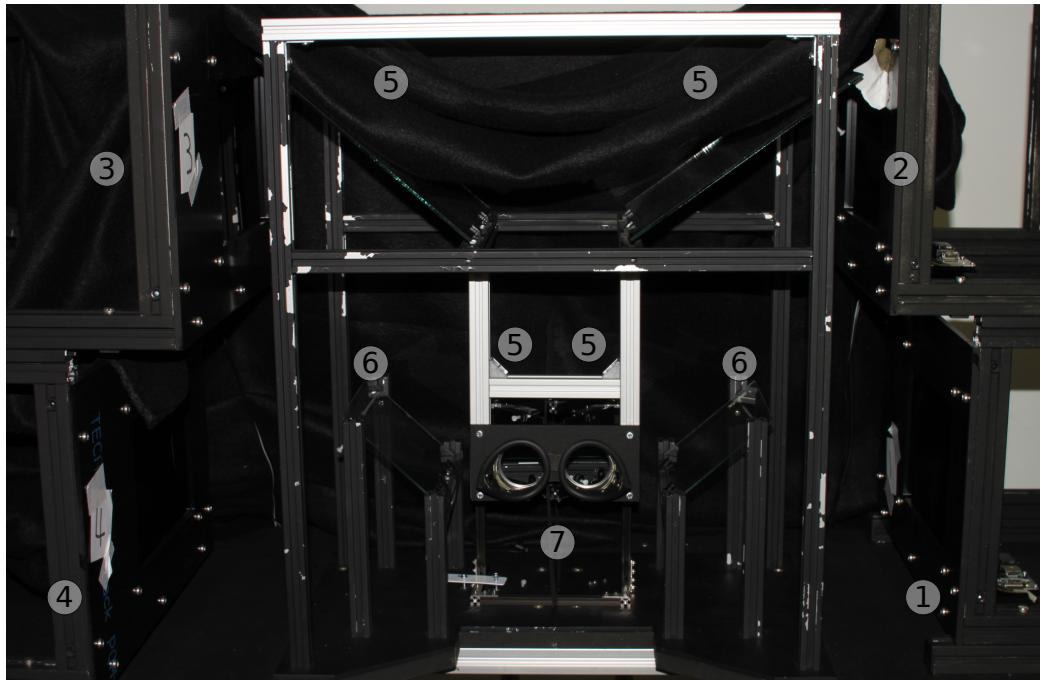
To achieve the requirements of the display we will be using four high resolution displays to get maximum quality in rendering per view and reduce visible problems from low pixel density. Full details of the panels in Table 4.1.

These will be configured with two screens per eye. One at the distance of the required near plane and one at the distance of the required far plane. For each side of the display the images are seen through a combinations of mirrors and a 50/50 beam-splitter which merges the two images into one and then another mirror directs the combined image to the users eye. See Figure 4.1 for a more detailed plan of the physical layout.

As the image is merged through the beam-splitter it is essentially additively combining the colour values of the two screens. To ensure a clear image of both views we need to isolate the beam-splitter, mirrors and all screens from external light to prevent obscuring or offsetting colour as it is merged towards the eye. To attain this, we will be shielding the constructed display with matte black boards to prevent any light entering the display from outside

and to reduce internal reflectance.

An extra consideration for combining the images and maintaining stereoscopic correspondences is that each of the images being displayed on each screen must be matching in colour range and intensity when they reach the eye. This will mean that the displays will have to be calibrated for any differences in the displays as well as error from light absorption from the mirrors or beam-splitter. Additionally, this will also help mitigate the error for any external light or internal reflection we are not able to remove.



- ① Screen 1 (Right near plane) ③ Screen 3 (Left far plane) ⑤ Mirror
- ② Screen 2 (Right far plane) ④ Screen 4 (Left near plane) ⑥ Beamsplitter
- ⑦ View goggles

Figure 4.2: The front view of the display with the mirrors, beam-splitters and screens labelled.

4.2.1 Display Panels

The display panels used in this display are replacement screens for the iPad 3. These have been chosen due to the high pixel density and good colour reproduction for the price point.

These displays are also a good size for our test setup. Any larger screen would have made the desk prohibitively large and impacted other features we would like to look into in the future, such as HDR support.

Resolution	2048 x 1536
Width	169.5 mm
Height	240.0 mm
Type	LED-backlit IPS LCD
Colours	16 million
Model Number	LP097QX1 6091L-1579A

Table 4.1: iPad Display Panel Specification

The panels are mounted into the display and fixed in place on the configurable near and far planes. They are powered and controlled through a 3rd party control board and each screen is connected to the PC using *mini display port* with the two left screens being connected to one GPU and the two right screens to the other.

4.2.2 Display Configuration

The display has ten configurable components to allow support for varying distance and angle from the screens to the eye.

The screens themselves are on fixed beams that allow the screens to slide to be nearer or further from the mirrors so the total distance to each screen can be easily calibrated.

There are two mirrors and a beam-splitter for each side of the display. All three components can be rotated and skewed to reach alignment.

Additionally, the mirrors that are placed directly in-front of the user can also be translated to account for offsets in eye position.

4.2.3 Machine Specification

Although this display will work on any machine supporting 4 *mini display ports* it is worth mentioning the setup we are using and why for easier replication.

CPU	Intel(R) Core(TM) i7-4790K CPU @ 4.00GHz
GPU	2 x NVidia 970
Memory	16GB
OS	Ubuntu 14.04 LTS

Table 4.2: Controlling Machine Specification.

CPU The CPU in our test machine is a little over specification for what is required as we will only be running simple scenes, however, we want to ensure that any analysis or logging applications we are using alongside the main multi-focal program will not interfere with the performance of the display. It also allows for more other research which may involve more intensive video processing that may not be suitable for the GPU.

GPU This machine has two GPU's to allow for a lot of monitors to be attached. In this case we have four display panels for the multi-focal display and one monitor attached to control the testing. In the future we would like to expand this to allow for up to another four outputs to possibly allow the iPad panels to be used as High Dynamic Range displays using additional projectors [11].

We have quite powerful GPU's due to the need to render to quite a high resolution which requires a lot of memory and to process potentially very complex scenes.

OS We have chosen to use Ubuntu on this machine to maximise the support for research projects in the academic community and maintain compatibility with other projects in the Cambridge University Computer Laboratory.

4.2.4 Known limitations

Limited Field of View. As our screens will only cover a limited field of view when compared to the full coverage of HMDs, so we are limited in our ability to give as full an immersive effect, rather for full scenes it will look like peering through a window into another room than the full VR experience people may be accustomed to. This could be improved in a less experimental setup through the use of lenses or different focal lengths.

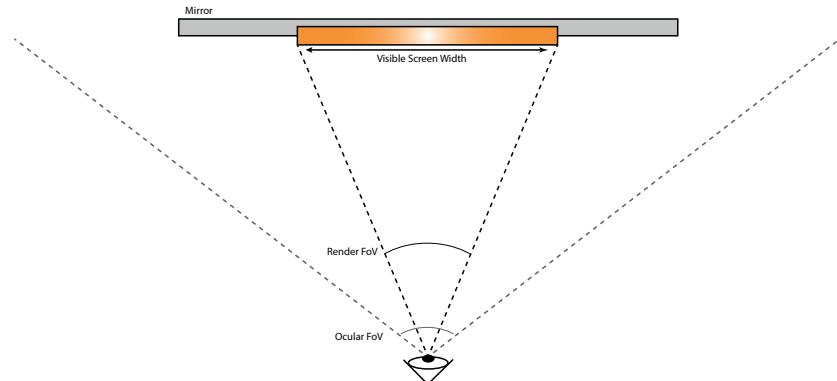


Figure 4.3: This image demonstrated the limited field of view when using this method to display multi-focal stereo.

iPad Displays While working with the displays we have found that the glossy coating on the screen increases light pollution within the display and from some angles within the display there is a clear reflection of another screen. This can be mitigated with more obstructing panels to prevent it interfering with any testing but it raises the potential improvement from using matte display panels in the future.

Relative Head Position As this display is not physically attached to the user the user is able to slightly move the head which will cause parallax from misalignment with the screens. This is especially true when using all four displays as small head motions will result in a large change of position of the near screen in the view direction. To alleviate this, extra consideration will have to be made in software design and user testing to ensure correct calibration throughout the use of the display.

Large display. The users view eye coverage is limited by the size of the screen at the furthest distance. This means that if we want to have a display which covers all of the user's view then the screen would have to be of the correct size to cover the full view at the given focal distance. Because we are using iPad panels in our display we are limited to quite a small view of the scene due to the limited size. With a more complex setup using custom lenses it would be possible to reduce this problem but it would be more expensive and less easily modified and is therefore out of the scope of this project.

Benefits of head mounted displays As this display is desk mounted instead of head mounted we lose the ability to do head tracking and rotation which greatly help the user by giving subtle relative motion depth cues. The fixed view point means we need to use motion of the scene rather than motion of the user which is less intuitive. If user movement was possible it would have been particularly useful for measuring how small motions may help determine depth.

Varying resolutions Due to the cameras being at physically different distances and no use of lenses to increase the size of the displayed screens we have a reversal of the ideal resolutions. In the best case we would want the objects which are appearing closest to the user to have the highest pixel density and the objects further away to have the lowest. In our display the image which is closest is scaled down to match the distant screen and as such is only using a small portion of the possible resolution.

Head motion As this is a desk mounted display the head position in the scene should be fixed. Motion of the camera in VR without actual head motion can cause motion sickness from mismatching motion cues from the ears when compared to the what the scene shows [22]. So in order to give the user cues of depth from relative motion we are relying on objects in the scene moving relative to the camera and avoiding any scenes which could feel like the user is moving. This may mean relying on static object to be points to ground the user perception. Correct depth in the scene is only maintained when looking at the centre of the view so to avoid the user from moving focus around the displayed image we will want objects to try and only be in motion in a single position unless we are measuring how distance tracking is changed when they are in motion.

Chapter 5

Software

5.1 Software Requirements

Configuration Four render outputs - One per screen Full standard rendering support - To be able to support objects to test depth + textures and what have you. Configurable positions for each screen - For alignment. Adjustable scene depth planes - to allow testing of mismatch.

In addition to the blending we also need to ensure that the field of view being rendered in the scene is the same as the real field of view of the human eye. Investigations have shown [21] how decreasing the field of view causes the user to misjudge distances. This could affect the perceived distance to the near plane and as such in our software the field of view will have to be correct to maintain that depth cue accurately.

Rendering As this implementation will require the use of multiple outputs and be displaying real-time 3D it will also need to support 3D mesh, texture and shader loading as well as lighting control. For this we will be using OpenGL as the graphics API and building support onto that.

Testing The software will need to be able to support real-time configuration of the screen position within each display panel to allow it to be setup for multiple users for testing. This will mean accounting for error from head position and slight motion during the test.

It will also be required to support and switch between different rendering modes without significant delay to allow for comparison of different techniques.

5.1.1 Projection Modes

When rendering stereo pairs there are a number of techniques available that each have unique features. The aim of the stereo pair is to simulate the viewing conditions of the user in the real world and rely on having the plane of projection at a fixed convergence distance and at that distance there should be zero vertical or horizontal parallax between the left and right eye.

Vertical parallax is generally avoided due to it causing discomfort and effecting stereo correspondence [5] so in our setup there should only be a very small amount that should differ per user as the eyes sit approximately on the same horizontal plane but this varies person to person. This error can break the illusion, cause diplopia vision and cause discomfort in the user. However, a certain amount of horizontal parallax is required for the stereo effect to work. This comes from positive (Figure 5.2) and negative parallax (Figure 5.1). Positive parallax is when the point is beyond the projection plane and negative is when the point is in front of the projection plane. Generally, points with positive parallax are more comfortable and we aim to avoid too much negative parallax as it can quickly become extreme or cause clipping from the screen when it moves very close to the eye position.

For early testing of the display we are going to support three main projections of the scene, 'Toe-In', 'Off-axis' and 'Oblique'.

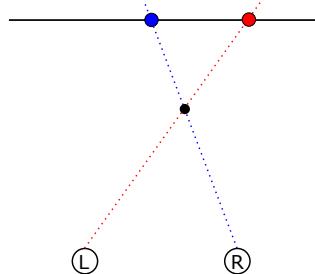


Figure 5.1: Example of negative parallax

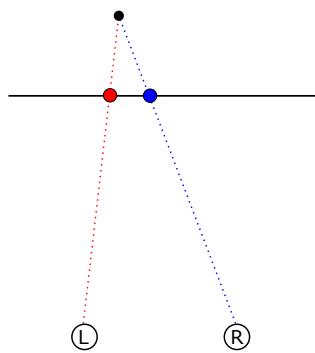


Figure 5.2: Example of positive parallax

Toe-in This projection mode points both cameras at a single focal point. This method produces reasonably correct stereoscopic vision on the projection plane but points in front and beyond that plane and particularly towards the left and right side of the image suffer from quite severe vertical parallax caused by the different rate of change of depth due to the non-parallel projection planes. This conflict is increased when the field of view of the viewing camera is decreased as the difference in depths between the left and right images become more prominent nearer to the centre of the image.

Off-Axis Off-Axis projections corrects the non-parallel projection planes of the 'Toe-In' method and forces the camera direction to be parallel. These changes remove all vertical parallax making for a more comfortable viewing experience. This method requires the creation of non-symmetric camera frustums which can look incorrect when viewed individually. An added benefit of this method which is used in 3D cinema experiences is to alter the

$$\begin{bmatrix} \frac{near}{right} & 0 & 0 & 0 \\ 0 & \frac{near}{top} & 0 & 0 \\ 0 & 0 & \frac{-(far + near)}{far - near} & \frac{-2far * near}{far - near} \\ 0 & 0 & -1 & 0 \end{bmatrix} \quad (5.1)$$

Figure 5.3: Symmetric simplified OpenGL matrix (OpenGL depth is in the range -1.0 to 1.0) [27]

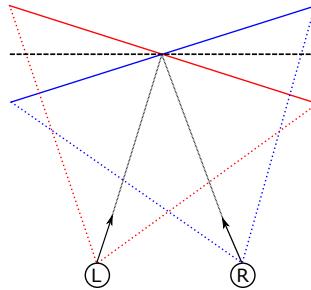


Figure 5.4: Toe-in projection layout

intraocular distance to exaggerate depth.

$$\begin{bmatrix} \frac{2near}{right - left} & 0 & \frac{right + left}{right - left} & 0 \\ 0 & \frac{2near}{top - bottom} & \frac{top + bottom}{top - bottom} & 0 \\ 0 & 0 & \frac{-(far + near)}{far - near} & \frac{-2far * near}{far - near} \\ 0 & 0 & -1 & 0 \end{bmatrix} \quad (5.2)$$

Figure 5.5: Standard frustum OpenGL matrix [27]

Oblique Our oblique projection is very similar the Off-Axis projection in that it also removes vertical parallax on the projection plane by sharing the same plane between the two eyes, but it has the added benefit of better modelling vergence for the central position on that plane?. It also keeps

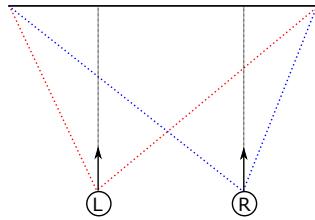


Figure 5.6: Off-Axis projection layout

the benefits of the Off-Axis projection while emphasising depth due to the converging eye direction. This leads to increased disparity between the left and right image as objects move towards and away from the projection plane. In our implementation the oblique projection is an accurate model of vergence at the projection plane to support the non-parallel optical axis shown in Figure 4.1.

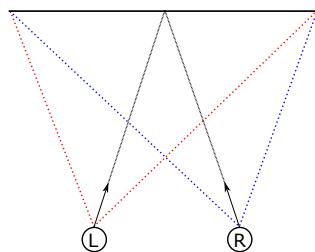


Figure 5.7: Oblique projection layout

Should I put the derivation of the Oblique matrix in here?

5.1.2 Depth Configurations

The scene is being modelled in real world units to easily match our physical configuration and allow for comparison in the future to real world scenes such as those taken from light field cameras.

When rendering the scene all the points closer than the near focal distance will only be displayed on the near screens and only the points beyond the far focal distance will be displayed on the far screens.

For the points which lie in the distance between the two planes we do not



Figure 5.8: This is an illustration of how the near and far planes have different images rendered on them for each pixel depending on depth. In this example the cube is having the nearest corner which is in front of the near plane rendered onto the near screen and then the parts of the cube which are beyond the far plane rendered onto the far screen. The points which exist between these two depths are blended between the two screens. When these two images are combined through the beam-splitter and presented to the user they appear once again as a whole image, however the appropriate parts of the image will now be at the correct focal depth.

have a physical screen to display them at the correct focal distance so we will try different blending methods of the two distances to try and determine if it is possible to convince the user that these points exist at the appropriate distance between planes.

As we are using beam-splitters which work additively we display black for points which are being displayed on the other screen and not within the blend depth range.

The primary methods we will try are:

Box: All points less than half way across the middle space will be considered on the near plane and all the ones more than half

way across will be considered fully on the far plane.

$$n = \frac{n_i - n_1}{n_2 - n_1} \quad (5.3)$$

$$col_{out} = f(n) = \begin{cases} col_{near} & \text{if } n \text{ is } < 0.5 \\ col_{far} & \text{if } n \text{ is } > 0.5 \end{cases}$$

We expect this to produce the effect of the scene feeling like it is made out of two pictures shown to the user. As there is a clear “focal seam” where the edges of each depth are visible and this is exacerbated by any calibration error.

Linear: As the points move across the middle space they will be linearly interpolated between the two views.

$$n = \frac{n_i - n_1}{n_2 - n_1} \quad (5.4)$$

$$col_{out} = (n * col_{near}) + ((1 - n) * col_{far})$$

Non-linear: As the points move across the middle space they will be non-linearly interpolated using a modified sigmoid curve between the near and far plane.

$$n = \frac{n_i - n_1}{n_2 - n_1} \quad (5.5)$$

$$blend = \frac{1}{1 + exp((-n * 2 + 1) * 6)}$$

$$col_{out} = (blend * col_{near}) + ((1 - blend) * col_{far})$$

Projective: In this mode the calculation of the depth interpolation value through the blending area is scaled inversely to match the depth divide in perspective projection transform.

$$n = \frac{(1/n_i) - (1/n_1)}{(1/n_2) - (1/n_1)} \quad (5.6)$$

$$col_{out} = (n * col_{near}) + ((1 - n) * col_{far})$$

Fixed: Fix all to either the near or far plane. This method mostly exists as a way to test and configure the views and will only be used in the testing as a comparison to none focally split images.

$$col_{out} = col_{near}$$

or

$$col_{out} = col_{far} \quad (5.7)$$

The aim of the blending is to produce a sum result of combined rays which would approximate the rays from the target distance and to make the shift from one viewing plane to another less noticeable.

Blend Comparison

It showed in our early testing that linear and non-linear blending gave inaccurate results when compared to the projective blend. The linear and non-linear blends caused a false sense of depth as objects remained in the near focal image too long and the depth appeared inconsistent as well as showing a visible seam.

The non-linear blend was particularly susceptible to calibration errors similar to that of the box blend as the change in the focal plane was too quick in the middle ranges causing very strong border artefacts.

It makes sense that these symptoms were relieved with the projective blend as it is mapping the change in focal depth to the same '1/Depth' projection that is used in the projection matrix. Combining this with the linear depth calculation we are maintaining correct focal depth consistency throughout

the blend.

5.1.3 Reflection Depth

In our setup we are interested in providing correct depth cues through light rays reaching the eye from the correct focal distance.

For a given diffuse object when light hits it the light is scattered with varying amounts of uniformity which results in the light hitting the eye with an angle appropriate for distance to the object.

This is different for reflective objects where a portion of the light is directly reflected without diffusion towards the eye. In this case the rays of light are arriving at an angle similar to that of the object at the distance to the reflecting object plus the distance from the reflected object to the source of the reflection.

As we are not modelling the scene to take into account multiple reflections or the depth of those reflections, we are not able to successfully map these reflections onto the depth that is being used to split the scene into different focal ranges.

A naive approach could be attempted but any mismatches could potentially break the illusion for the surface we are mapping. REWORD We will be able to fully test whether this method of distance splitting is effective using a purely matte test scene.

Show diagram of diffuse distance vs specular distance

5.1.4 Rendering costs

State Change

For rendering simple scenes with OpenGL a high proportion of the costs can be the switching of GPU render state [20] which can cause stalls if enough

data is not being submitted and the GPU is sat idle during the process.

When using two cameras the common approach is to render all the left view and then all of the right view. This means that the camera state is being changed many times per object per camera view.

A more optimal approach is for each set of objects being rendered switch the currently bound camera and render target (or multiple render targets and mask out the opposing view).

In this configuration it is only a maximum of two sets of camera and render target state changes per object instead of twice the textures, meshes and data per object.

$$\begin{aligned} m &= \text{Object count} & c &= \text{View count} \\ n &= \text{State changes per object} \\ \text{Per view} &= c * m * n \\ \text{Per object} &= m * n + m * c \end{aligned} \tag{5.8}$$

GPU Memory Usage

Memory consumption is an important consideration when using multiple screens, particularly at a high resolution and high bit rate.

The display being used with this software requires four screens outputting at eight bits per pixel so we start with a minimum of 96MB of GPU memory being dedicated to the screen buffer.

We would like to render in a linear XYZ colour space High Dynamic Range setup to allow for future tests with HDR displays. This means we are required to use a linear (non-srgb) format. When we come to present the rendered result on screen will be transforming that result with an XYZ to RGB colour space matrix and gamma correction, as such as want to ensure that each texel colour has a high enough bit-rate to ensure that the rendered result will

be transformed accurately into its corresponding RGB colour value without banding or artefacts in the resulting image. It is because of this we will be using one of the floating point formats and aim for a higher bit rate per pixel. As this is purely an experimental setup we have selected to use the 32 bit per pixel floating point format, `GL_RGBA32F`, to ensure maximum quality and reduce the chance of errors from unwanted quantisation before the transform to RGB colour space. This has big impact on the total memory being used for the render buffers as it is four times as large as the standard `RGB8` formats but it is worth the cost to ensure correct results in our tests and to ensure that any colour calibration can be correctly supported now, or in the future.

Texture	Resolution	Bits/Pixel	OpenGL Format	Size (MB)
Near Plane Render	2048 x 2048	32	<code>GL_RGBA32F</code>	128
Far Plane Render	2048 x 2048	32	<code>GL_RGBA32F</code>	128
Near Screen Buffer	2048 x 1536	8	<code>GL_RGBA8</code>	24
Far Screen Buffer	2048 x 1536	8	<code>GL_RGBA8</code>	24
TOTAL: Single GPU				304
TOTAL: Both GPUs				608

Table 5.1: Memory consumption of the display buffers used in this display. The large linear colour buffers used for rendering the scene are the most costly. We are using a significant portion of the GPU memory with just the rendering pipeline. If we were to test a more complex scene this could become prohibitive and accuracy of the colour calibration transform might need to be sacrificed.

5.2 Software Configuration

5.2.1 Rotational Consistency

A major part of this software is deciding where we need to partition the images being displayed. That partitioning needs to be correct for the real world distance to objects and should only take into account position of the user view and distance to the point in space.

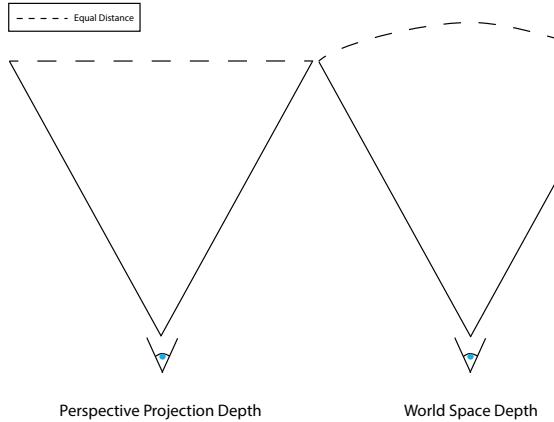


Figure 5.9: This is an illustration to show the different of position relative to the eye position of the same depth when using projective depth instead of world space depth.

The depth that is produced from a standard projection matrix is not the real world scene depth. The non-linear divide gives a non-linear depth from zero to one when what we need for calculating depth is the real distance from the ocular centre to the point in the scene. The perspective depth also gives all points at the far plane an equal distance from the camera, as shown in Figure 5.9 which causes changes in depth as the screen is rotated as points move from being on the edge of the far plane to the centre.

To calculate accurate depth, we will be using the objects positions multiplied by the world matrix to get its world coordinates and then subtract from them the world space position of the camera and calculate the length of the resulting ray.

This will give us a linear depth to each rendered point in the scene which will be consistent under any scene projection, translation or rotation.

[Show image of different depth](#)

5.2.2 X11 Window Controller

With modern Operating Systems a windowed applications maximum frame rate is tied to the refresh rate of the desktop. This would not be suitable for our application as we need to maximise frame rate to maintain realism and ensure persistence of vision.

Only full-screen applications are completely decoupled from the desktop screen refresh rate. Since we are using multiple discrete GPU's it is not possible to create a graphics context controlled by both, so we need to support multiple full screen context windows which is not possible in the standard "extended desktop".

In our setup we are using X11 as the windowing system which supports a mode to allow the user to run multiple independent screens rather than just extending one and the user can select which screens are controller by which GPU. Using this we are able to launch windows directly on the separate screen and run them full screen which allows us full control of the presenting of rendered images up to the maximum supported refresh rate of the displays and GPUs.

We want to remove as many barriers to presenting to the screen as possible to try and ensure that the screens are kept in sync and we do not fall out of alignment which could cause strange effects when objects are in motion,

5.2.3 OpenGL MRT's

When rendering to multiple screens we want to try and do it as optimally as possible to reduce wasted CPU or GPU time so that this display can support as complex a scene as possible.

The hardware setup has two GPUs powering four screens in a non-SLI configuration. As we are not able to share data between the two GPUs we are forced to render the scene at least twice. As this is also a requirement of rendering stereo views without reprojection this is not a limiting factor in

performance.

In order to take advantage of the data sharing we do have available we can make use of multiple render targets in our shaders where it is possible so that we only process the vertex data once per eye and then in pixel shader we perform our depth calculation and write the appropriate blend of the lighting value to separate render targets representing the near or far screen. This limits our lighting calculations to once per eye and by running through the same GPU and OpenGL context we can be more sure of matching VSync on both screens so we are less likely to suffer from screen mismatches from the screens not being synchronised.

This is more of a factor for matching the views between each eyes as we currently have no method to ensure that the left and right views are refreshing on the same schedule. To overcome this, we are using screens with a high refresh rate and low persistence and ensuring the test scenes are running above the required frame rate so that even if they are out of sync the difference between the two scenes should be very low.

If we are not able to share context across multiple screens, then the costlier method of using four individual contexts will have to be used. This would involve storing the data twice on each GPU and will prevent any fragment shader optimisation to write to multiple render targets, essentially doubling the pixel shading cost of the application.

5.2.4 Colour Calibration

As we are sharing the rendering of an image across multiple displays it is important that the parts of the image from each display are indistinguishable by colour and intensity.

In our display we are using four separate displays and a number of mirrors and beam-splitters. Each of these can interfere with the colour and intensity of light that is reaching the user and to maintain the merging of images for multi-focal rendering and correspondences for stereographic rendering this

has to be avoided.

The source of error in the displays come from how they are provided from the manufacturer. Some are produced with variance in light intensity and colour ranges.

The beam-splitters suffer error as light is absorbed or diffused in a direction other than the expected reflected direction. To try and reduce this we are using high quality first surface mirrors to prevent diffusion or absorption within the protective medium. They are more susceptible to damage but as in our design they are covered and can be calibrated without touch them they should be safe from damage or problems.

To correct for this error, we need to calibrate the screen to show the true colour being represented to the eye from each display.

Implementation

To begin to calibrate the screen we must use a high quality spectro-radiometer to measure the output from each screen for a range of colours and intensities. We do this with the display setup as if it is going to be used normally so that it is being configured for the real lighting conditions.

For each screen the spectro-radiometer is setup and all the other screens are set to display black, to account for the light they still emit when in a blank state which will be mixed in the beam-splitters. The screen then displays a wide range of colours at different intensities which are measured to produce a map of what the spectro-radiometer expected to see and what it actually received. From this map we can construct the calibration parameters needed to ensure that each display for each colour input will output a matching colour out.

The calibration from each screen produces 'black level', 'gamma' value and matrix to map from the CIE1931 XYZ colour space to RGB for each display [23].

$$col_{rgb} = (screen_{XYZtoRGB} * (col_{xyz} - screen_{black}))^{(1/screen_{gamma})} \quad (5.9)$$

Figure 5.10: Equation for colour correction.

We have chosen to use XYZ colour space as our scene rendering colour space as it is a good approximation of the human eye colour reception and has a larger supported colour gamut than RGB. It is also a good fit for our 32-bit per pixel linear render target textures which we are using to gain more accuracy during the transformation into RGB colour space than the standard 8 bit per pixel render targets would allow.

Once the scene is rendered in XYZ colour space it is then transformed with the equation showing in Figure 5.10 into the calibrated RGB colour space which is sent to the screens.

Calibration Results

Screen ID	Black Level Adjustment(CIE31)
Screen 1	[0.5074, 0.4216, 1.1063]
Screen 2	[0.5045, 0.4233, 1.0869]
Screen 3	[0.4420, 0.4321, 0.8115]
Screen 4	[0.4373, 0.4325, 0.8009]

Table 5.2: Black levels - Representing the light leaking through the LCD panels when attempting to display a completely black screen.

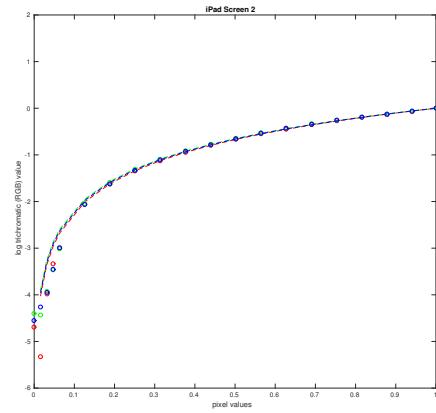
Screen ID	RGB Gamma value
Screen 1	[2.2368, 2.2064, 2.2247]
Screen 2	[2.2319, 2.1663, 2.1936]
Screen 3	[2.4438, 2.4475, 2.4438]
Screen 4	[2.2406, 2.1956, 2.2554]

Table 5.3: Gamma correction values for each display panel.

Explain different screen colour configurations. Sort latex to not throw the figures everywhere...



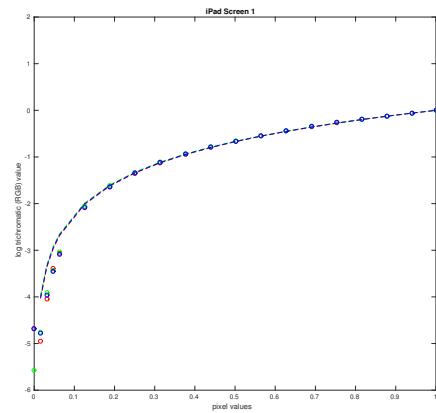
(a) Far Plane Left Display Panel.



(b) Far Plane Right Display Panel.



(c) Near Plane Left Display Panel.



(d) Near Plane Right Display Panel.

Figure 5.11

$$\begin{array}{ll}
 \left[\begin{array}{ccc} 0.0324 & -0.0095 & 0.0006 \\ -0.0147 & 0.0180 & -0.0017 \\ -0.0051 & 0.0006 & 0.0081 \end{array} \right] & \left[\begin{array}{ccc} 0.0345 & -0.0078 & 0.0003 \\ -0.0159 & 0.0149 & -0.0011 \\ -0.0058 & 0.0007 & 0.0062 \end{array} \right] \\
 \text{(a) Screen 3} & \text{(b) Screen 2} \\
 \left[\begin{array}{ccc} 0.0115 & -0.0038 & 0.0004 \\ -0.0050 & 0.0070 & -0.0009 \\ -0.0018 & 0.0002 & 0.0034 \end{array} \right] & \left[\begin{array}{ccc} 0.0118 & -0.0031 & 0.0001 \\ -0.0055 & 0.0059 & -0.0005 \\ -0.0020 & 0.0002 & 0.0028 \end{array} \right] \\
 \text{(c) Screen 4} & \text{(d) Screen 1} \\
 \end{array} \tag{5.10}$$

Figure 5.12: CIE XYZ to RGB colour matrices for each display panel.

5.2.5 Full pipeline

Once the screen is geometrically calibrated and the environment has been setup, the process of rendering scenes for the multi-focal view is relatively straight forward.

The cameras should be setup to match the projection that you would like to use and a blend mode should be chosen and implemented in the shaders.

The geometry is then loaded into each OpenGL context, and the cameras and projection matrices for the correct views are applied to each from the appropriate camera and projection.

When it comes time to render the scene for each view we set the fragment shaders to render to two linear 32-bit render targets (Frame buffer objects) each. One represents the near plane and the other the far plane. We then apply the pixel shader controls lighting and the blend functions as described in Section 5.1.2.

In the fragment shader the blending is performed on its real world depth and the result is then applied appropriately to the near and far render targets. For example, if a triangle is submitted which sits in front of the near plane and we have selected “projective” blending then 100% of the value of each

pixel in front of near plane will be applied to the near plane render target and black will be written to the far plane. This effectively splits the scene between the two planes as shown in Figure 5.13.

After all of the rendering is complete the resulting render targets are then written to a plane on each window for the correct screen.

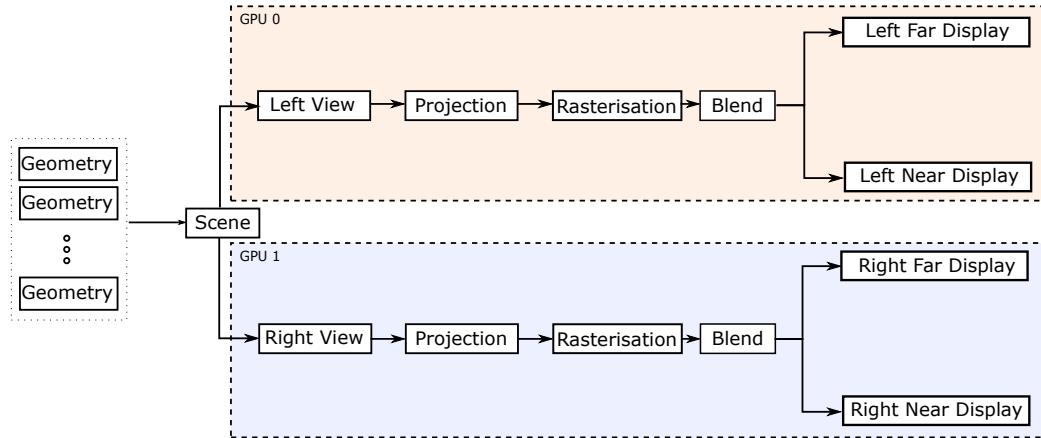


Figure 5.13: A high level overview of the steps to separate work between GPU's and display panels.

Chapter 6

Methodology and Testing

In experimenting with the device we are aiming to find out to what degree, if any, the use of multi-focal viewing planes increases the users perception of depth in a scene when compared to stereo and standard 2D viewing conditions. Our hypothesis is that by alleviating the vergence-accommodation conflict we should be introducing a more comfortable and realistic depth viewing experience which may allow the user to more accurately judge depth than when the focal cue is missing. However, we are open to the idea that the change in focal depths as the user looks around a scene could introduce discomfort from other means, which are less researched as it is not what users are typically accustomed to when using stereoscopic 3D devices.

The display and software design has given us lots of options for testing through varying projection, blending and real focal distances. However, to keep the experiment simple and within scope we have performed some early testing to narrow the total number of experiments. As such we will be investigating using the “oblique” projection method (Section 5.1.1) as it provided correct near and far plane correspondence and with projective blending gave us the least error from misalignment in the scenes. Misalignment is a large concern for us during experimentation. We have seen that misalignment can completely ruin the effect we are trying to achieve and can lead to a lot of discomfort for the user.

In order to address our hypothesis, we will be testing the users perception of depth by showing two objects at different depths to the user and asking them to select which object appears closer. This will be performed with the user viewing objects with zero disparity, stereoscopically and stereoscopically with multiple depth planes. This will allow us to compare how accurately the user was able to determine the relative depth when given different depth cues and therefore determine if the additional focal depth cue allowed for a higher perception of depth.

6.1 Method

This is an experiment that will be measuring the perception of depth so it is necessary for this to be tested on a range of volunteers rather than just ourselves to ensure that any conclusions are conclusions for the general case of the larger population. The participants selected for this experiment will not be selected for any visual strengths or weaknesses, such as stereoscopic perception, as we want the participants to represent the general population.

We have setup the display to have the distance between the far and the near plane approximately 0.6 dioptres (see Section 2.2) apart, as this is seen to be the optimal distance for retinal image quality [15] and is the a large enough distance to for optimal stimulation of the accommodation response [16] so the transition between the two objects at the most extreme offsets should not be jarring. For this experiment the near plane will be at 0.54m and the far plane set to 0.81m.

6.1.1 Depth Comparison Setup

The depth comparison scene is a small scene in which the user is asked to look at two objects (see Figure6.4) in the display and then report which of the two objects appears to be closer. This is then repeated for different distances between the two objects (see Table 6.3). The aim of this scene is

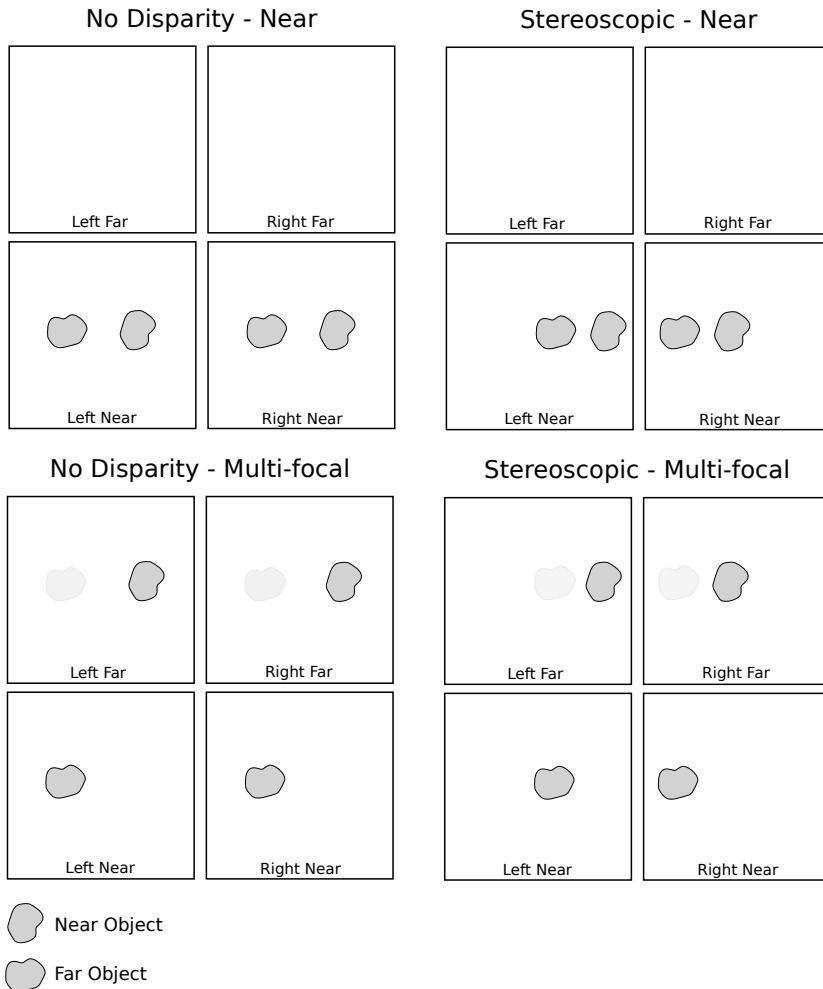
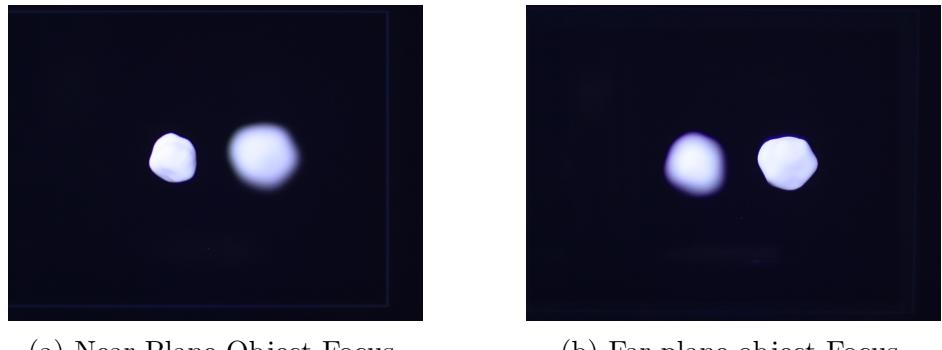


Figure 6.1: Example of a setup explain...

Near Focal Distance	54cm — 1.85 Dioptries
Far Focal Distance	81cm — 1.23 Dioptries
Near-Far Range	27cm — 0.62 Dioptries
Interocular Distance	6.5cm

Table 6.1: This is the distance configurations the display has been setup to use in this experiment. It approximately maintains the optimal 0.6 dioptries between focal planes so that the difference in focal depth should be very perceptible to the user.

to accurately measure the effects of the different depth cues to be able to determine if the addition of focal depth cues from accommodation improves



(a) Near Plane Object Focus.

(b) Far plane object Focus.

Figure 6.2: These photographs are from a run of the experiment showing a large offset between the two objects and displaying the images in the multi-focal render mode. As you can see by changing the focal length of the camera from 0.54m to 0.81m we are able to selectively focus on both objects and there is a large visible difference when that changes. The images were taken with an aperture of `get app from file`.



(a) Correctly calibrated.

(b) Incorrect calibration.

Figure 6.3: This image shows the error from incorrect geometric alignment. It shows the far plane out of alignment with the near plane and the ‘shadowing’ artefact becomes apparent. When this happens it is very clear to a user that the image is comprised of two separate planes. We aim to reduce the occurrence of this in our experiment using a calibration screen and frequent updates.

user perception of depth. To do this we need to be able to isolate the user from all other cues except the ones we are investigating, namely the presence binocular disparity, vergence, accommodation and the absence of all cues.

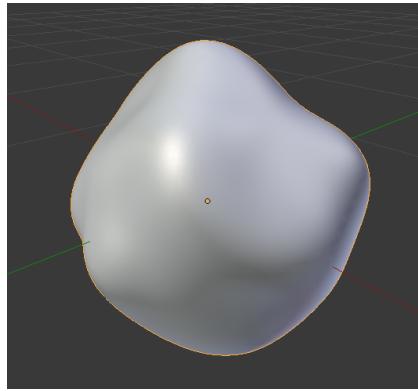


Figure 6.4: This is an example of the deformed sphere models that are being used in the experiment. They are scaled within the scene based on depth from the camera so they maintain the same size in screen space and are then scaled by 5% up or down in the scene to help reduce any false cues from perspective.

In a regular scene the user is given many hints at the depths of objects, see Section 2.3. In our scene we have taken many measures to isolate the user from them so we can accurately measure the ones we are interested in.

- **Perspective:** To eliminate perspective cues we enlarged more distant objects to revert the effect of perspective projection. The objects being displayed also have no geometric parallel lines for comparison of convergence. Additionally we have introduced a random scale of up to 5% of the objects size
- **Known Size:** We are using randomly extruded spheres so they are not a recognisable object.
- **Detail:** The objects have no texture detail. The only cues from detail come from a slight pattern of shading from the shape of the object but as the two objects have different shape this is not comparable as a cue.
- **Occlusion:** The objects sit either side of the optical axis and do not

occlude each other.

- **Lighting:** We have used fixed directional lighting from points at infinity so the lighting is invariant to the position of objects in the scene. This prevents the distance being judged from the rate of change of lighting on the surface.
- **Relative motion:** There is no motion in the scene to allow the user to judge depth from rate of change of size and position.

We have also had to consider hints at position that can come from the display setup:

- **Colour:** As we are using multiple mirrors and beam-splitters in the display there is a small amount of chromatic aberration which was quite obvious when using separate colours for each object in the scene. This gave hints to the number of mirrors being used to display that object which in turn told the user whether it was on the near or far plane when testing the multi-focal part of the experiment. As a result of this we had to switch to using a single colour for the objects in the scene.
- **Head Position:** If the user is misaligned when they change scene they will be able to notice outlines of any objects partially drawn on the near plane overlaid with the percentage of the object on the back plane, Figure 6.3. This will show the user which object is physically closer. To avoid this have added a calibration step between each display of the scene at different depths and advised the participants to try and avoid head motion while viewing the scene.

With these changes we are left with two randomly deformed spheres which will allow us to isolate and measure the cues we are interested in by varying which render mode (Figure 6.2) we use.

From our early pilot tests we found that in stereo and multi-focal viewing modes we were able to very accurately determine the relative depths of objects when the distance between the objects were large. To confirm this and determine at what distance this breaks down we have selected to keep one

RENDER MODES	Near Plane Only	Both Planes
6.5cm Disparity	Stereoscopic	Stereoscopic + Multi-focal
No Disparity	No depth cues	Multi-focal

Table 6.2: This table shows us the four possible combinations of the render modes we will be testing and which cues they allow. We are particularly interested in the combination of ‘Near Plane’ and ‘No Disparity’ as this combination will show us how well we have isolated other depth cues. If that combination is still able to be accurately judged for its depth then there is other depth cues available or we have failed to block the ones we wanted.

object on the far plane and then move the other object away from the far plane at fixed offsets up to the near plane with more samples being taken near the far plane, see Figure 6.3, to help determine the largest range that works within the multi-focal setup and determine where it breaks down.

In our chosen offset distances, we have included a zero offset. At the zero offset the two objects are at the same distance from the camera. In this situation the computer chooses a random object as the correct answer. This has been included in the test as a check for our data collection. The correct answers on this offset should trend towards $50\% \pm$ error from sample size, see Figure 6.6. If this is significantly different in our data, it will indicate a problem.

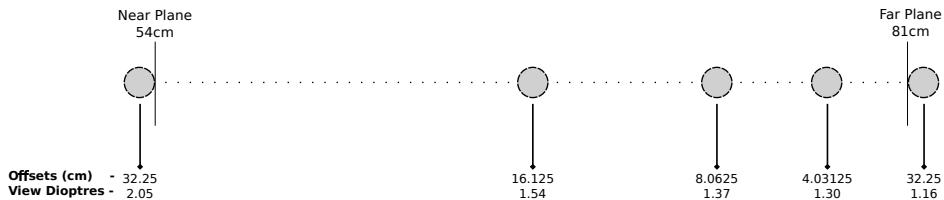


Figure 6.5: This diagram shows different offset locations and the relative distances between them. This diagram shows the right object at different locations but in the experiment either blob can be in the offset position but one is always on the far plane.

To be able to get accurate and unbiased results we have made sure the sphere that is closer to the observer is randomly selected.

In experiments such as these the participant will become accustomed to what

Index	Offset (cm)	Depth (cm)
0	0	86.25
1	4.03125	76.97
2	8.0625	72.94
3	16.125	64.88
4	32.25	48.75

Table 6.3: This table shows the offset positions in distance from the camera. The depth is central position of the object. On the far plane at zero offset the value is not 81cm as we have adjusted for the size of the object and random scale to ensure that is entirely behind the far plane in its starting position.

they are seeing and are expected to improve as it goes on. Because of this we will be randomising the order of offsets which the user is shown so that either the small or large offsets, or certain view modes are not unevenly improved. This is random for each user performing the experiment so that we are accounting for any pattern that may arise in a single randomisation.

For the experiment we are asking the participants to do 20 samples per render mode and offset. Ideally we would have wanted to perform up to 40 comparisons per offset per rendering mode but time is a limiting factor for our participants. With 20 samples we are able to reduce the margin of error from random choice (Figure 6.6) to be low enough to extract the information we need but for further study on any findings we would want to want to be more thorough.

From our pilot studies with this test we found 20 samples for all render modes and offsets took around 20 minutes. As we are accustomed to using the display we are assuming participants will take between 20-30 minutes including calibration steps.

Calibration can take a short amount of time. The display is setup in its default calibration assuming the mean interocular distance with a convergence point on the near plane. If a users intraocular distance varies from this then we will need to spend a few minutes using the software's calibration screens (Figure 6.7) to adjust the positions of the displayed visual planes. The software supports scaling and translation of the different planes to ac-

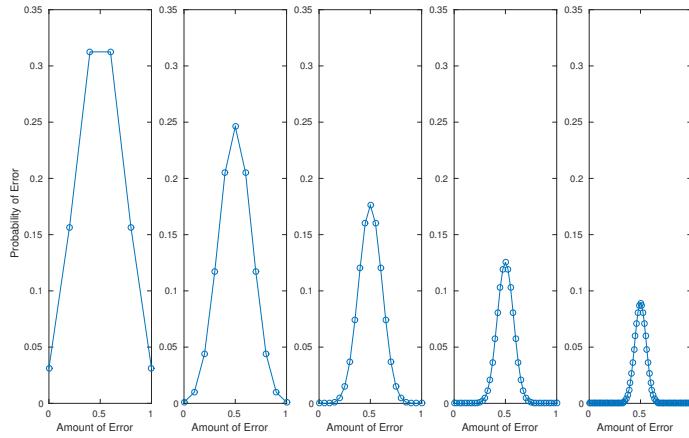


Figure 6.6: These graphs show the binomial graph of expected error.

commodate for participants who's eyes which may differ from the average in vertical alignment as well as horizontal intraocular distance. This also allows us to ensure that the display is calibrated for a head position which is comfortable for the user.

Experiment Procedure

The user will first be given a guide explaining what the experiment is and what is required. See Appendix.9.1 for the briefing form. Then the participant will be shown the display with the calibration screen and asked to get into a comfortable position. The screens are then aligned so that the user can comfortably see the near and far plane and converge the images into a correct stereo pair.

The participant will then be shown an example of the scene and shown the controls for how to select between the two blobs.

Once the participant is comfortable at the display with the controls the experiment proper can start.

The participant will be shown the scene, make a decision on which they believe is closer and then they will be shown the calibration screen to ensure

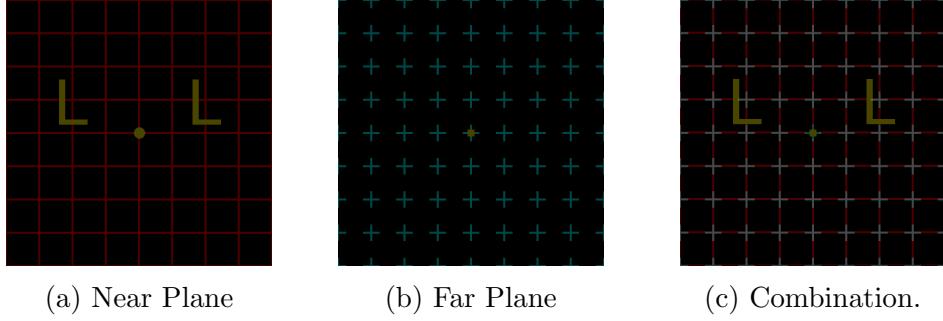


Figure 6.7: Software Geometric Calibration: The near plane calibration screen shows a central point and two ‘L’ characters. The point helps in centering the image at the correct position and the ‘L’ is a simple way to confirm the orientation of the screens are correct. The far plane has a series of cross marks to align with the near plane as well as central point to align.

the calibration did not change during the scene. This is repeated twenty times for each combination of render mode (Table. 6.2) and each offset distance (Table.6.3) in a random order.

During the experiment the participant is advised to try and avoid head motion during each scene.

After the participant has completed all the required decisions an image will inform show them that the test is over.

Data Collection

From our experiment we will be storing an ID to represent each participant and a list of whether the participant was correct or incorrect for each sample of each offset and render-mode configuration.

We will then analyse each participants results individually to determine any obvious patterns in multi-focal depth perception for that user and compare it to other users. We will then look at any apparent groupings of types of results and the combination of all results.

We will look at each participants results individually first as we expect there may be some quite interesting results that may be unique to each participant

or groups of participants. In our early testing we found some quite large discrepancies in the perception of different depth cues which we hope to elucidate. We haven't filtered any of our participants for ability to see stereo or judge depth from focal cues so this is something we predict will occur.

Once we have analysed the data individually we are also going to look for any trends in the whole data, with consideration to anything we may find in the individual analysis.

Chapter 7

Results and Discussion

The experiment was ran with **x** participants. With most experiments taking between 20 and 25 minutes, as we expected. The results have fallen roughly in-line with what expected from our hypothesis with a few notable exceptions. They also have noise from error which is consistent in most entries with what we predicted. There are a few discrepancies which fell outside of this expected error which are explained in Section 7.1.

7.0.1 Problems during the Experiment

There were initially a few issues when we ran the test with the setup that we had not considered in our initial setup.

The first minor problem was that we had not taken into consideration the height of the user. The desk was too tall for some of our participants and it is not height configurable. This meant that we had to repeat an experiment after it was noticed and the participant mentioned it was difficult to keep the correct head position due to stretching to reach correctly use the mounted goggles.

The next minor issue was caused because we had not taken into consideration that people have varying sensitivity to bright images. The combination of the

brightness of combined images, particularly the calibration and end screens, which did not have their brightness averaged to be the same as one display, caused some participants discomfort and had to have the brightness reduced.

For some participants the test was a long period of time to maintain the same head position. That led to more breaks and slight head motion during the test than was expected and could have impacted the results of the test particularly the later comparisons which could impact the amount of noise in the data.

7.0.2 Loss of data

There was a fault in the original run caused by a lack of rotation in the displayed objects which caused the zero offset scenes to be in an arrangement which gave the illusion of one of the objects to appear closer to some users. Coupled with a bug in the seed generation for random numbers for selecting which object is closer when there is no offset caused a problem in the data resulting in very extreme correct or incorrect selection at this offset.

As we had not used a random rotation this could have caused misleading selection for all objects in the ‘Near plane zero disparity’ render mode.

As a result, we had a lot of noise in our data and it was difficult to reach any convincing conclusions. This has meant that the experiment has had to be completely ran again with new participants. Due to our limited time to perform this we have ended up with a smaller population sample than is ideal.

7.0.3 Individual Results

This section contains the results of each individual who took part in the experiment.

For each participant we have graphed the four different render mode com-

binations (Figure 6.2) along with the results of what ratio of answers were correct for each offset position. For each result we have included the standard error of the mean as an indication of expected error and the participants names have been anatomised to letters.

7.0.4 Combined Results

As well as looking at the individual performance of each participant we have also found it useful to group the data together so that we can identify any overall trends.

There was a very noticeable grouping in our individual results of those who were not able to discern the depth of objects using only stereoscopic depth cues. As such for further analysis we have separated those into two groups and plotted the results separately (Figures 7.5a and 7.5b).

7.0.5 Personal Results

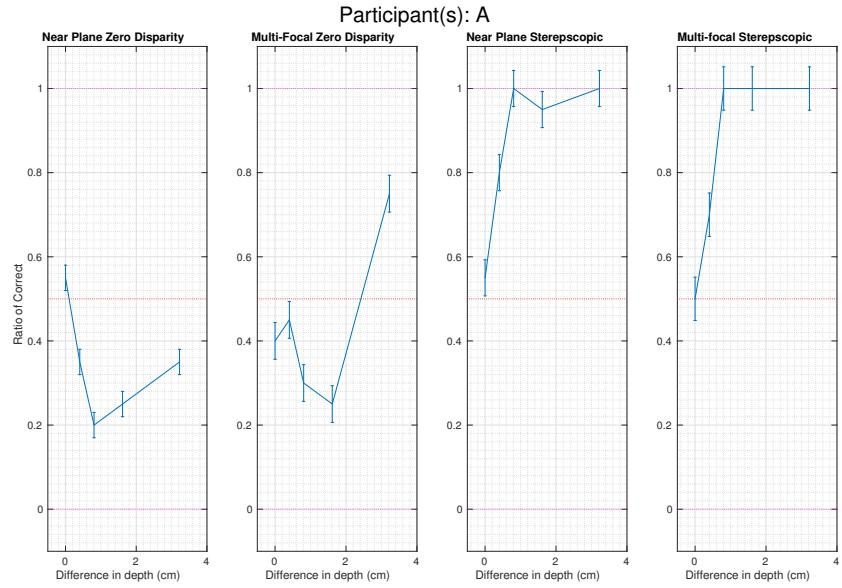
Due to a problem encountered during the initial data collection resulting in a loss of a lot of participant data we have included the data from the author of the paper in Figure 7.6 to give as broad a picture of the results as possible.

This data is for two sequential runs of the experiment by the author.

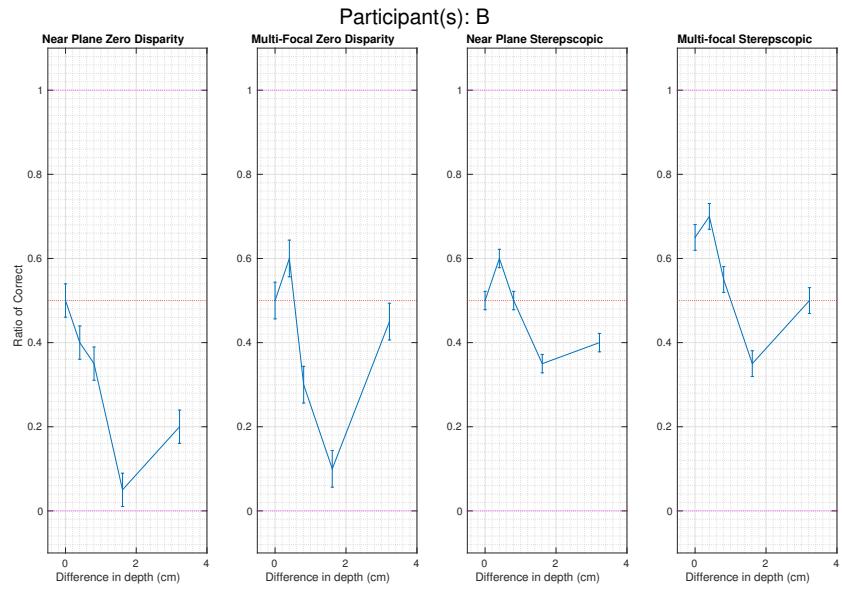
7.1 Discussion

7.1.1 General Overview

From an initial look at the overall results for all users (Figure 7.4 we can see that depth was fairly accurately judged when the participant had any stereoscopic cues available but the performance did not seem very different when multi-focal cues were added.

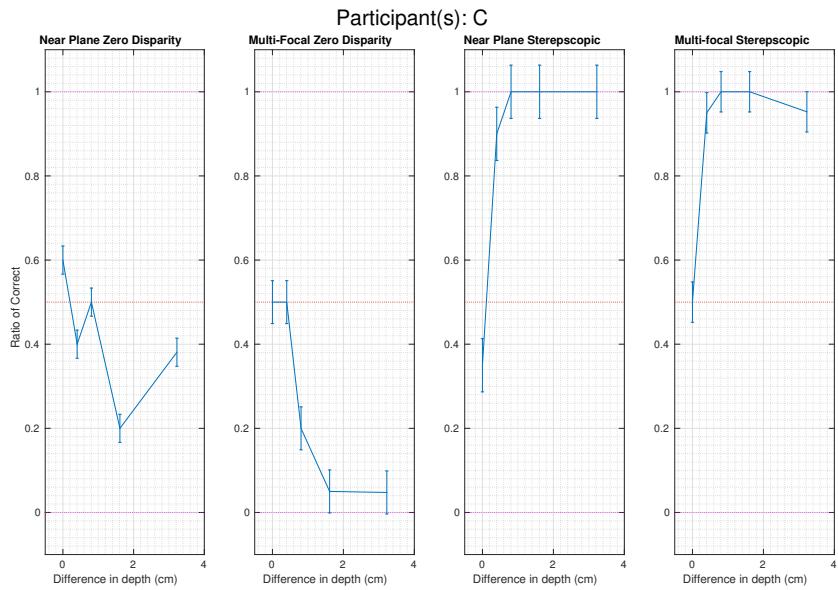


(a)

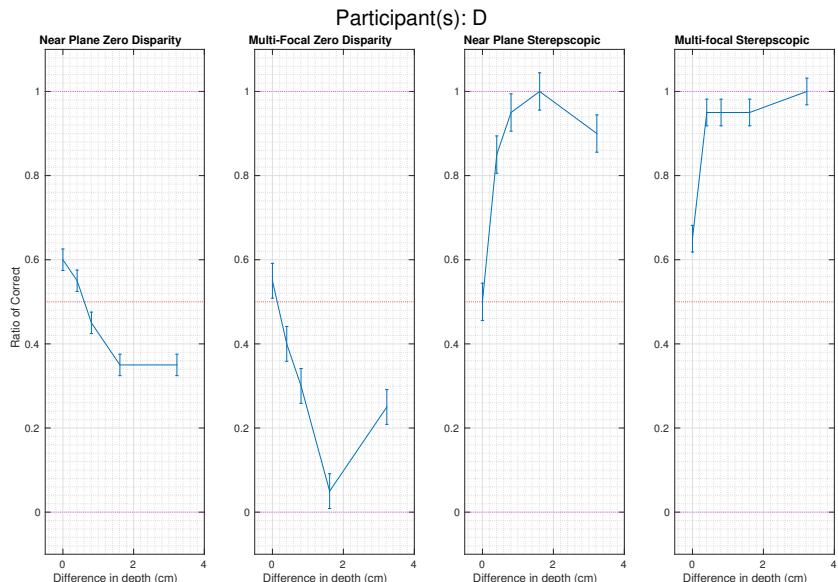


(b)

Figure 7.1: (Part 1 of 3) Individual results from participants in the depth comparison experiment. The graphs show the ratio of correct answers at each offset. The error range on each point is the standard error of the mean. The point of subjective inequality is marked in red at $y = 0.5$.

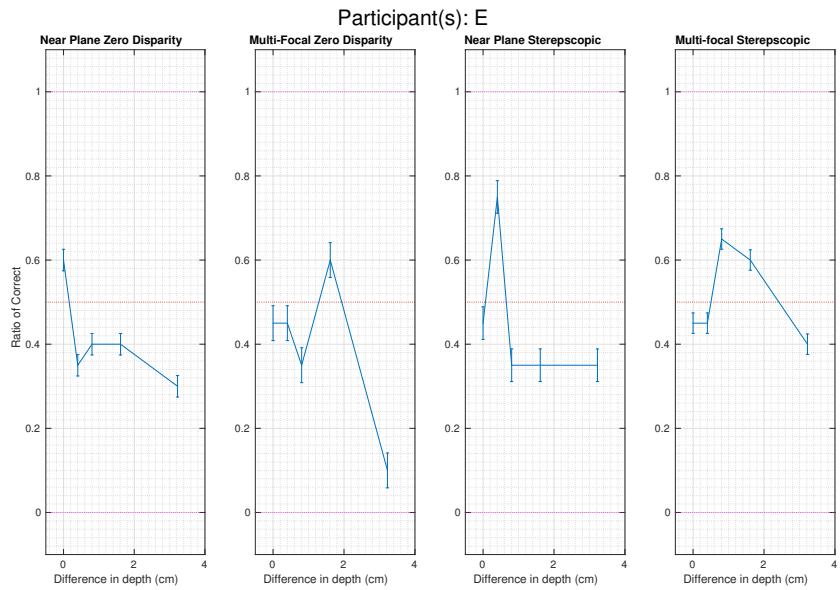


(a)

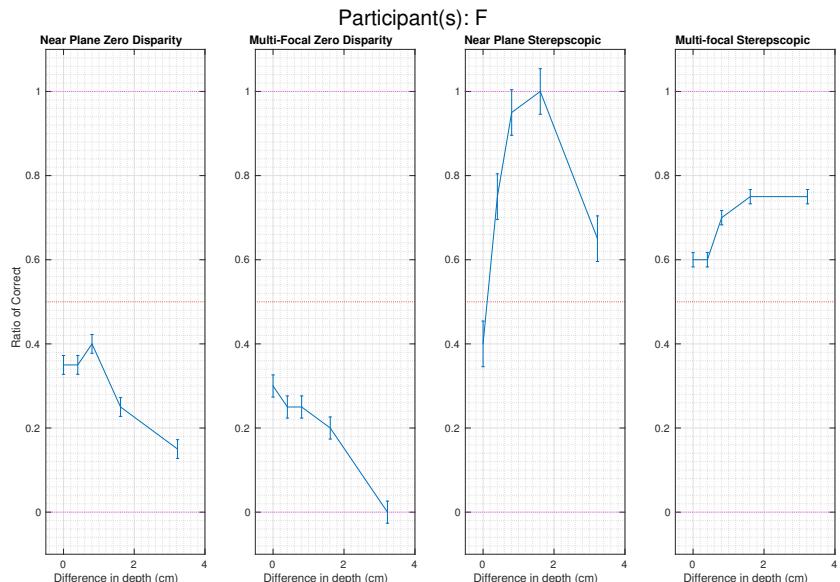


(b)

Figure 7.2: (Part 2 of 3) Individual results from participants in the depth comparison experiment. The graphs show the ratio of correct answers at each offset. The error range on each point is the standard error of the mean.



(a)



(b)

Figure 7.3: (Part 3 of 3) Individual results from participants in the depth comparison experiment. The graphs show the ratio of correct answers at each offset. The error range on each point is the standard error of the mean.

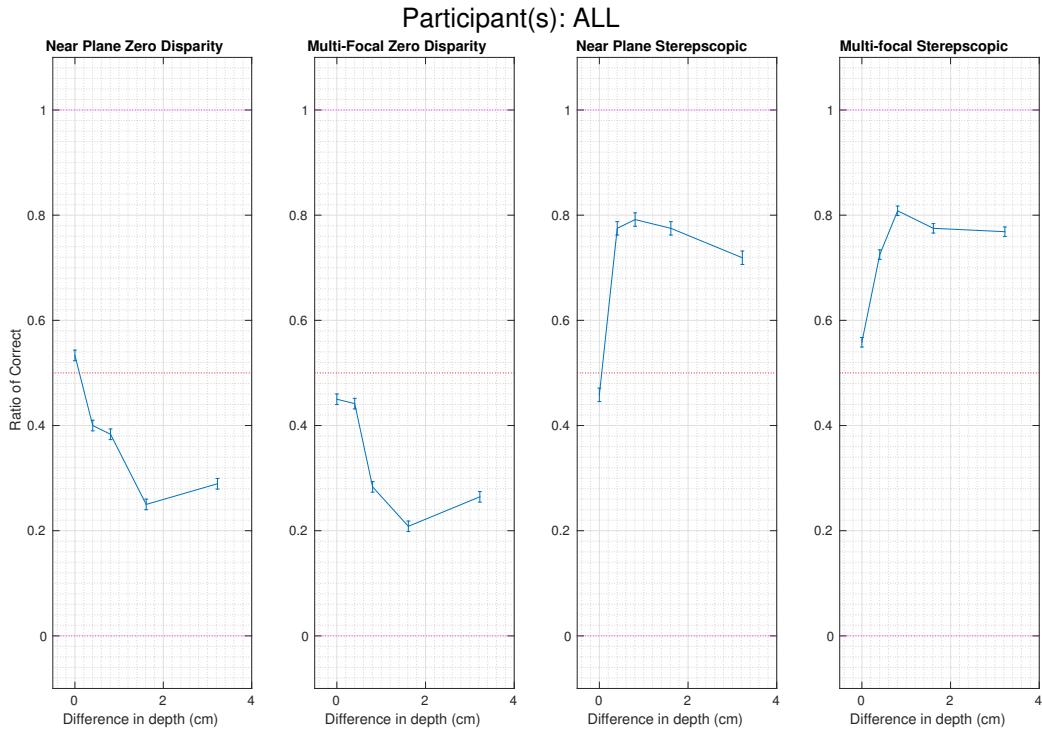
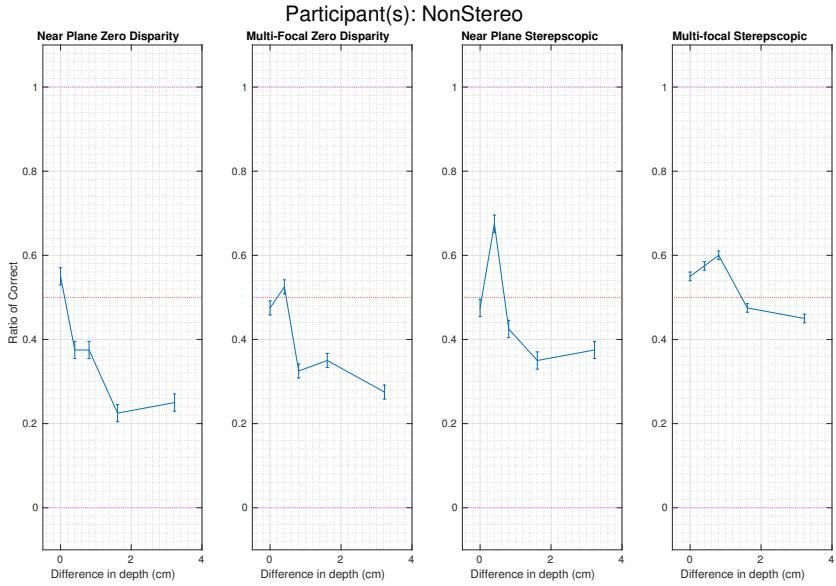


Figure 7.4: This graphs shows the combined results of all participants for all rendering modes and offsets.

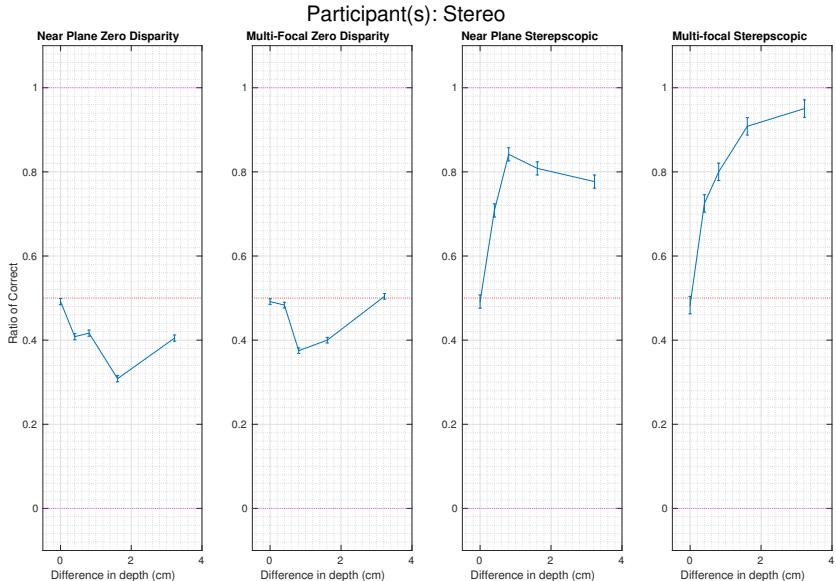
The data is quite hard to understand for each individual due to appearing to be quite noisy pm some of the plots. We have performed a short investigation into this to ensure the quality of the collected data in Section 7.1.2.

We see that there may be a small increase for participants who were able to correctly judge depth from stereographic cues in Figure 7.5b. This is further discussed in Section 7.1.4.

For the multi-focal cues alone in the results showing averages across the users there appears to be no strong suggestion that the cues from accommodation improved the sense of depth. The data oddly seems to suggest that the presence of only accommodation depth cues caused the participants to select the furthest objects rather than the nearest. We discuss this result and what may be causing it in Section 7.1.5.



(a) Participants unable to see stereo depth. (Participants B and E)



(b) Participants able to see stereo depth. (Participants A,C,D,F)

Figure 7.5: These graphs show the separate results of participants who were or were not able to perceive depth from only stereographic cues.

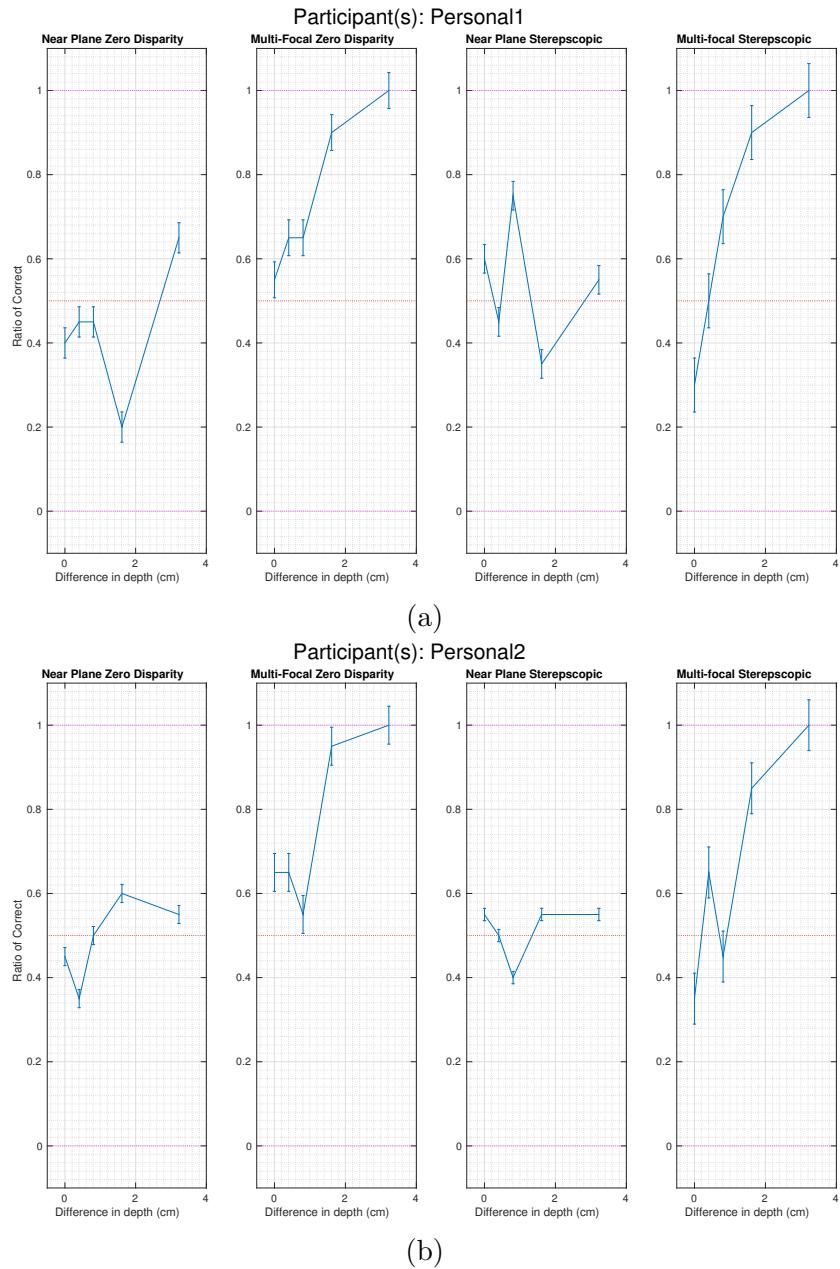
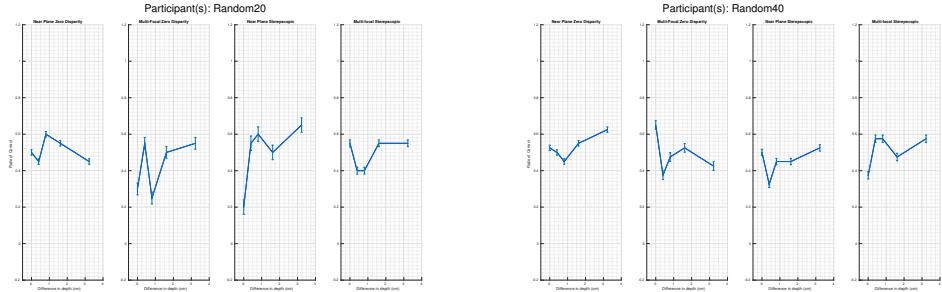


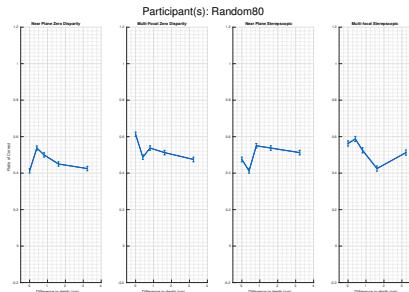
Figure 7.6: Personal runs of the experiment

7.1.2 Error Margins

The results, which are themselves a rerun of the original pass of the experiment, still exhibited some strong error in the ‘Near Plane Zero Disparity’



(a) 20 samples (400 data points overall) (b) 40 samples (800 data points overall)



(c) 80 samples (800 data points overall)

Figure 7.7: Random choice for different samples sizes per offset and render-mode. The random noise is consistent with what expect for this distribution (Figure 6.6).

scene for some participants. It is not nearly as large and unpredictable an error as what caused the experiment to be restarted, but it is significant and points to a problem in our experiment.

Firstly we wanted to check that the software controlling the experiment was correct. To do this we ran the experiment with varying numbers of samples per offset and render mode and allowed the software to select choices randomly to see if the results would converge on the point of subjective equality with 50% of the answers being correct. This gave us the results shown in Figure 7.7, which do in fact converge to 50% correct.

To further validate the software we ran the same process again but this time only allowing it to select the left object, and then again only selecting the right object. This is to check that there was a proper balance of each answer in each set of comparisons we showed the participants and to check that the 50% convergence we saw when using random selection was not the result of

a problem from our pseudo random number generator. This test also gave us the same convergence to 50%

This combination of tests gave us confidence in the selection process of which object is closer and the distribution of results.

The next part we checked was whether the selection of the right and left objects was being consistently and correctly processed by the software. In this test we altered the generation of the offsets and random selection of which object was closer to allow us to specify these explicitly. We then ran the experiment and selected the correct answers. We then confirmed that the answers we entered were all correctly registered as correct. We then repeated this experiment for incorrect answers. This validated that our input control and data storage were all working correctly. It is an area that wasn't expected to have errors due to the good scores from the binocular disparity scenes, but was worth sanity checking.

This leaves only possible errors in the rendering of the scene that could be giving clues to the user allowing them to select an object which appears further away consistently.

For the rendering, the only differences in the scene with no depth cues is the blend mode that is being used to show the scene on the screens. That scene uses the near blend mode which displays objects only on the two near planes. This can be visually validated by running the experiment and checking which screens the objects are being rendered on. This appears to be correct. We have also looked at the source code which sets the blend mode and writes the data to the screen to check in case there was any differences between what is being displayed on the left and right display panels. The hypothesis being that if there was a bug setting the left or right screen pixels correctly it may bias the scene somehow. This was not the case however as the blend modes were all set and behaved correctly.

The only culprits left that could be giving us such differences is purely random noise or there were some depth cues in the scene that we were not able to fully eliminate.

I am fairly confident in thinking that this is not simply random noise as it has a persistent pattern between most participants in which there is a significant choice of the wrong object which then becomes the roughly 50% correctness which we expect when the distance between the objects becomes zero.

That only leaves the content of the scene as the difference between each to the hints. In Section 6.1.1 we outlined the depth cues we were looking to remove from the scene. From that list the most likely to suspect the error we are seeing is from a perspective convergence to the vanishing point. We did not consider this motion, we only considered the perspective scaling and geometry of the objects being transformed. If we show two objects to a camera as the object moves closer it also becomes less central in screen space if it is not exactly on the optical viewing axis. Each of our objects are only slightly offset from this axis so we did not consider this motion to be significant but given that 200 images with no disparity were shown to the user, many of which may have appeared without an image with disparity in between, it is possible the user may have subconsciously noticed this part of the perspective depth cue. This does not explain why the error gave consistently incorrect results but it is a depth cue we can identify in our experiment that would effect these scenes only and could give the curves we have seen. Ideally we would like to have access to more participants to see if this is effecting everyone as this is not a depth cue which we picked up on in our pilot testing (Figure 7.6) which also show patterns of stereo-blindness but do not have as consistent of an erroneous trend in the scene with no depth cues.

7.1.3 No depth response

Some couldnt get anything beyond a random response participants B,E.

7.1.4 Stereoscopic Cues

For the majority of participants in this trial the presence of depth cues from binocular disparity was a strong hint at the depth of objects and those who could pick up on it were able to answer correctly fairly consistently upto a short offset between the objects. This is what we expected from the binocular disparity cues.

It is difficult to tell whether the presence of accommodation depth cues with binocular disparity gave an increase to the accuracy of the judgements as in many cases there is only a small difference in the results between the binocular disparity results with accommodation depth cues and the ones without. It is pretty clear than when the user could see the cues from disparity that the addition of accommodation cues did not reduce the strength of those cues but it is difficult to say with any certainty if they were improved.

To be able to find this out we would have to run a test that would allow a greater number of samples, possibly over a wider range of offsets, to be taken so that we would be able to match it to the Psychometric curve and with greater accuracy find the points of just noticeable difference for each result and see if we were able to maintain the accuracy longer with or without accommodation cues.

Looks like we maintained strong stereoscopy throughout.

The participants could see the depth cues and it did harm the experiment.

Stereo slightly more effective.

7.1.5 Multifocal Depth

The results of the

Looks like a very strong indication of something going wrong. Checked against random inputs to be sure the test was sound in section ??.

It could be a genuine problem. Not something we see in some other users or in the personal pilot tests.

This could be the effect of training on the user. Further work would be needed to investigate this by isolating and comparing with and without other depth cues to see if it is a totally inversions

We are fairly confident that the error should not be coming from a mistake with the experiment, so must be a product of the scene.

The average result for the zero depth cues has the similar psychometric fall off as stereoscopic scenes with a similar pattern to the location of the 'just-noticeable-difference'. This indicates that we were not able to fully remove all depth cues in the scene.

By what margin is it better or worse? NOT A LOT IN STEREO

What does this point to for only multi-focal viewing? Considering people are trained for stereo. STEREO ENCHANCES.

Talk about alignment problems. Point camera not pupil distance means that edges are not approximated correctly. Ref mark banks

Chapter 8

Summary and Conclusions

Mention if it reduced the vergence problem. Mention if it appeared more real.

Which blend methods were convincing?

The results were a little lacking to draw any significant conclusions but the process of running the test on the display has shown where further research can proceed and there is limited evidence to suggest that even if the depth perception has not been improved entirely it has been shown to work in some cases. It raises the possibility of needing to train users to be able to recognise the cue alone.

Not enough significant data to say whether depth perception was increased in multifocal over stereo, no strong indications of overcoming the vergence-accommodation conflict.

The blending chosen was not significantly in error to reduce the effectiveness of stereo.

Can only conclude for our hypothesis that it did not harm stereo when present.

Some reports during use of "seeing three objects". Could the multi-focal setup be breaking the ability to form correct stereo pairs for some people?

The multi-focal definitely had an effect on its own but cannot say for certain it

was positive because of the inversion. Worth further investigation. Possibility of accommodation ordering being dependent on other depth cues.

potential future work.

Test different focal distances.

Test comfort.

Test depth feeling.

Longer user testing for middle blend distances.

Auto-calibration.

Chapter 9

Appendix

9.1 BRIEFING FORM

Experiment: Depth Perception with a Multi-focal Stereo Display Date: 31 May 2016

Thank you for taking part in the experiment. The experiment will take approximately 20 minutes and will be comprised of one 20-25 minutes section. Please read the following instruction carefully before starting the experiment.

The purpose of this experiment is to compare the effect on perceived depth when given extra depth cues. The results of this will help in the design of future displays.

You will be shown two objects at different depths. The size, shape and lighting on these objects is no indication of the depth of the object. You will have to select which of the objects is nearest using the 'j' and 'l' keys to select the left or right object. After each selection you will be shown a calibration screen to ensure the screens remain calibrated correctly for your eyes, press '/' when this is correct to move onto the next comparison. This will be performed for 400 times.

In this experiment you are asked to avoid making any decision which based

on misalignment of the screens and are encouraged to take a break between comparisons if you feel any discomfort.

[END]

Bibliography

- [1] Alex Paul Pentland. “A new sense for depth of field”. In: *Pattern Analysis and Machine Intelligence, IEEE Transactions on* 4 (1987), pp. 523–531.
- [2] Claire C Gordon et al. *1988 Anthropometric Survey of US Army Personnel-Methods and Summary Statistics. Final Report*. 1989.
- [3] Frank Biocca. “Will simulation sickness slow down the diffusion of virtual environment technology?” In: *Presence: Teleoperators & Virtual Environments* 1.3 (1992), pp. 334–343.
- [4] Mark Mon-Williams, John P Warm, and Simon Rushton. “Binocular vision in a virtual world: visual deficits following the wearing of a head-mounted display”. In: *Ophthalmic and Physiological Optics* 13.4 (1993), pp. 387–391.
- [5] Andrew J Woods, Tom Docherty, and Rolf Koch. “Image distortions in stereoscopic video systems”. In: *IS&T/SPIE’s Symposium on Electronic Imaging: Science and Technology*. International Society for Optics and Photonics. 1993, pp. 36–48.
- [6] John P Wann, Simon Rushton, and Mark Mon-Williams. “Natural problems for stereoscopic depth perception in virtual environments”. In: *Vision research* 35.19 (1995), pp. 2731–2736.
- [7] Tetsuri Inoue and Hitoshi Ohzu. “Accommodative responses to stereoscopic three-dimensional display”. In: *Applied optics* 36.19 (1997), pp. 4509–4515.
- [8] Kurt Akeley et al. “A stereo display prototype with multiple focal distances”. In: *ACM transactions on graphics (TOG)*. Vol. 23. 3. ACM. 2004, pp. 804–813.
- [9] Neil A Dodgson. “Variation and extrema of human interpupillary distance”. In: *Electronic imaging 2004*. International Society for Optics and Photonics. 2004, pp. 36–46.
- [10] Simon J Watt et al. “Focus cues affect perceived depth”. In: *Journal of Vision* 5.10 (2005), pp. 7–7.

- [11] Rafal Mantiuk, Karol Myszkowski, and Hans-Peter Seidel. “A perceptual framework for contrast processing of high dynamic range images”. In: *ACM Transactions on Applied Perception (TAP)* 3.3 (2006), pp. 286–308.
- [12] David M Hoffman et al. “Vergence-accommodation conflicts hinder visual performance and cause visual fatigue”. In: *Journal of vision* 8.3 (2008), pp. 33–33.
- [13] Sheng Liu, Dewen Cheng, and Hong Hua. “An optical see-through head mounted display with addressable focal planes”. In: *Mixed and Augmented Reality, 2008. ISMAR 2008. 7th IEEE/ACM International Symposium on*. IEEE. 2008, pp. 33–42.
- [14] Gordon D Love et al. “High-speed switchable lens enables the development of a volumetric stereoscopic display”. In: *Optics express* 17.18 (2009), pp. 15716–15725.
- [15] Sheng Liu and Hong Hua. “A systematic method for designing depth-fused multi-focal plane three-dimensional displays”. In: *Optics express* 18.11 (2010), pp. 11562–11573.
- [16] Kevin J MacKenzie, David M Hoffman, and Simon J Watt. “Accommodation to multiple-focal-plane displays: Implications for improving stereoscopic displays and for accommodation control”. In: *Journal of Vision* 10.8 (2010), pp. 22–22.
- [17] Takashi Shibata et al. “The zone of comfort: Predicting visual discomfort with stereo displays”. In: *Journal of vision* 11.8 (2011), pp. 11–11.
- [18] Yasuhiro Takaki, Kosuke Tanaka, and Junya Nakamura. “Super multi-view display with a lower resolution flat-panel display”. In: *Optics express* 19.5 (2011), pp. 4129–4139.
- [19] Parth Rajesh Desai et al. “A review paper on oculus rift-A virtual reality headset”. In: *arXiv preprint arXiv:1408.1173* (2014).
- [20] Cass Everitt. “Beyond Porting”. In: *SteamDevDays*. NVidia. 2014.
- [21] Bochao Li, Ruimin Zhang, and Scott Kuhl. “Minication affects action-based distance judgments in oculus rift HMDs”. In: *Proceedings of the ACM Symposium on Applied Perception*. ACM. 2014, pp. 91–94.
- [22] Nick Whiting. “Lessons from Integrating the Oculus Rift into Unreal Engine 4”. In: *Oculus Connecy*. Epic Games. Oculus, 2014.
- [23] Rafal K. Mantiuk. “Perceptual display calibration”. In: *Displays: Fundamentals and Applications*. Ed. by Rolf R. Hainich and Oliver Bimber. 2nd. CRC Press, 2016.
- [24] Michael Abrash. *Down the VR rabbit hole: Fixing judder*. <http://blogs.valvesoftware.com/abrash/down-the-vr-rabbit-hole-fixing-judder/>. Accessed: 2016-06-05.

- [25] Paul Bourke. *Calculating Stereo Pairs*. <http://paulbourke.net/stereographics/stereorender/>. Accessed: 2016-06-05.
- [26] Ben Lewis-Evans. *Designing to Minimize Simulation Sickness in VR Games*. <http://www.gdcvault.com/play/1022772/Designing-to-Minimize-Simulation-Sickness>. Accessed: 2016-06-05.
- [27] OpenGL. *OpenGL - GLFrustum*. <https://www.opengl.org/sdk/docs/man2/xhtml/glFrustum.xml>. Accessed: 2016-06-05.