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Abstract

Stereoscopic and automultiscopic displays suffer from crosstalk. An effect which greatly reduces image quality, viewer comfort and distort the perception of depth. Previously, only a limited work has been done on understanding the relation between crosstalk and the perceived depth with respect to the nature of the stimuli. Moreover most of the previous work is carried on simple monochromatic scenes. Since the human visual system uses numerous other cues than disparity to estimate the depth of an object in a stereo scene, monochromatic scenes are poor choice for understanding the above mentioned relation. Moreover, the model for depth resolution via disparity as provided by the current literature fails to justify why and how the perceived depth is affected by the crosstalk. In this work, we improved and performed more generalized experimentation to see how the depth perception is affected by the crosstalk for different kinds of stimuli. Based on the result of these experiments, we derived a model for human visual system's resolution of depth from disparity that accurately measures the depth of a stimulus as perceived by the human in presence of cross-talk. Finally some improved algorithms for removal/compensation of crosstalk in automultiscopic are developed.

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Chapter 1

Introduction

Discuss General idea behind crosstalk and why is it so bad. How it affects the depth and what current literature think about it. Context: 3D stereo, 3D displaysvision Problem + its importance Crosstalk relevance.

1.1 Goal and overview

1.2 Contributions

Experimentation, mitigation, HVS model.

Chapter 2

Relevant Background

Depth perception is the ability of the Human Visual System to visualize the three dimensional world as well as measuring the distance of an object based on two dimensional images obtained from the eyes. Depth perception is imperative for performing basic everyday tasks such as avoiding obstacles without bumping into them or interacting with the world with relative ease. In animals (specially predators), it is critical to estimate the distance of a prey for an efficient attack. Depth sensation is the term used for animals as it is not known whether they sense the depth in the same way as humans do or not[30].

Human visual system uses several monocular and binocular cues to determine the depth of objects in the view. These cues can be categorized into two categories i.e. cues extracted from a single image (Monocular Cues) and cues extracted from two images (Binocular cues)[19][30]. Figure 2.1 gives an outlook of the depth cues used by the HVS. These cues are then dynamically weighted according to their robustness by the HVS in order to estimate a depth value for each object in the view [15]([Write details of those cues in Appendix](#)).

2.1 Binocular vision, stereopsis and its limits

Generally speaking, all the animals with two eyes have binocular vision and they can integrate the information from two eyes based on the binocular overlap. But the term Binocular vision is usually used for the animals that have a large area of binocular overlap (Human and most other predators) and use it to get the depth information of the world around them. In addition to calculating depth, binocular vision also has advantages in performing other tasks such as detection, discrimination, detecting camouflaged objects or eye-hand coordination. Even the resolution of the observed world is increased with

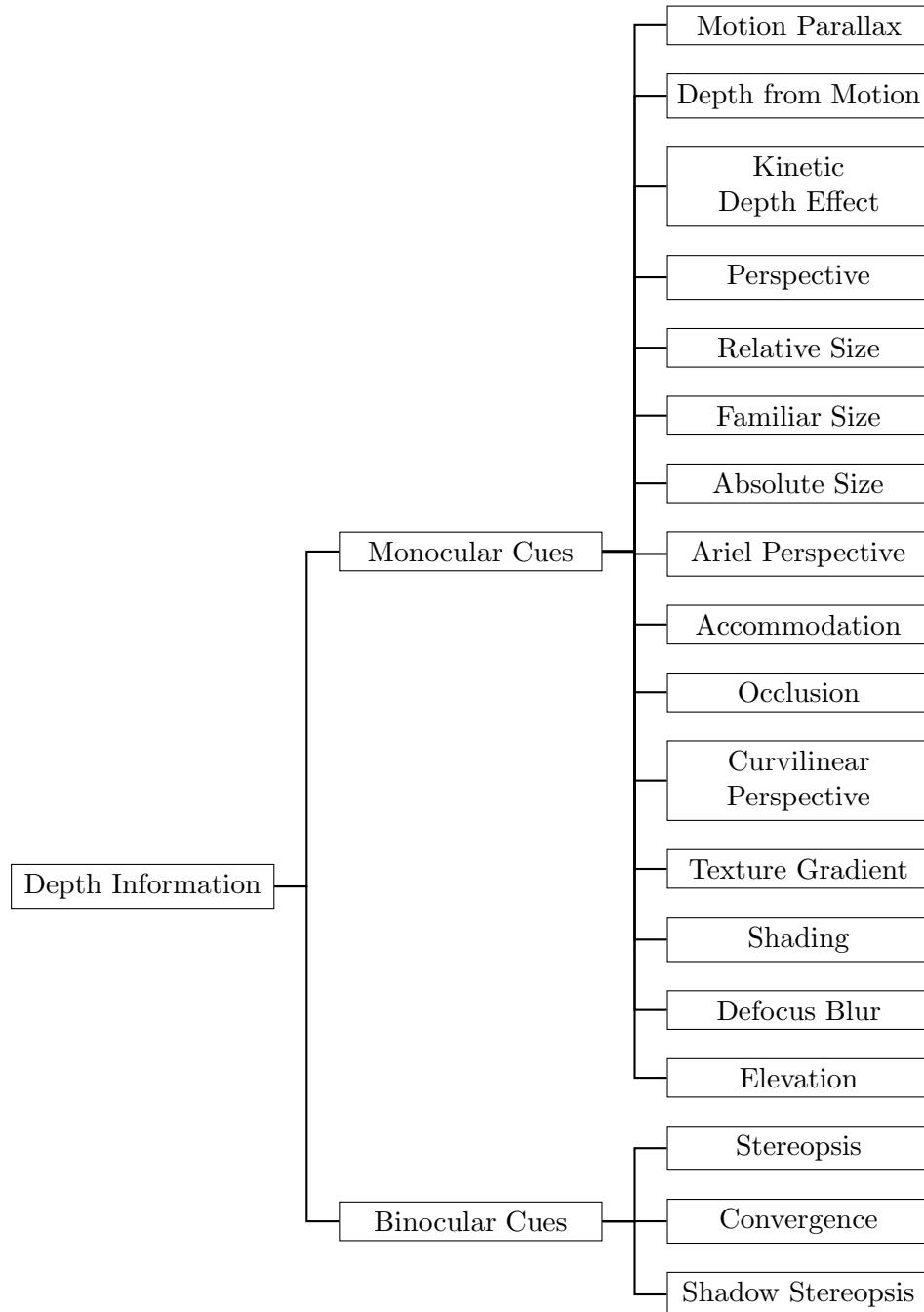


FIGURE 2.1: HVS Depth Cues

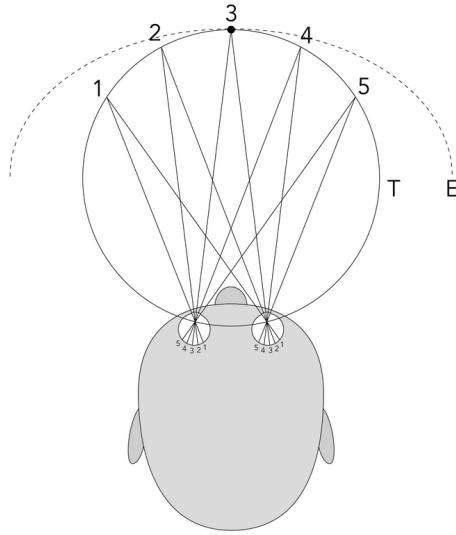


FIGURE 2.2: Representation of theoretical (T) and empirical (E) horopter

binocular vision[8]. Among all the depth cues discussed in the section above, Stereopsis is the most influential of them all. Since the human eyes are located at different lateral positions on the head, the images formed on the retinas of these two eyes are slightly different. The difference is mainly the horizontal positions of the objects[35]. The process of obtaining a fused (Binocular fusion) image (Cyclopean image) and obtaining a depth map based on the horizontal disparities of the objects in these two images is known as stereopsis.

When the eyes verge in order to focus on some object (or point) in space, that object is projected at identical corresponding points in the retinas. It means that the difference between their horizontal positions is zero. This process is called fixation of the eyes and the distance of the object (point) at which the eyes are fixated is called the fixation distance. The locus of all the points in space that is projected on identical retinal points is called the horopter[31]. Theoretically, via geometrical principles, the horopter is a circular segment that passes through the fixation point. However, Wheatstone in 1938 observed that the actual/empirical horopter is much larger than that. Figure 2.2 shows both the theoretical and empirical horopter. Any object that is farther away from the horopter has uncrossed disparity in the retinas i.e. the eyes need to be diverged (uncrossed) in order to fixate on that object. Similarly, any object that is closer than the horopter has crossed disparity in the retinas i.e. the eyes need to be converged (further crossed) in order to fixate at it.

Stereopsis is believed to be processed in the binocular neurons of the visual cortex of mammals. The binocular neurons have receptive fields in different horizontal positions

in each eye. These cells are active only when the object of interest is in certain range of disparity in one eye relative to the other i.e. there is a maximum disparity limit. As the objects in the images formed at the retinas of both eyes are slightly shifted horizontally, presenting two different images with shifted object to both eyes can fool the HVS into perceiving depth. This process is called stereoscopy. The first stereoscope was invented by Sir Charles Wheatstone in 1838[36]. It used two mirror both tilted at 45 degrees w.r.t eyes that reflected two different images from the sides. Currently all the stereoscopic screen present a different perspective image to both eyes with different technologies that will be discussed in later sections.

2.2 Crosstalk

As discussed in the previous section, stereoscopy includes the process of displaying different perspective images to each eye in order to mimic the effect of depth in a scene. However, it is critical that the perspective of these two images should be segregated completely from each other. Currently, all the commercially available 3D displays (with exception of head mounted displays or Wheatstone setups) fail to isolate the two images completely. That means that a percentage of the image of one eye leaks to the other eye as well. This unintended leakage is called the crosstalk in stereoscopic screens[38]. Figure 2.3 Shows one such example where the screen has a simulated crosstalk of 14%. This means that 14% image intensity of the right eye image is leaked into the left eye image and vice versa.

“System crosstalk” is the term used to define the amount of light leakage that occurs between two views and is independent of the image contents. In simplest form, it can be mathematically defined as:

$$\text{Crosstalk}(\%) = \frac{\text{leakage}}{\text{signal}} * 100 \quad (2.1)$$

Here, “signal” is the luminance of the original image intended for an eye and “leakage” is the luminance of the light that leaks from the unintended image. Usually, on a stereoscopic screen, the amount of crosstalk is measured by observing the luminance of the left channel while a black (minimum luminance) image is displayed in the left channel and a white (maximum luminance) image is displayed on the right channel and vice versa. This definition is accurate for the screens that can manage to display a true black i.e. zero luminance. Almost all of the LCDs can not produce zero luminance as their minimum luminance hence resulting in a non-zero black level at its minimum. Another

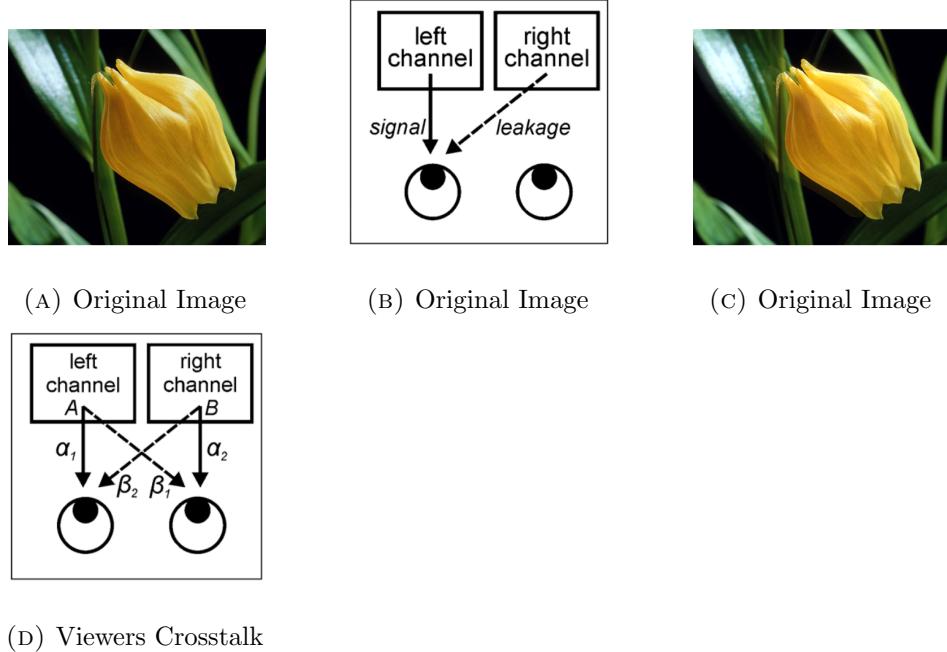


FIGURE 2.3: (a-c) A simulation of 14% crosstalk. An Image intended for the left eye containing 14% of image intended for right eye. (d) Illustration of Viewers crosstalk with the transfer functions as defined by Andrew J. Woods [38]

mathematical representation of crosstalk take into effect this non-zero black level and is defined as:

$$\text{Crosstalk}(\%) = \frac{\text{leakage} - \text{blacklevel}}{\text{signal} - \text{blacklevel}} * 100 \quad (2.2)$$

Throughout the rest of the thesis, we will be using crosstalk as mentioned in eq 2.2.

Viewers crosstalk on the other hand is the amount of crosstalk that can be perceived by the viewer as ghosts. It is dependent on the image contents i.e the contrast at the ghosting point and the parallax of objects in the scene. If the system crosstalk is defined as

$$\text{System Crosstalk (left eye)} = \frac{\beta_2}{\alpha_1} \quad (2.3)$$

Where α_1 denotes the percentage part of the left-eye image at position (x,y) as observed by the left eye and β_2 denotes the percentage amount of right eye image at the same location (x,y) leaked into the left eye. Then the viewers crosstalk is defined as

$$\text{Viewers Crosstalk (left eye)} = \frac{B\beta_2}{A\alpha_1}. \quad (2.4)$$

Where “A” is the luminance of that particular point in left-eye image and “B” is the luminance of that particular point in right-eye image (as described in Fig 2.3d). The Variables α and β are characterizing the transfer functions from the displayed image to

the observed image i.e. the amount of light reaching the eyes after being displayed on the screen and going through the glasses or any other medium that resides between the screen and the eyes. In most displays, crosstalk is an additive process and is roughly linear. This means that to simulate crosstalk, adding a desired amount of unintended image to an intended image should be sufficient. The simulation of crosstalk in our experiments was carried out in the same manner.

The perception of crosstalk obeys the Webber's law which means that leaked light will be greatly perceivable by the viewer on the dark image areas rather than bright areas. Also, the perceived crosstalk is dependent upon the contrast of the image and the binocular parallax of the stimuli i.e. crosstalk perception will increase with increase in contrast or increase in binocular parallax. It is commonly believed that ghosting plays the most critical role in determining the image quality. Wilcox and Stewart [37] observed that over 75% of the observers in their experiments reported ghosting to be the key feature that deteriorated the image quality. Apart from reduction of image quality, perceivable ghosting is also responsible for loss of depth, viewer's discomfort, reduction of sharpness and contrast, decreased fusion limits, and difficulty in fusion. Two objects can not be fused together if the angular separation between them is smaller than the disparity[4]. In fact since the ghost and the stimulus lie in the same (x, y) position but at different depth, the angular separation becomes zero and the disparity gradient of the ghost and the stimulus becomes ∞ . Hence both of them can not be fused together. In this case the more luminant object i.e. the stimulus will be fused while the ghosts will remain in diplopic state. Crosstalk in still images is perceived to a larger extant than crosstalk in dynamic scenes (e.g. a movie). This means that motion of objects in a scene can mask the perception of crosstalk.

The stereoscopic literature provides a lot of advices for the acceptable and unacceptable crosstalk for the viewers. Woods[38] points some of these advices as:

- Crosstalk between 2% to 6% significantly affects the visual quality and increase the viewers discomfort.
- In order to produce accurate depth range between 40 arcmin, the crosstalk should be as low as 0.3%.
- Crosstalk is visible even at 1% to 2%.
- 5% of crosstalk is enough to induce discomfort.
- JND for crosstalk is 1%.
- 2-4% of crosstalk can significantly decrease the amount of perceived depth.

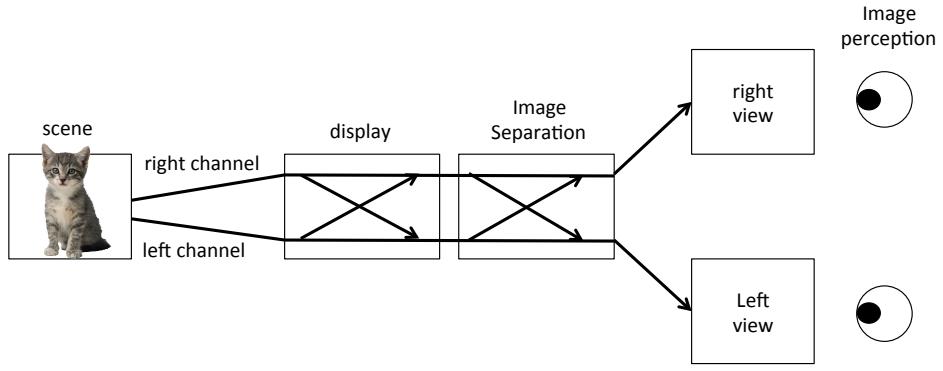


FIGURE 2.4: A flow diagram showing the process of stereo image perception starting from stereo scene capture. The crosstalk can be induced by the display (light generation) and by the image/view separation mechanism(3D glasses or autostereoscopic parallax barrier).

As one can observe, there is a variability in these guidelines. The reason for this variability might be because of the different setups and types of stimuli that were used by the researcher in their experiments. We observed that currently the literature is not quite thorough on how the depth perception is affected when it comes to different kinds of stimuli and relatively more complex scenes. Which is why we performed some experiments of our own to verify and expand the current knowledge in this area. This is also one of the main contributions of this thesis.

2.3 Stereoscopic/Automultiscopic Screens and its cross-talk

In this section we will review some of the stereo technologies and their associated crosstalk. The basic setup for a stereoscopic displays involves a display screen that has typically higher (above 120 Hz) refresh rate and a view separation mechanism. A high refresh rate is required so that images from two different view perspective can be displayed alternatively without the user realizing any glitches (after the views has been separately delivered to the eyes). Various Stereo display technologies are available in the market such as CRT, DLP, Plasma, PDP and LCD screen. Active/Passive 3D glasses or anaglyph glasses are generally used as view separation mechanisms. Figure 2.4 illustrates that the crosstalk is induced by the display as well as the view separator.

2.3.1 Time sequential stereo using active shutter glasses with an LCD display

LCD screen coupled with active shutter glasses is the most common 3D technology that is commercially available. It produces an image by back lighting a two dimensional individually addressable liquid crystal (LC) matrix. The back light is typically a cold cathode fluorescent lamp (CCFL) or light emitting diodes (LEDs). The LC matrix consists of crystals that rotate according to the voltage applied to them. This rotation limits the flow of the light that passes through each cell hence producing different gray levels. Each pixel of the screen consists of three LC cells coupled with red, green and a blue filter. Hence the color and luminance of each pixel is created by controlling the light that flows through these individual filters which is regulated by the LCs. It should be noted that even at its best i.e. crystals are perpendicular to the light source, they fail to block the light completely and hence an LCD screen can not display true black color.

The time required for the LCs to rotate from one position to another desired position is known as the pixel response rate/time. This response time is higher if the delta between the rotation is smaller and vice versa^[38]. This means that the refresh rate of an LCD display is dependent upon this response time. LCD displays usually utilize top to bottom image update method i.e. in order to update the image being displayed, the rows of pixels is addressed individually from top to bottom.

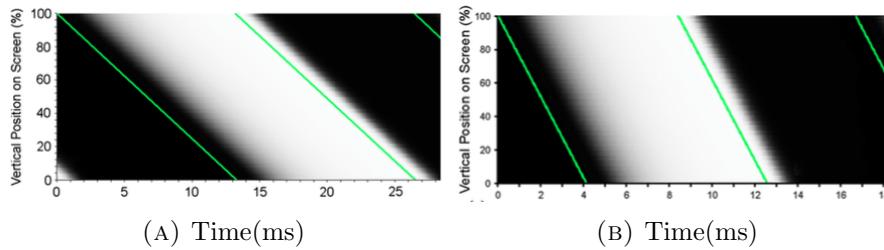


FIGURE 2.5: (a) Response of a conventional LCD display (in time domain). (b) Response of a high refresh rate LCD display [38].

figure 2.5 shows the time domain responses of LCD displays. The green line represents the row of the pixels that are being updated while the images is being changed from complete black to complete white. It can be seen from 2.5a that there is no time (a vertical line) where a complete black or white image is observed. However if the refresh rate is increased (Figure 2.5b), one can see that there is an interval in time where a stable image can be displayed.

Active shutter glasses consists of lenses that can turn opaque or transparent in order to gate the left or right image being displayed on the screen to the respective left or right eye (at any given time, one lens is in opaque state while the other in transparent

state). Each lens of these glasses has a liquid crystal called LC shutters(just like an LCD display) that blocks the light when a voltage is applied to it. The time required for these LCs to go from completely opaque to completely transparent and vice versa is called the rise and fall time [38]. It is observed that

- LC shutters do not perform identically for each wavelength.
- The LC shutters have a non zero transmission even when it is in opaque state.
- The rise and fall time are not instantaneous.

In addition to that, the light transmission in active shutter glasses also varies with the viewing angle. The highest blocking of the light occurs at an angle perpendicular to the shutters. This means that while viewing a scene through these shutter glasses, one would observe greater leakage of light in the border areas of the shutters as compared to the center (provided the position of the eye is in the center of the shutters). It is important that the shutters are opened and closed with the right timings with respect to the image being displayed on the screen. Incorrect image will be observed if the shutters are opened too early or too late that will result in crosstalk.

Hence, the methods according to which crosstalk can occur when using active shutter glasses combined with an LCD display are:

- Optical performance of the liquid crystal cells i.e. crosstalk is proportional to the amount of light leaked while in opaque state.
- Incorrect synchronization of shutter glasses with respect to the display.
- Viewing angle through the shutter glasses.
- Pixel response rate of the LCD display. Higher response time will result in higher crosstalk.
- Image update method. The ideal time for opening of a shutter would be when an image has been completely displayed on the screen. However most LCDs update the image using vertical scanning and hence usually there is no time at which the image is completely displayed stably.
- The x,y location of the image on the screen. This is related to both the image update method and the viewing angle through the shutter glasses.
- The gray level being displayed. If the change in gray level is small then the response time will be large hence causing larger crosstalk.

2.3.2 Polarized Stereo

Polarization is a property dealing with the controlled oscillation of light (and other waves). Typically light waves oscillate in a way that their phase shifts over time are unpredictable. Passing the light through special polarizing filters forces them to oscillate in a controlled manner[34]. Light can be polarized in a linear manner where the light waves are forced to oscillate in a plane or is a circular manner i.e. the orientation of the oscillations vary circularly with respect to time. In stereoscopy, light intended for the left and right eye can be encoded using linear polarization i.e the polarization of the left eye light is orthogonal to the polarization of the right eye light or the polarization of one view is clockwise and anticlockwise for the other view in case circular polarization is used.

In a typical 3D cinema setup, images for the left and right eye are simultaneously projected on a silver screen by two projectors. Each of these projectors has a polarizing filter (opposite with respect to each other) attached to it. Viewers view the screen through cheap polarized glasses that has the exact same polarizing filters in its left and right lenses as the left and right projector. This way each of the polarized lens block the light from the other view hence giving an impression of 3D. However, as with every piece of technology, imperfections are also present in this setup. Firstly, the polarizing filters mounted on the projectors are not perfect and fail to properly polarize all light wavelengths and can not be made to be perfectly orthogonal (opposite to each other). [38]. Also the silver screen is unable to reflect the polarized light from the projectors without distorting the polarization. Different materials have different polarization properties and up till now a material that perfectly preserves the polarization for all wavelengths has not been discovered. Lastly, it is hard to match the the polarization orientation of the projector filters to the filters present in the glasses. For example, in case of linear polarization, the orientation mismatch can easily occur if the viewers head is slightly tilted hence causing crosstalk [7]. Circular polarization however is less prone to this mismatch as compared to linear polarization hence it is more commonly used in 3D cinemas. In any case, failing to deliver properly polarized left and right image light to the glasses and any mismatch in the orientation of the glasses with respect to the projector filters will hinder the ability of the polarized 3D glasses to block the light from unintended view completely hence causing crosstalk.

In summary, the important factors to consider when dealing with the crosstalk in a typical 3D cinema setup are as follows:

- The optical properties of the polarizing filters used in the projectors and the glasses.
- The polarization preserving properties of the screen.

- The mismatch between the orientation of the projection filters with the orientation of the filters present in 3D glasses.

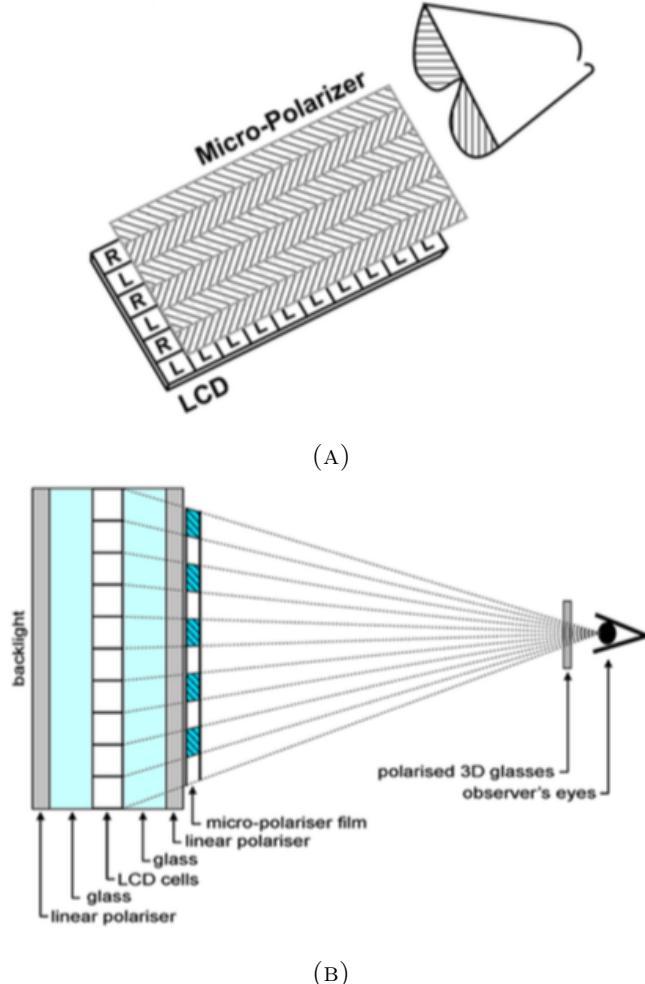


FIGURE 2.6: (a) A layout of a micro-polarized LCD screen where odd and even numbered rows are oppositely polarized. In this example, the viewer viewing the screen using the polarized glasses will see odd numbered pixel rows through the right eye and even numbered pixel rows in the left eye [38] (b)Construction of a typical micro-polarized LCD screen.

A stereo 3D setup can also be obtained by using a micro-polarized LCD screen used in conjunction with polarized 3D glasses that are similar to the cinema setup discussed above. A micro-polarized LCD screen consists of polarization filters (linear or circular) mounted on top of a conventional LCD screen. However, unlike the projective method where two images can be projected on the screen simultaneously, alternative rows (odd and even rows) of the LCD screen pixels are polarized oppositely to each other. Micro-polarized LCD screens have an advantage over the 3D screens used with active shutter glasses that crosstalk induced due to low refresh rate of the screen is not a problem. But this also comes at a cost of vertical spatial resolution of the displays as the light from half of the row pixels will be blocked by each of the lens of the polarized

glasses. Figure 2.6a illustrates a typical polarized LCD setup where the user will see different pixel rows in each eye. Figure 2.6b shows the construction of a typical Polarized LCD screen. It can be seen that the LCD cells are separated from the micro-polarizer film by a glass sheet that is typically 0.5 mm thick [38]. Hence a sensitivity to the viewing distance and position due to parallax is induced. This means that if the viewer is not located at the correct position or distance to the screen, he/she will be able to see the unintended rows of pixels along with the intended rows hence inducing crosstalk. In summary, the factors that contribute to the crosstalk in a micro-polarized LCD screen stereo setup are as follows:

- Matching of the orientation of the polarization filters in the glasses to the orientation of the micro-polarizing film present on the screen.
- The quality and ability of the micro-polarizing film to properly polarize the light.
- The accuracy of the alignment of micro-polarizing film to the LCD cells.
- x, y screen position of the screen. Due to the fact that viewer will typically be in a position where parallax error mentioned above will vary with the screen position.
- Viewing angle of the viewer as this will affect the matching between the orientation of the glasses and the screen polarization filters.

2.3.3 Automultiscopic Screens

All the stereo display technologies mentioned earlier needs some kind of glasses to be worn by the viewer in order to separate the different perspective views for each eye. One of many disadvantages of using glasses is that none of them are perfectly transparent and hence absorbs a portion of incoming light. This makes images darker than they actually are. Automultiscopic displays addresses this problem by placing a (vertical or tilted) parallax barrier or a lenticular sheet on top of a conventional LCD panel that results in only a specific column of pixels to be seen by an eye at some position while the adjacent columns remains occluded as seen in figure 2.7[39]. The number of adjacent pixels columns occluded from one view determines how many different views can the screen display. Viewer can sense proper motion parallax by changing the position of his/her head in case the screen displays more than 2 views simultaneously.

Light fields is a vector function that represents the radiance of light flowing through every direction at every point in space [32]. In computer graphics, light field of a scene can be approximated as a 4D function by capturing the scene while moving the camera in space in steps. Automultiscopic screens displays this 4D light field where the fourth

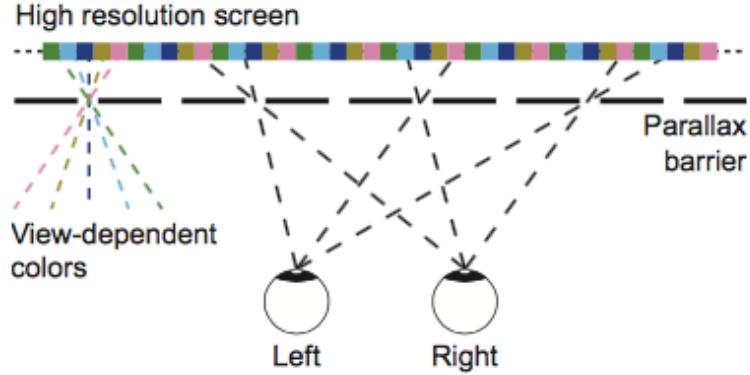


FIGURE 2.7: A five-view automultiscopic screen using a parallax barrier. The actual pixels on the LCD panel are called sub-pixels whereas the gaps in the parallax barrier can be thought of as a single view dependent pixel. Each of the observer's eyes can only see a specific set of sub-pixels through a view dependent pixel[39].

dimension represents the view number (more information about this can be found in chapter 6). Since the light field is usually captured at a resolution that is equal to higher than the automultiscopic screen's resolution, the view images are re sampled differently for each view. This further reduces the sampling frequency and hence cause smear aliasing if displayed directly. To resolve this problem, the re sampled view images have to be blurred in order to remove the undesired higher frequencies [39]. As seen in figure 2.7, placing the parallax barrier vertically reduces the width dimension of the view displayed by a factor proportional to the number of views. In order to preserve the aspect ratio of the images, the parallax barrier can be tilted by some angle. This further complicates the anti aliasing and hence special filters need to be applied to the images before displaying [2].

As with every 3D display, automultiscopic screens also exhibits light leakage (crosstalk) between adjacent views. One reason for this is that the lenticules of a lenticular sheet are not perfect and does not separate the incoming light from different views completely. In case of a parallax barrier, light from the neighboring views can be occluded completely if the gaps in the barrier are extremely small (just as the case with a pinhole camera). However, there is a limit on how small the gaps can be made to be before distortion via diffraction kicks in. Hence the gaps are made large enough so that distortion due to diffraction can be avoided with the side effect of light leakage from neighboring views. Moreover, the lenticular sheet or parallax barrier are extremely hard to align perfectly to the pixels on such a small scale and is impossible in case the sheets are tilted. The latter will always cover a portion of pixels (figure 2.8) which further increases the crosstalk. Typical light leakage pattern can be seen in figure 2.9.

Crosstalk in automultiscopic screens have one advantage though. I.e. it helps smoothen the view transition while switching the position of the viewer. Hence ideally it

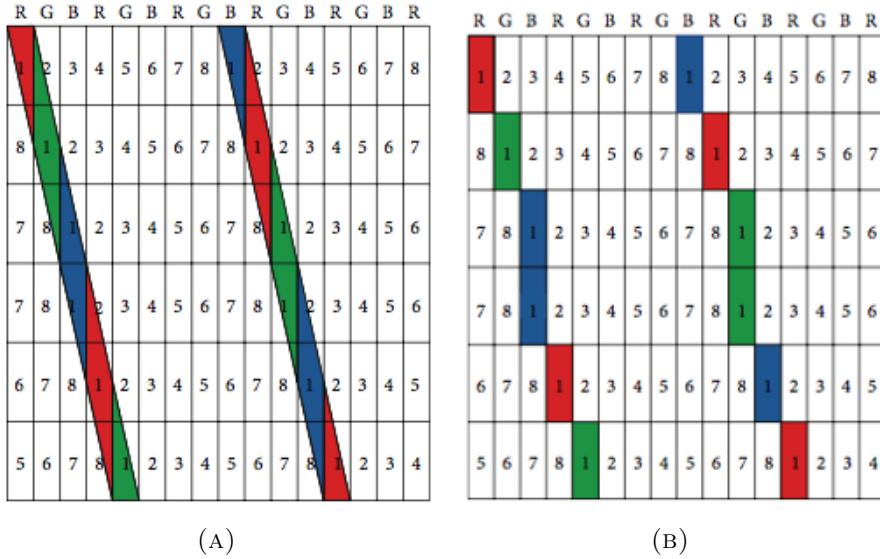


FIGURE 2.8: (a)Visible pixels observed through the slit of a tilted parallax barrier. It can be seen that the view is covering more than one pixels for every pixel. (b)The view that covers majority portion of a sub-pixel is assigned to it which is the reason why some light from that particular view will be leaked into the adjacent view [28]

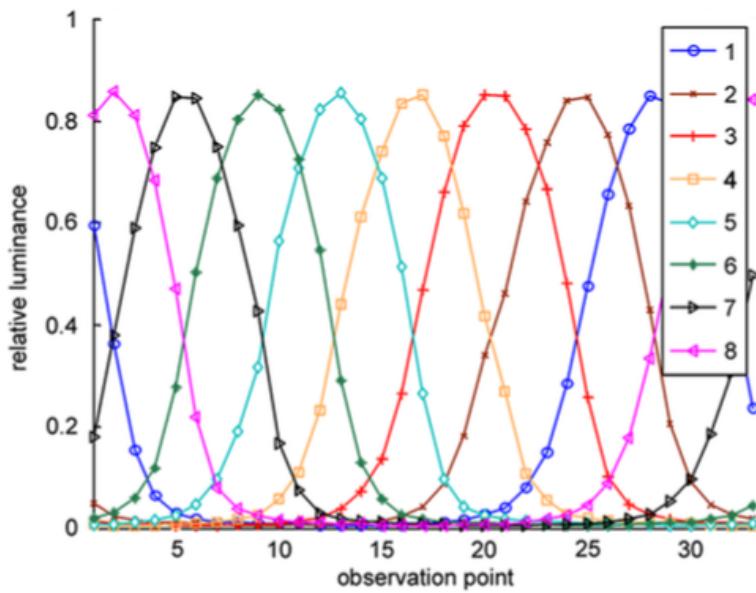


FIGURE 2.9: The experimentally observed luminance distribution of all views across different view points. It can be seen that some portion of the adjacent views is leaked even at the sweet spots. The light leakage increases as the observation point is moved away from the sweet spot [38].

would be desired if there is no crosstalk present at sweet spots (the points in space where the viewers line of sight is perfectly aligned to the view image being displayed) along with some crosstalk present at points that are at the boundary of view transitioning.

Chapter 3

Related work

It is widely believed that crosstalk in stereoscopic or automultiscopic screen results in reduced visual comfort, reduced disparity range, reduced contrast and most importantly, reduction of perceived depth. However, the literature is not thorough about how the crosstalk effects the perceived depth. Wilcox et al [37] performed a large scale experiment in which 77 observers were shown a small stereo footage in two commercial large-formate 3D theaters. The typical stereo degradations in theaters that were considered were crosstalk (ghosting), brightness, and the other qualities of 3D. The test subjects were asked to evaluate which one those degradations affected their experience the most. 75% of the subjects reported that ghosting was the most prominent in degrading their viewing experience. Below is a review of some of the work that has previously been conducted in order to understand the effects of crosstalk on the perceived depth.

3.1 Effects of crosstalk on perceived depth

K.C.Huang et al [9] performed intensive experiments in order to obtain a threshold for the system crosstalk that on average will not mitigate the effects of the depth from disparity. Since the viewer crosstalk is dependent upon the system crosstalk and the local contrast of the desperate object in the image, a uniform level of crosstalk (same crosstalk all over the screen which does not change with time) should not have the same effect on all kinds of stereo images. This is because the HVS sensitivity to detect the change in luminance follows Webber's law [3]. Which means that compared to areas of the image with high local contrast, the HVS is more tolerable towards crosstalk where the local contrast is low. Based on this idea and the fact that the HVS also uses monocular cues to estimate depth, they performed experiments using a Wheatstone setup (similar to ours) and a set of images with various contrasts and disparities to finally propose that

10% system crosstalk is the maximum crosstalk that will mostly not nullify the depth estimation via disparity. We observed in our experiments that even though above 10% of crosstalk heavily degrades the perceived depth, it still does not result in total depth loss due to disparity. On our high contrast images, we determined that crosstalk level of greater than 16% usually resulted in the total loss of depth.

Ghosted images due to crosstalk as seen in figure 2.3c can be seen as locally decreasing the contrast of the desperate object. Rohaly et al [20] determined the effects that contrast exhibits on the stereoscopically perceived depth. They concluded that decrease in contrast made the objects (crossed and uncrossed) appear to be farther from the viewers. Which means that the crossed objects with decreased contrast appeared to be moving towards the horopter whereas the uncrossed objects appeared to be moving away from the horopter. She also found that monocular contrast reduction amplified this effect more compared to the contrast reduction in both eyes **Note to self: Mention this in the discussion of the results.** It was also argued that the contrast exerts its effect before or at the extraction of depth.

The work that is most relevant to our work was performed by Tsirlin et al. They quantified the amount of depth loss due to crosstalk on objects of various dimensions and disparities. In 2011 [24], they performed experiments where the test subjects were asked to specify the observed depth at various depths of a stimulus (a rectangular structure) the width of which was chosen to be such that at any disparity, the ghost would not be completely separated. The luminance of the structure was set to be the maximum (white) on a completely black background. The subjects reported the observed depth via a slider bar located under the stimulus without any reference. They observed that the perceived depth decreased with the increase in crosstalk as well as increase in disparity. In the second part of the experiment, they observed the effect of crosstalk on binocular occlusion and found out that effect of crosstalk on the perceived depth due to occlusion was even more swear. In 2012 [25], they performed similar experiments to observe the effects of crosstalk on thin structures where the ghost is always completely separated from the stimulus (which is usually the case with vertical thin structures present at a significant distance from the plane of focus). Again they found that observed depth degrades significantly as the disparity or the crosstalk level was increased. However this time the degradation was observed to be higher than the case where the ghosts always overlapped the stimulus. One problem with these experiments is that the stimuli are presented as a uniformly luminant objects on a black background where there is no other depth cue present. This is usually not the case with the complex scene that we typically observe in 3D movies. We observed in our test experiments that in such monochromatic scenes, the depth of the stimuli was extremely hard to perceive even at moderately high disparities. Tsirlin also observed that the perceived depth degraded with disparity even

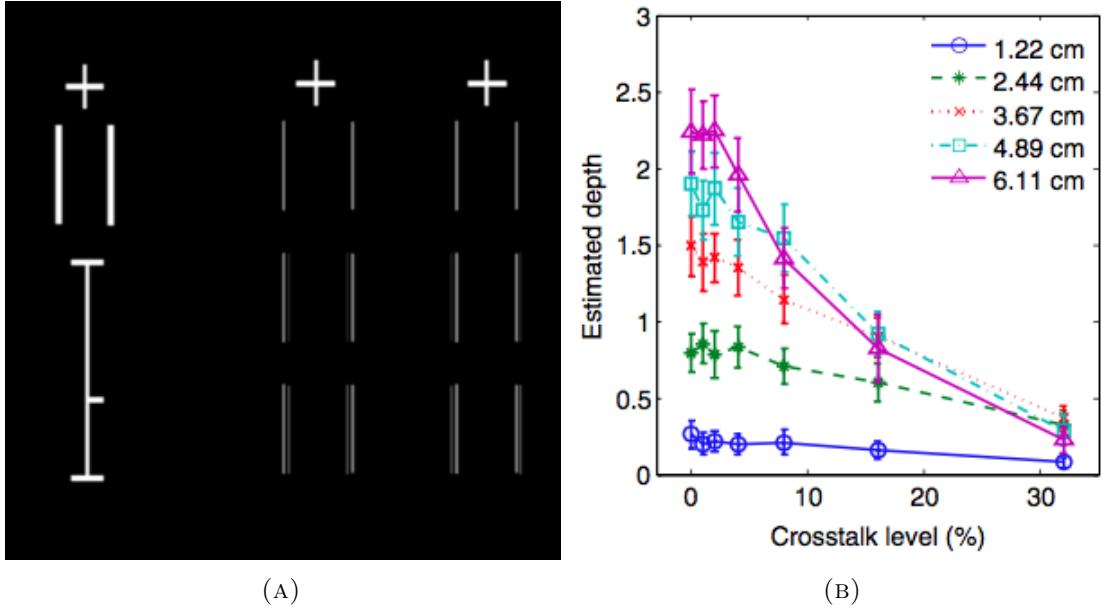


FIGURE 3.1: (a) The setup of Tsirlin’s experiments. Left side represents the complete experiment where the viewers see the vertical lines as a single line in depth. The right side shows the same line with 0, 16 and 32% simulated crosstalk. (b) Depth degradation averaged over the test subjects.

in the base case i.e. the case where crosstalk was set to zero. This is not usually the case in complex scenes. Secondly, there was no reference used and the subjects were simply asked to report the observed depth via a slider bar that was controlled with a mouse. This ‘rating’ setup can be problematic because it can not be guaranteed that all the subjects would rate the same depth equally. And finally, the relation of the stimulus width to the perceived depth at different disparities was not determined which we think is also necessary.

Tsirlin et al [23] again performed similar experiments but this time with complex natural scenes. The subjects were shown a complex scenes with the objects of interest marked by arrows. Later, they were shown the exact same images with crosstalk induced and were asked to rate the depth difference they observed between those two objects. The results again concluded that the perceived depth difference decreased as the theoretical depth difference between the objects of interest and the crosstalk increased. One problem with this experiment is that it reports the observed depth in a complex cluttered scene where the ghosts from the neighboring objects will play a significant role in determining the observed depth difference. Hence it does not tell us anything about how the HVS will respond to the geometry of the stimulus. Moreover, the users rating can be deviated from each other.

3.2 Depth resolution mechanisms in HVS

It is clear that crosstalk in stereoscopic displays reduce the perceived depth proportional to the level of crosstalk and the disparity of an object. However, in order to understand why the perceived depth is degraded, we had to look into some literature where the depth information extraction by the HVS from disparity is investigated.

It is widely believed that the HVS uses some kind of cross-correlation of retinal patches between the two eyes in order to determine the location (or in other words the disparity) at which some object is located in a retinal image with respect to the other. Cormack [5] investigated the binocular fusion process with respect to contrast of the stimuli and concluded that the binocular fusion was dependent upon the contrast and the strength of the binocular cross-correlation profile of the stimuli. The cross-correlation was computed as a function of image luminance. The stimuli used in his experiments were random dot stereograms in which the number of white dots matching between the left and the right eye images at some disparity represented the interocular correlation. He concluded that at low contrast, the binocular fusion increased when the contrast of the stimuli (white dots in the stereograms) increased. The reason behind this can be seen in figure 3.2a where the cross-correlation (interocular correlation IOC) profiles at different contrasts has been plotted. The peaks in these profiles represents the disparity at which the two images matched the most. It is clear that as the contrast decreases, the distinctness of the these peaks also degrades which might make it difficult for the HVS to identify. Same is also true if noise is added to the images as seen in figure 3.2b. This can be one of the reasons for the degradation of the perceived depth in ghosted images as the ghost (due to crosstalk) in an image is just a low contrast version of the stimulus added into the image at some disparity effectively reducing the local contrast. We used these finding in deriving our own model for the HVS that will be explained in chapter 5.

Filippini and Banks [6] explained the limits of stereopsis and modeled them by using windowed interocular cross-correlation. The neighborhood of each pixel in one stereo images (say left) was weighed by an isotropic Gaussian window followed by horizontally displacing a similar window in the right eye image. For each displacement, the cross-correlation of the windowed patched was computed. The disparity was obtained at the displacement value where the maximum correlation for the patches was obtained. The 2D cross-correlation formula used was as seen in equation 3.1.

$$c(\delta_x) = \frac{\sum_{(x,y) \in W_L} [(L(x, y) - \mu_L)(R(x - \delta_x, y) - \mu_R)]}{\sqrt{\sum_{(x,y) \in W_L} (L(x, y) - \mu_L)^2} \sqrt{\sum_{(x,y) \in W_R} (R(x - \delta_x, y) - \mu_R)^2}} \quad (3.1)$$

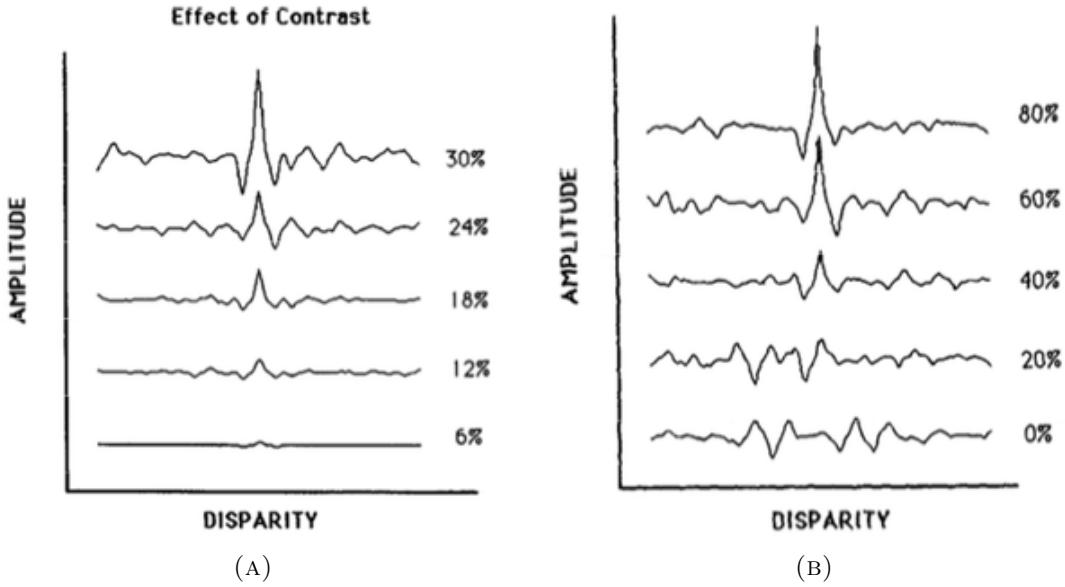


FIGURE 3.2: (a) 1D cross-correlation with varying contrast. (b) 1D cross-correlation with variable level of added noise.

Where $L(x,y)$ and $R(x,y)$ are the image intensities for the left and right eye, W_L and W_R are the Gaussian windows applied to the images, μ_L and μ_R are the mean intensities within the two windows, and δ_x is the displacement (disparity) of window W_R relative to W_L . This way, the correct disparity for each object in stereo images can be computed. The problem is that this method also computes the correct non-degraded disparity even if the crosstalk is induced to the images. This does not correspond well to the HVS behavior. Hence we need an HVS model that can simulate not only the correct disparity estimation but also the degraded disparity when crosstalk is added to the images. **note to self:** Mention the disparity gradient as explained in this paper in the discussion.

3.3 Reduction of crosstalk

As mentioned in the previous sections, crosstalk severely hinders the perceived depth and reduces the overall visual quality and viewer comfort. Hence it is imperative for the crosstalk levels to be mitigated or at least lowered to an unperceivable level. Almost all of the 3D displays using present hardware technologies have some amount of crosstalk present in them. Fortunately it is possible to calculate the amount of leakage between views at any position for any display. Usually a luminance meter is used to detect the amount of light leaked between views. Once the leakage levels for a display system are computed, image processing techniques can be used to preprocess the stereo images in such a way that results in mitigation or minimization of the perceived ghosting once they are displayed on any traditional 3D screen. Early attempts relied on subtracting from one view

image, the leaked image intensity from other perspective view before displaying. This technique might result in negative light intensities in low contrast areas of the images. Since negative light can not be produced by any display, the areas of the preprocessed image that has negative intensities are clamped to zero. Which means that the crosstalk in these areas is not fully subtracted and hence the ghosting still persists. One way to avoid such problem is to increase the overall image intensity by some value such that no negative values are obtained after crosstalk subtraction. This however comes at a cost of decreased average contrast of an image hence degrading the overall image quality. In the following sections we will review some of the contemporary techniques that are used in order to remove the crosstalk as well as maintaining the overall image quality.

3.3.1 Stereoscopic screens

Konard et al [12] proposed a crosstalk reduction technique that took the ghosting perception thresholds into consideration. For every possible combination of crosstalk level and the contrast of the scene, they experimentally computed the minimum level of light intensity that after subtraction would bring the ghosting to an undetectable level by a human observer. Ghosting was later minimized efficiently by storing and using these values from a lookup table. In order to avoid the negative light intensity values after crosstalk subtraction, they proposed to increase all the pixel values by the maximum negative intensity obtained hence reducing the overall image contrast. Limpcomb and Wooten [17] took the specially non-uniform nature of crosstalk in the display into consideration and proposed a technique that consisted of dividing the screen into 16 horizontal bands. The crosstalk was evaluated for each of these bands followed by the crosstalk subtraction in the images accordingly. The problem with this technique is that the non uniformity of the crosstalk level between and across the bands is continuous in nature which is why it resulted in over and under subtraction of crosstalk between bands that was still perceivable by the viewers. Another problem is that all of the above mentioned techniques assumes static scenes and hence ignore the temporal aspects.

In a time sequential displays, crosstalk is induced not only by the view image from the opposite aspect (i.e. left and right view) but also from the views in the previous frame. Smit et al [21] took this phenomenon into consideration as well. However, as the problem with every subtractive approach, this technique also suffered from the over subtraction. Sohn and Jung [22] proposed a technique that utilized disparity adjustments for a scene such that the least amount of uncorrectable crosstalk occurs in perceptually important regions. A crosstalk visibility estimator that simulated human sensitivity to luminance changes according to Webber's law was used in order to determine the areas in a scene where the spatio-temporal crosstalk was visible. In the second step, the

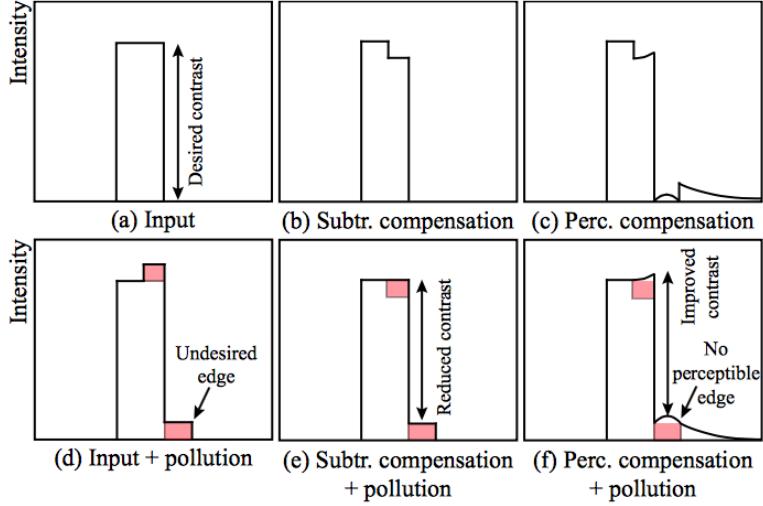


FIGURE 3.3: (a) Input image. (b) Subtractive compensation. (c) CSF weighed compensation. (d-f) Observed images [26].

global disparities in the scene were changed (shifting the zero plane) and the amount of perceptible uncorrectable crosstalk was computed using the crosstalk visibility estimator for every step. The global disparity shift that yielded the lowest amount of uncorrectable visually important crosstalk was chosen for displaying. In order to remove the already minimized uncorrectable crosstalk, the intensities in the scenes was locally increased in order to preserve as much dynamic range as possible.

Most recently, Baar and Poulakos et al [26] proposed a crosstalk reduction minimization that utilized the contrast sensitivity function CSF to steer the minimization in such a way that only perceptually important areas in a scene are corrected.

$$\operatorname{argmin}_x \|\lambda_l \cdot r\|^2, \quad s.t. \quad 0 \leq x \leq 1. \quad (3.2)$$

$$r = x + \phi(x) - \bar{x} \quad (3.3)$$

where λ_l is a diagonal matrix of the CSF spectral coefficients, x and \bar{x} denotes the original and the compensated images respectively and $\phi()$ denotes the non-linear function representing the crosstalk. The constraints on the optimization are necessary so that the minimized image values does not exceed the displayable range. Using the CSF helps spread the intensities of the uncorrectable crosstalk to the areas which are perceptually less important (as seen in figure 3.3). Also in this figure, it can be seen that the optimization introduces a cornsweet profile at the edges effectively improving the local contrast. One other factor that is important for the perception is visual masking i.e. the phenomenon where a signal is undetectable in presence of another signal with similar pattern. Baar and Poulakos further improved the optimization by incorporating into

equation 3.2 an additional weighing with visual masking operator.

$$\underset{x}{\operatorname{argmin}} \|\lambda_n \cdot \lambda_l \cdot r\|^2, \quad s.t. \quad 0 \leq x \leq 1. \quad (3.4)$$

Here λ_n is a visual masking binary operator that will help ignoring the optimization for non-perceivable areas of the ghosted image due to visual masking. This idea can also be used for optimization of light fields in automultiscopic displays.

3.3.2 Automultiscopic screens

As discussed in chapter 2, crosstalk in an automultiscopic screen is introduced by the neighboring views i.e. the horizontal neighbors of a pixel in case the lenticular sheet is not tilted as well as the vertical neighbors of the same view in case the lenticular sheet is tilted. This is because a tilted sheet can not cover a whole pixel of the underlying LCD panel completely. Due to this reason, eliminating crosstalk from automultiscopic displays is trickier than stereoscopic displays.

Barkowsky and Campisi [1] proposed that for each view of an automultiscopic display, the ghosting from within and across the views can be observed and composed as coefficients of a circulant Toeplitz matrix. Hence for an automultiscopic screen with 8 views, the perceived views can be modeled as

$$L_p = (E + A) \cdot L_d \quad (3.5)$$

where L_p and L_d are the vectors of displayed and perceived images in luminance domain, A is the circulant Toeplitz matrix approximating the crosstalk coefficients and E is 8x8 identity matrix. A generic reduction of crosstalk was derived from equation 3.5 for each channel

$$L_{rd} = (E + A)^{-1} \cdot L_{ri} \quad (3.6)$$

where L_{ri} is the gamma corrected intended luminance of the red channel. The implementation of this will generate luminance values that are beyond the range of the display (negative values) hence equation 3.6 can be modified in order to increase the average contrast of the image.

$$L_{rd} = (E + A)^{-1} \cdot \left(\frac{r_i \cdot (255 - \beta) + 255 \cdot \beta}{255^2} \right)^\gamma \quad (3.7)$$

here the term β denotes the level to which the black level must be shifted up. As expected, this will avoid getting any negative values for luminance but decrease the image contrast. The authors claimed that a certain level of negative values can be tolerated hence for

each view, the value of beta was computed iteratively that resulted in no more than a desired number of negative values.

Since the light leakage from neighboring left and right views can be considered as non energy preserving blurring, inverse filtering might be applied to the images in order to minimize the perceivable ghosting. Jain and Konard [10] derived a blurring filter that simulated the light leakage from the neighboring views, combined it with the anti-aliasing filter typically used in automultiscopic displays and used Weiner inverse filtering to preprocess the images in order to mitigate the crosstalk. Li [16] argued that light leakage from the same view due to incorrect sub-pixel approximation is more severe than light leakage from the neighboring views and hence proposed to use an appropriate filter that mimics the sub-pixel light leakage in order to be used for inverse filtering.

Generally, the simulation of crosstalk can be written as a system of equations $AX=B$ where A is the crosstalk coefficient matrix as described above, X is the set of intended images and B is the set of crosstalk added view images. Naively, one can compute crosstalk free X by solving $X = A^{-1}B$. However, for this to work, A should be a full rank matrix and even then the result will be unacceptable since the resulting preprocessed images will contain negative values. Wang and Hou [28] first proposed a mathematical model for computing the crosstalk coefficient matrix A only by using the parameters of the screen such as screen resolution, pixel dimensions, and the angle of the tilt of lenticular sheet. They argued that usually the crosstalk is measured experimentally which is always prone to errors. The mathematical model should provide a more reliable crosstalk estimation. Secondly, they proposed solving this linear system of equations in a constrained manner where the values of X can not exceed the range [0,255]. They named it as Box-Constrained Integer Least Square (BILS) solution.

$$\begin{aligned} \min_{X \in BOX_x} & ||B - AX||_2^2 \\ BOX_x = X & \in \mathbb{Z}^{w*h} : L \leq X \leq U \end{aligned} \tag{3.8}$$

where $||\cdot||_2$ denotes the Euclidean norm, w and h are the width and height of the screen resolution, and L and U are vectors of 0 and 1 respectively.

Chapter 4

Crosstalk Experiments

In this section we discuss the details of thorough experiments that we conducted in order to quantify how the crosstalk affects the perceived depth. For the sake of completeness, we performed various experiments on considerably complex (realistic looking) rendered images that consisted of stimuli of various widths and geometric complexities. The effect of crosstalk were observed for both stereoscopic and automultiscopic displays.

4.1 Motivation

Even though previously some work has been done by Tsirlin [24][23][25] in order to understand these effects, we **felt that the experiments were incomplete and needed some more thorough investigation..** The reason for that is that firstly Tsirlin's experiments were performed on monochromatic images where no other depth cue other than disparity was present. As mentioned in chapter 3, we conducted such a pilot experiment on ourselves (the author and one colleague) with a thin rectangular white bar on a black background using a similar Wheatstone setup and found that it took some getting used to to sense any depth of the stimulus even at high disparities. Even after spending some time on it, it was extremely hard and unreliable to guess the apparent distance of the stimulus from the screen in length units. This would mean that the naive test subjects would also have encountered the same problems. This observation is backed by the fact that the test subjects in [25] and [24] reported reduced depth of the stimuli even when no crosstalk was present. More reliable experiments would be ones where the test subjects report the actual theoretical depth in the base case i.e. when no crosstalk is present. Coupled with the fact that the test subjects were simply asked to report the perceived depth via a sliding bar representing zero or some maximum depth at extremes of the bar, it is likely that generated results could have been unreliable. The scenes of the natural

world usually have at least some other monocular cues e.g. proper light shading, texture gradients and defocus blur etc. Moreover, since one factor contributing to visibility of the ghosts is also how much it is separated from the object, wide objects at some disparity will exhibit less visible ghosting than thin stimuli.

It is commonly believed that the reason for degraded observed depth in the presence of crosstalk is due to the fact that the human visual system is confused in choosing the correct location (or disparity) of the correct match for an object in the corresponding binocular retinal image. To the best of our knowledge, it is yet unclear whether this HVS confusion is elevated or reduced when the geometric complexity of the object (stimulus) is increased. Which is why we thought it would be important to understand the relation of crosstalk on observed depth on stimuli of different widths and geometric complexities. Current studies suggests that for a certain crosstalk level and considerably smaller width of a desperate object, the extent of observed depth degradation increases as the disparity increase. This sounds counter-intuitive because for substantially high disparity of a thin object, the ghost will be completely separated and far away from the actual object itself. If the reason for degraded depth is actually the confusion of HVS in finding the proper match, then in such case the HVS should be able to find the proper match relatively easily because it is easy to distinguish between the ghost and the object as compared to the case of overlapping ghost. We hypothesized that the observed depth of any object with respect to the actual theoretical depth should degrade as long as some part of the ghost overlaps the object itself and the observed depth should improve when the ghost completely separates. Hence the graphs of figure 3.1b should be “U shaped”.

In stereoscopic displays, the arrangement of object-ghost pair is antisymmetric between the eyes **maybe make a diagram for this from the notebook**. This however is not the case with automultiscopic screens. As seen in figure 2.9, at least two of the neighboring views are responsible for adding crosstalk at any view point. Also, at the sweet spots, the number of views involved in light leakage from the left is always equal to the number of light leaking views from the right. Because the automultiscopic screen displays light fields, the arrangement of object-ghost tuple is symmetric in both eyes (at sweet spots). The HVS might react differently to this major difference. Again, to the best of our knowledge, until now there have been no studies that observed the effect of crosstalk on perceived depth in automultiscopic displays.

4.2 stimuli

Our stimuli consisted of an object (cylinder or a dragon) placed in front of a plane that had a light wooded texture. The reason for choosing a textured background was the HVS's efficiency in distinguishing between textures. This would make it easy for the observer to correctly guess the distance between the background and the foreground object. In order to make sure that our stimuli contains most of the basic monocular cues, we properly rendered them on computer using blender 2.73. The blender scene as shown in figure 4.1 consisted of a an object of interest placed at origin. The background plane with wooden texture was placed 3 meters (world units) behind the object parallel to the camera plane. In order to capture the shading effects on the object, the scene was lit with a light source (sun) that was placed 10 meters in front and 3 meters at height of the object. Finally the camera was 10 meters in front of the object. The stereo scene was generated by capturing the two images at some distance on each side parallel to the image plane. This distance represented the baseline of the cameras.

Our experiments were based on test subjects judging the observed distance between the cylinder and the textured plane. This could have been achieved by either moving the cylinder or by moving the background plane in space relative to the camera. This however would have changed the object or the texture size which could have been used as a cue by the observers. In order to avoid that, we simply generated a dense series of images with varying camera baselines and keeping the position of the background plane in lock with respect to the camera. This way, the background was always at zero disparity (i.e. the plane of focus) and the cylinder always had a crossed disparity meaning the cylinder always appeared to be in front of the plane by some distance. In order to avoid resizing, images were rendered at the resolution of 768x432. With the smallest baseline, the observed distance between the cylinder and the plane was negligible where as this distance appeared to be increasing as the baseline increased all while keeping the size of object, size of texture and the proximity of the object to the texture constant. For the objects we chose four cylinders of different radii and a dragon from Stanford's 3D scanning repository. The details of each of those objects can be found in table 4.1.

TABLE 4.1: Description of objects used as stimuli.

Object	Scene Dimensions (xyz)	Rendered Dimensions (arc min)
Cylinder(thin)	5cm x 2m x 5cm	18.9
Cylinder(medium)	10cm x 2m x 10cm	37.8
Cylinder(thick)	45cm x 2m x 45cm	56.7
Cylinder(thickest)	80cm x 2m x 80cm	75.6
Dragon	0.31m x 0.22m x 14.17cm	380 (max)

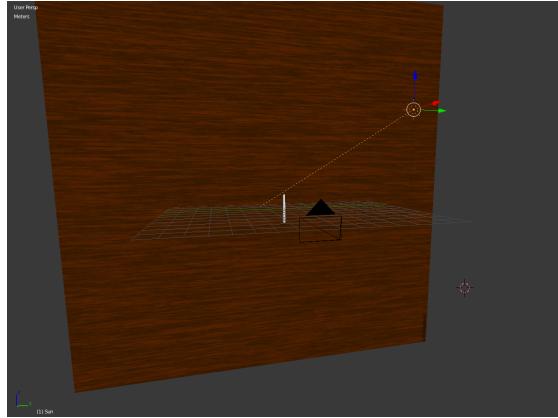


FIGURE 4.1: Typical arrangement of the scene rendered with blender.

4.2.1 Stereo and Automultiscopic stimuli

For the stereo experiments, captured the scene with the camera baseline starting from 0.002 meters till 0.12 meters with the step of 0.002 meters. This gave us sixty sets of stereo images where the theoretical depth of the object of interest ranged from 0.04 cm to 3.45 cm (0-10.5 arc mins in terms of crossed disparity) in front of the plane of focus. Figure 4.2 shows stereo images of one of the cylinder and the dragon. The step size was chosen small enough so that the transition from the minimum to the maximum depth for an object would seem continuous to the observer.

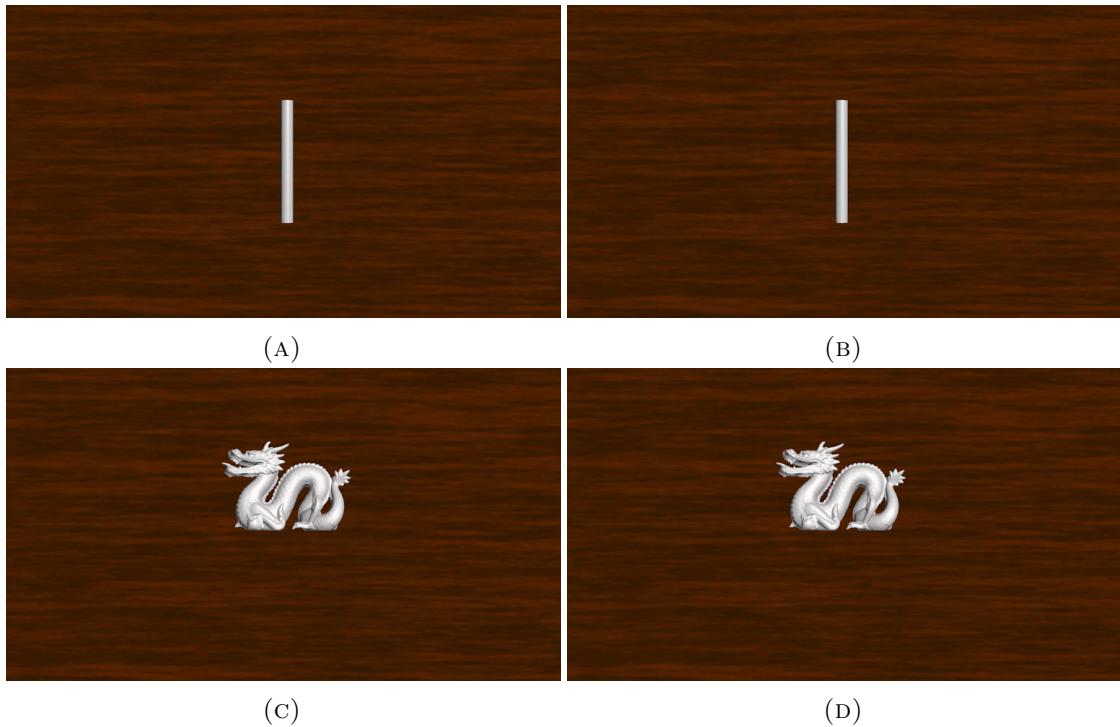


FIGURE 4.2: Stereo images of the cylinder of 5 cm radius and the dragon. The theoretical depth difference between the objects and the background is 3.44 cm. Viewer can cross-fuse to see in depth.

The images for automultiscopic experiments were rendered similarly. The only difference being that the range of baseline started from 0 until 0.24 meters. The reason for this is explained in the next section.

4.3 Apparatus and simulation procedure

The experiments were conducted on a commercial 47" SIMS2 HDR47E LCD display with a resolution of 1920x1080. The left and right half of the screen each with a resolution of 960x1080 were gated to the left and right eye using a custom built Wheatstone setup [36] that consisted of two mirrors M1 and M2 set at 45° angle with respect to the screen. The optical length from the eyes to the screen via mirrors M1 and M2 was measured at 87.3 cm. The whole setup was enclosed in a black box with an aperture through which the viewer could view the screen via mirrors M1. The display even though build for HDR viewing had a DVI plus mode for which the luminance measured with luminance meter via the aperture ranged from ?? to ?? cdm^{-2} . The DVI plus mode should (according to the documentation) mimic the traditional LCD display hence we chose to use this mode.

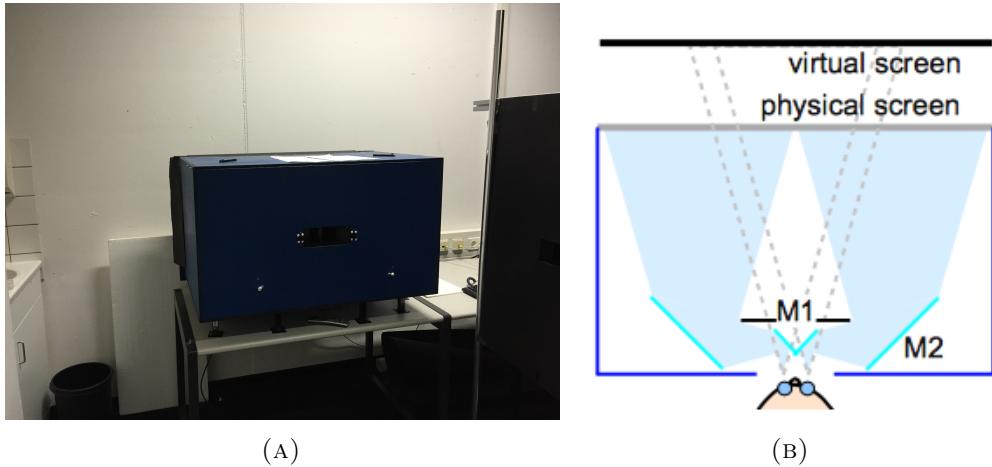


FIGURE 4.3: Our Wheatstone setup. Physical view frusta are shaded in light blue where as the virtual view frusta are depicted in dotted gray lines. The cyan lines represent the mirrors [27]

Since on an LCD panel, all the rgb channels equally and additively contribute to the crosstalk, we simulated the ghosted images simple by adding a percentage image of unintended view to the intended view image. For stereo, simple addition of a percentage of the right image into the left and vice versa sufficed. However, the automultiscopic case was a little tricky. First of all we simulated the view intensity profiles in figure 2.9 using Gaussians with $\sigma = 2$ and means located at the sweet spots of the automultiscopic displays (figure 4.4). To match the profiles in figure 2.9, the gaussians were upscaled such that the value 0.8 was attained at the mean. Using our simulated profiles, we found that

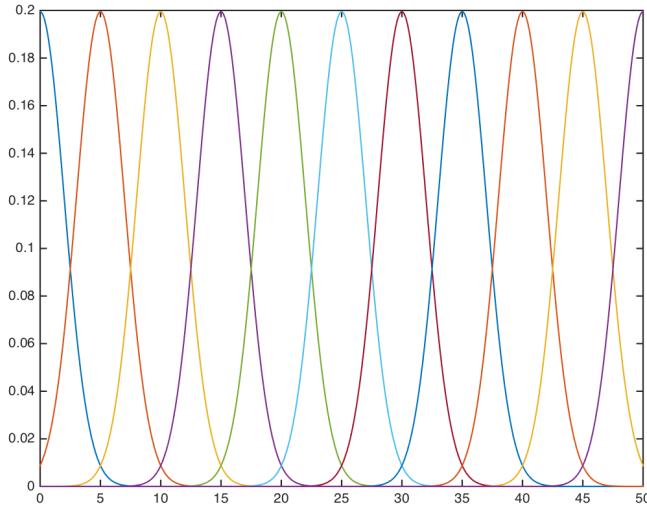


FIGURE 4.4: Luminance intensity profiles for an 11 view automultiscopic display simulated with Gaussians of $\sigma = 2$ centered at the sweet spots. X-axis denote the viewing position.

at any sweet spot viewing position, the amount of light leaked from views other than the two adjacent views was negligible. Hence in our simulation we only considered light leakage from the adjacent views. Considering that an automultiscopic screen displays light fields sampled at frequency $1/\delta_x$ (δ_x being the step size at which the images were captured along the camera baseline), the leaked light from a position ‘y’ to position ‘x’ can be modeled as

$$l(y, x) \simeq a_y(x) \cdot f(y) \quad (4.1)$$

Where $a_y(x)$ is the Gaussian(corresponding to location y) value at position ‘x’ and $f(y)$ is the light field image at position ‘y’. And the observe image “g” at any viewing position ‘x’ can be mathematically modeled as

$$g(x) \simeq \dots + l(x - 2\delta_x, x) + l(x - \delta_x, x) + l(x, x) + l(x + \delta_x, x) + l(x + 2\delta_x, x) + \dots \quad (4.2)$$

This would mean that the amount of ghost separation at any disparity of the object would be constant on either side. In order to keep the nature of the automultiscopic experiments similar to that of the stereo (where the ghost separation increase as the disparity increase), we changed the sampling rate δ_x with respect to the disparity of the object. i.e. For a disparity ‘2.d’, the observed left and right images can be written as

$$\begin{aligned} g(d)_{left} &\simeq l(2.d, d) + l(d, d) + l(0, d) \\ g(d)_{right} &\simeq l(-2.d, -d) + l(-d, -d) + l(0, -d) \end{aligned} \quad (4.3)$$

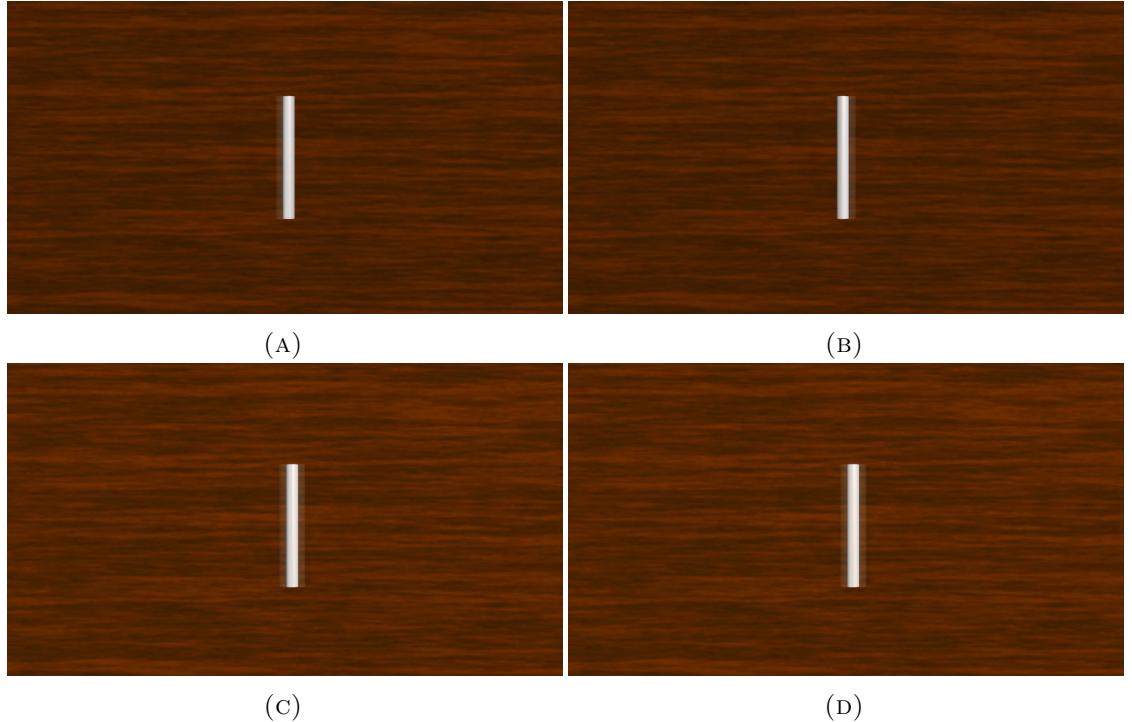


FIGURE 4.5: (a,b) Observed left and right stereo images with 14% crosstalk and crossed depth of 3.45 cm. (c,d) Same configuration for observed images on automultiscopic display)

4.4 Experiment procedure

4.4.1 Environment Setup

For our experiments, we subdivided the screen horizontally, the upper half where the test subjects would see the crosstalk added scene(stimuli) with some fixed depth of the object, and the lower half where the subjects were shown the same scene without any crosstalk. We will refer to the upper half of the screen as reference stimulus and the lower half as test stimulus. Also we will call the depth difference between the background (wooden plane at zero disparity) and the foreground object (at some crossed disparity) the depth of the object. As mentioned in section 4.2, the depths of the object in the presented stimuli ranged from 0.04 to 3.45 centimeters. The subjects could vary the depth in the test stimulus in the above mentioned range via left and right mouse buttons. Due to the dense sampling of the light field (small baseline distance change), the change in the depth appeared continuous, i.e. the viewers could not observe any jumps while changing it. Pressing the left mouse button for 6 seconds would change the depth of the object from 0.04 cm to 3.45 cm, and vice versa for the right click. During the experiment, the subjects were tasked with matching the depth in the test stimulus to the observed depth of the reference. Upon matching the depth, the subjects would register the answer using the center mouse click. Figure 4.6a shows the overall layout of the screen from a viewer's

perspective. To avoid the possibility of the subject matching the absolute depths of the objects rather than the depth difference between the background plane and the object, as required, we shifted the depth of the reference stimulus by 3.45 cm towards the viewer whereas the depth of the test stimulus was shift equally away from the viewer. Thus ensuring that the depths of the objects would never coincide, and hence the subjects would not be able to match the absolute object's depth. In addition, a nonious cross-hair representing the plane of focus was added at the bottom center of the screen. Figure 4.6b shows the top view of the visualized environment. The experiment environment was created using Psychtoolbox-3 package for Matlab.

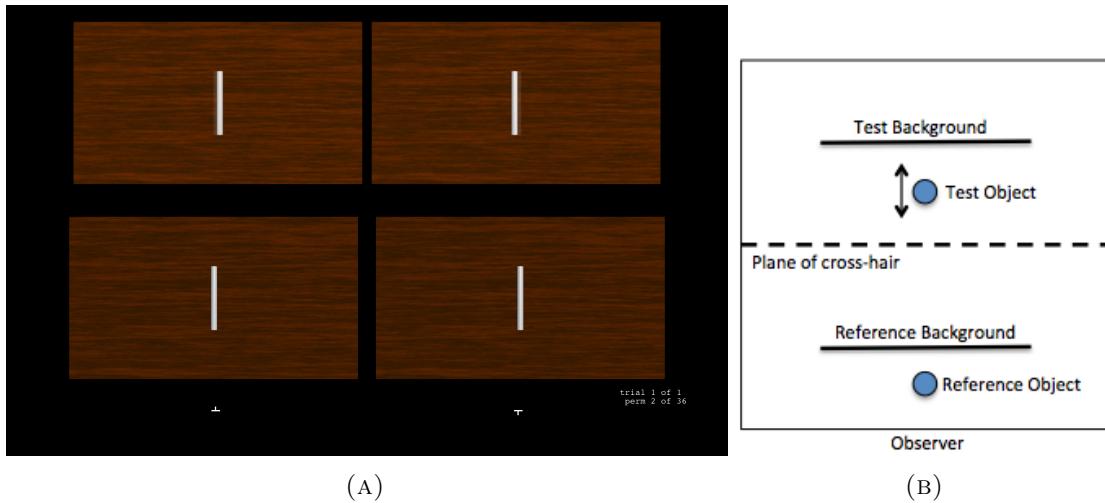


FIGURE 4.6: (A) Schematics of the complete display. Upper half of the screen shows the reference stimulus with 14% crosstalk. The bottom half shows the user controlled test stimulus free of crosstalk. (B) Layout of the experiment environment in terms of depth w.r.t. observer.

4.4.2 Subjects

Several paid test subjects and the author participated in the experiments. In order to ensure the subject's correctness of the stereo vision, they were first asked to identify the proximity of the test and reference stimuli with respect to the cross-hair. Also they were asked to identify the polarity of the change in depth of the test stimulus while the author changed it slightly in each direction. Table 4.2 shows the number of participants in each kind of experiments.

4.4.3 Experiment parameters

Four levels of crosstalk i.e. 0%, 3%, 7% and 14% and seven levels of depths (crossed disparity) i.e. 0.04, 0.73, 1.18, 1.53, 1.75, 2.76 and 3.44 centimeters were chosen to be

TABLE 4.2: Description of the number of subjects that participated in each experiment.

Object	Stereo	Automultiscopic
Cylinder(thin)	11	13
Cylinder(medium)	11	11
Cylinder(think)	7	13
Cylinder(thickest)	8	13
Dragon	13	13

tested. We neglected any level of crosstalk greater than 14% because in our pilot experiments we noticed that any greater crosstalk level almost always resulted in matching of the stimulus with the ghost resulting in total loss of depth. We couldn't find any commercial stereo display where the crosstalk levels were that high. Usually they are below 10%. During the experiment, each subject was asked to match the observed depths for all possible combinations i.e 28 trials (4 crosstalk levels \times 7 depth levels) in total for each kind of stimulus. Trials for stereoscopic and automultiscopic cases were conducted separately.

4.5 Results

In the following section, median data for all the observers along with the standard error for each crosstalk level (figure 4.7 to ??) are shown. Individual lines in the graphs denote the different objects i.e. cylinders of all widths and the dragon as mentioned in table 4.1. The axis defines the actual and the observed theoretical disparity-defined depths. Ideally, all the graphs should be diagonally coinciding lines indicating no effect of crosstalk on perceived depth. Even though generally it is not the case, it can be observed that in the base case (no crosstalk), all the graphs (for all objects) almost approximates a diagonal line for both stereo and automultiscopic experiments. This is an improvement over [25] meaning that the reported amounts of depth degradation for different cases would be more reliable.

4.5.1 Stereo

It can be seen in figure 4.7 that in absence of crosstalk, the observers mostly perceived the depths correctly. A slight overestimation of depth in case of the smallest depth (0.04 cm) can be seen for the thickest cylinder (width = 36 arc min). Given the fact that the user controlled depth variation of test stimulus was continuous, it is reasonable to

assume that it would be quite unlikely for the observers to exactly match the depths. Hence the slight overestimation of depth can be considered as an observer approximation error. The same however could not be straightforwardly said about the underestimation for the dragon at 2.76 cm depth which is mapped to approximately 2 cm observed depth. But since the next greater depth shows no underestimation, we can safely assume it to be a **human error**.

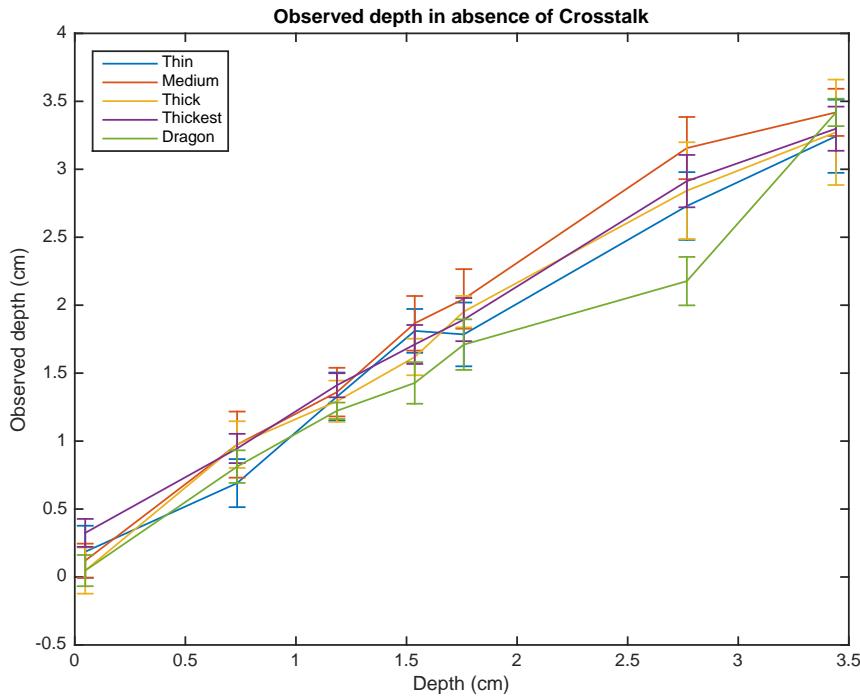


FIGURE 4.7: Abscissa shows the observed depth when no crosstalk is present. The error bars indicate ± 1 standard error.

When the crosstalk is increased to 3% (figure 4.8), it is clear that the observed depth of thin(18.9 arc min) cylinder starts degrading at depths greater than 1.75 cm. The angular disparity at this depth is 5.35 arc min which would give the ghost separation of 28%. A slight overestimation of the 2.76 cm depth for cylinder (75.6 arc min) can be considered as approximation error. The reason for this again is that the next greater depth is observed without any degradation. We think it would be reasonable to consider this as a human approximation error because the HVS probably does not get confused for some disparity and then behaves without any error for the following larger disparities. I.e. once the observed depth starts degrading at some disparity, provided all the other conditions are kept constant, it should keep on degrading for all larger disparities as well.

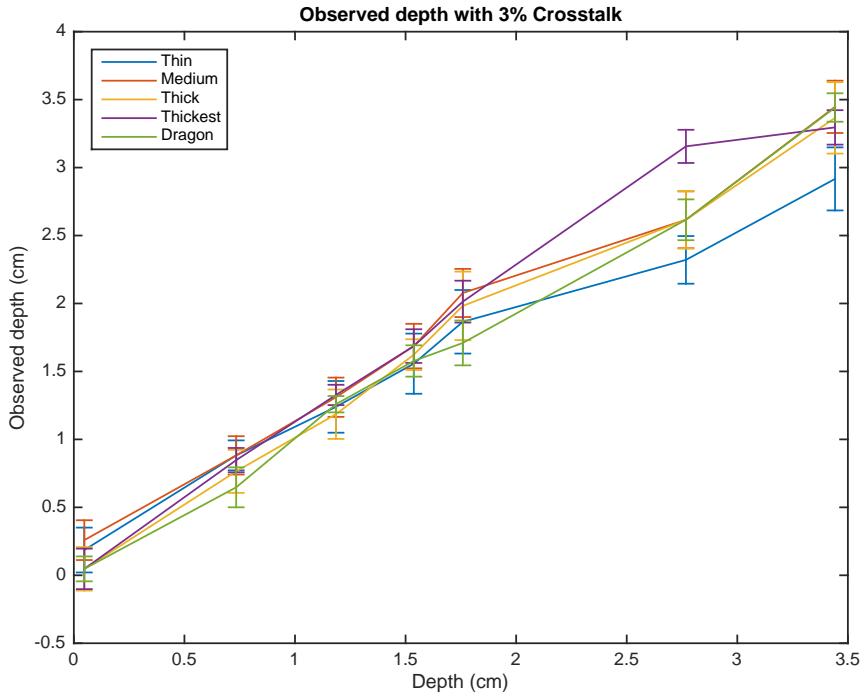


FIGURE 4.8: Abscissa shows the observed depth when 3% crosstalk is present. The error bars indicate ± 1 standard error.

Substantial effects on the observed depth starts appearing once the crosstalk level is increased to 7% 4.9. The cylinders of all widths show reduced observed depth. The reduction is most severe for the thin (18.9 arc min) cylinder. The loss of observed depth appears to be lower as the width of the cylinder increases while the observed depth of the dragon seems to be unaffected. One interesting point to observe is that for all the cylinders, the perceived depth starts degrading at the actual depths of 1.75 cm or higher. For the thin cylinder, the ghost is completely separated only at the maximum i.e. 10.5 disparity arc min. However the observed depth appears to be the same for the maximum and the second maximum i.e. 8.4 arc min disparity. *why*. Also it should be noted that the graph for the thin cylinder shows signs of degradation even at actual depth of 1.13 cm. The ghost separation at this point is ??*why also make a table of ghost separation*

Observed depth is severely affected for all the object once the crosstalk reaches 14% 4.10. The thin cylinder again shows signs of degradation starting at the actual depth of 1.13 cm where as the observed depths of all the other objects starts deteriorating at the theoretical depth of 1.76 cm. The pattern of wider objects showing less depth deterioration compared to thin objects is still observed. However, with such extreme crosstalk level, even the observed depth of the dragon is reported to be substantially affected.

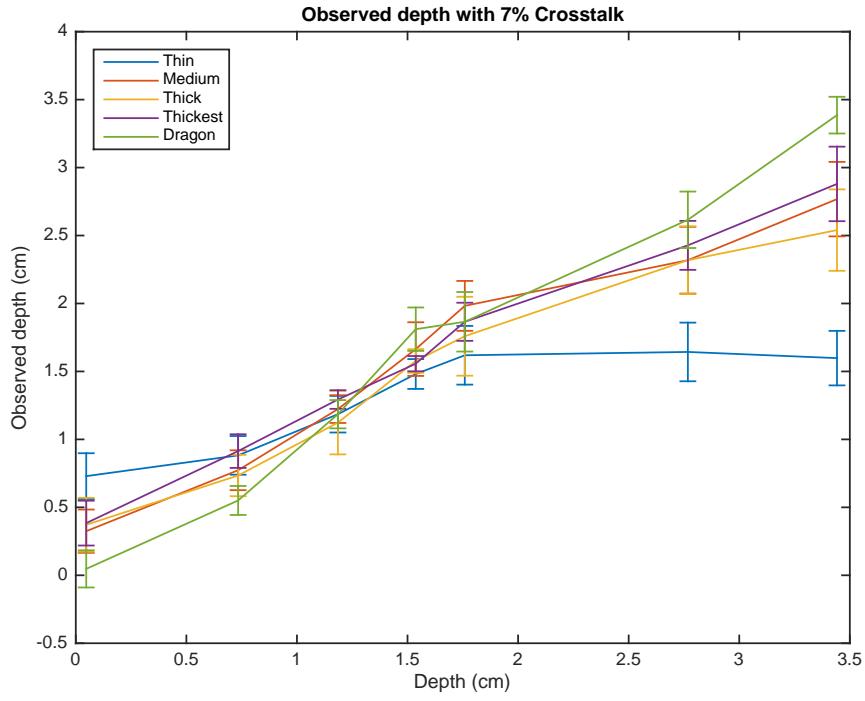


FIGURE 4.9: Abscissa shows the observed depth when 7% crosstalk is present. The error bars indicate ± 1 standard error.

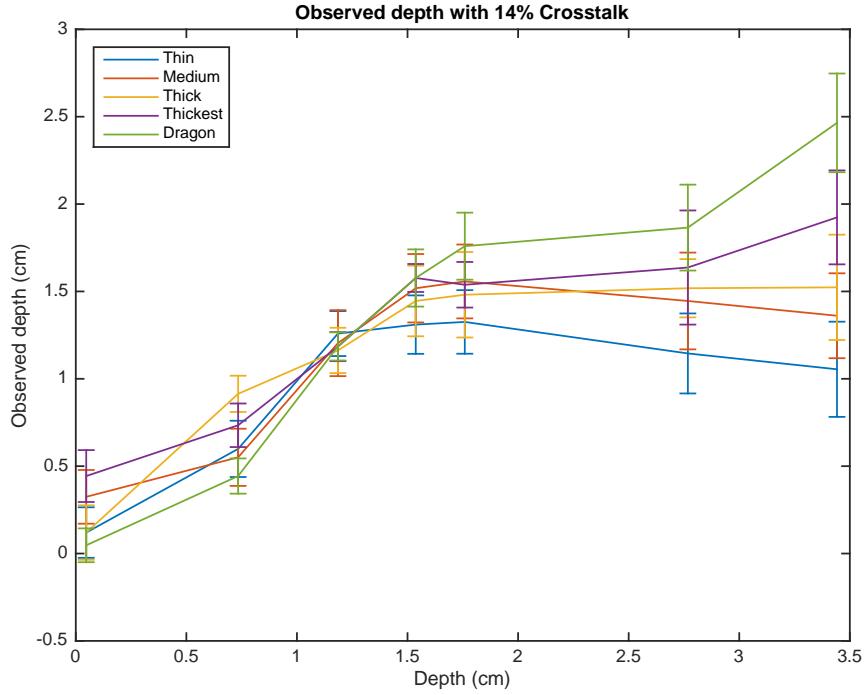


FIGURE 4.10: Abscissa shows the observed depth when 14% crosstalk is present. The error bars indicate ± 1 standard error.

4.5.2 Automultiscopic

Figure 4.11 shows the pattern of the observed depth in the base case. It appears that the observed depth for the dragon is slightly overestimated at the actual depth of 2.76 cm. At the same instance, the observed depth of the thick cylinder is underestimated. These exceptional cases can be considered as a **human error** firstly because the next greater depth is observed without any error and secondly because this case is exactly the same as the base case of the stereo experiments.

We notice that the crosstalk has no effect on the perceived depth when the crosstalk level is raised to 3% (figure 4.12). This is because for each of the perceived depth, the base case observed depth is in the range of the standard error [refer to the residual](#). This is different than the stereoscopic scenario where we observed some minute depth reduction for the thin cylinder. Increasing the crosstalk to 7% (figure 4.13) however shows signs of degraded depth for the medium (37.8 arc min) cylinder at actual depths of 2.76 and 3.44 cm. Meanwhile all the other object show no evidence of degraded depth even though the crosstalk level at 7% is higher than what we usually get from a conventional automultiscopic display [38].

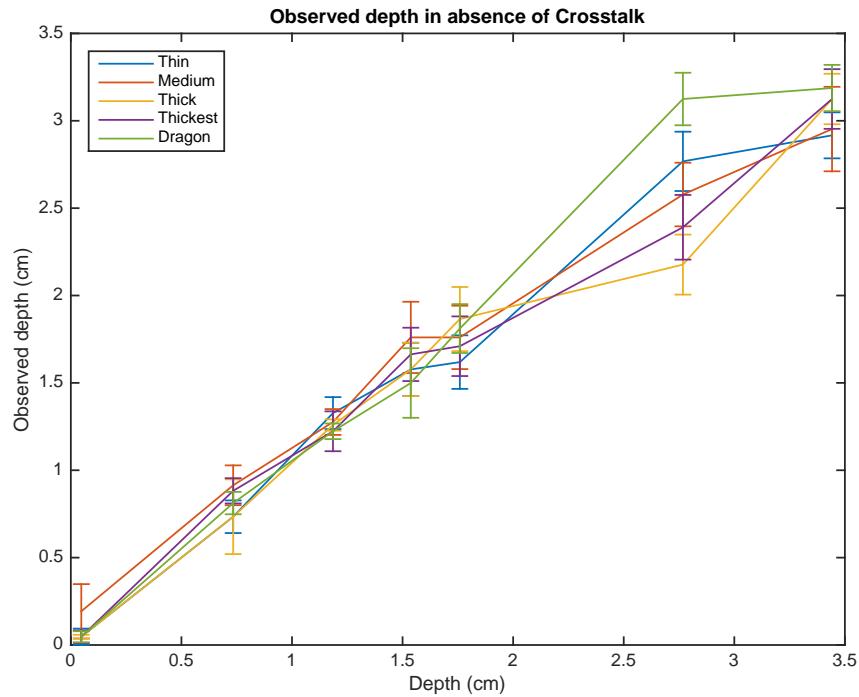


FIGURE 4.11: Abscissa shows the observed depth when no crosstalk is present. The error bars indicate ± 1 standard error.

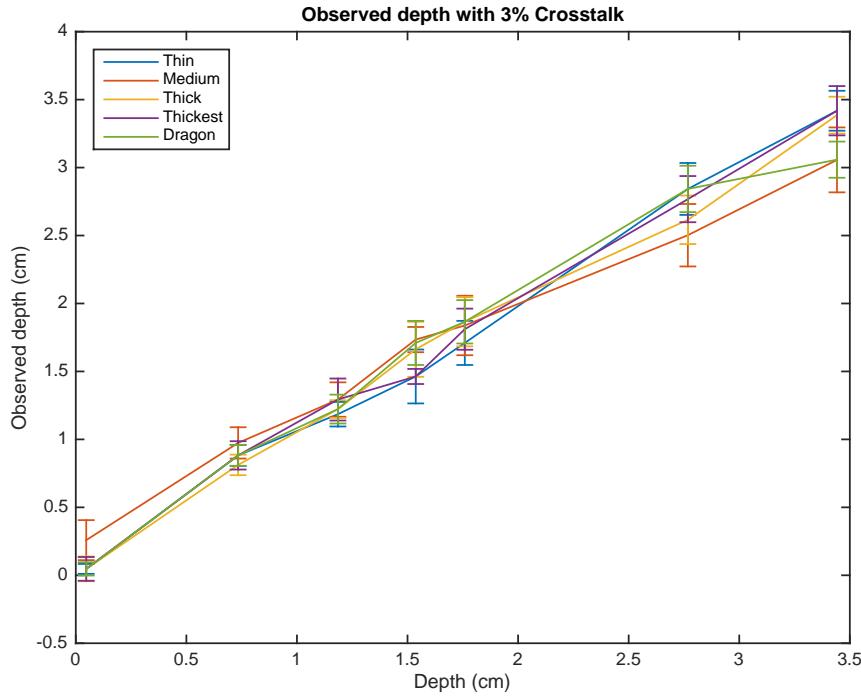


FIGURE 4.12: Abscissa shows the observed depth when 3% crosstalk is present. The error bars indicate ± 1 standard error.

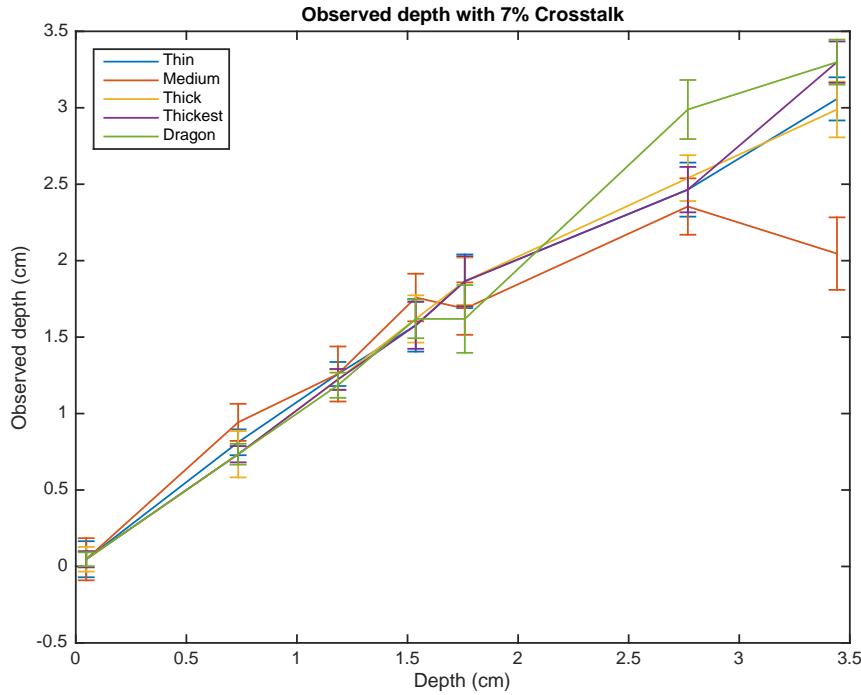


FIGURE 4.13: Abscissa shows the observed depth when 7% crosstalk is present. The error bars indicate ± 1 standard error.

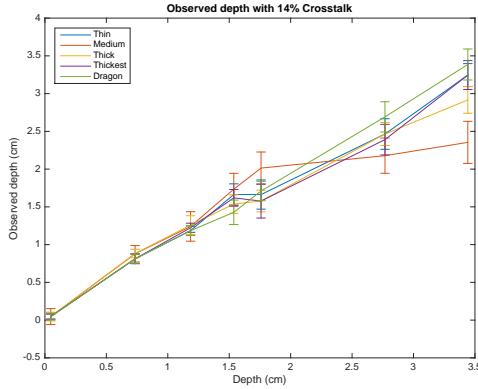


FIGURE 4.14: Abscissa shows the observed depth when 14% crosstalk is present. The error bars indicate ± 1 standard error.

Interestingly, increasing the crosstalk level to 14% also shows that for all objects (except medium cylinder) the perceived depth is not different than the depth observed in absence of crosstalk [refer to the residual plot](#). It is not clear why only the medium cylinder shows depth degradation in this case. However, based on the results it is clear that the effect of crosstalk on the perceived depth is significantly lower (or negligible) in the automultiscopic environment. Possible explanations for all these behaviors can be found in the next section. [Show the residual plots as well. This will better help understand the difference from base case](#)

4.6 Discussion

4.6.1 Stereo

In these experiments, we found that for the stereoscopic case, crosstalk has a substantial degrading effect on the magnitude of perceived depth. I.e. the perceived depth magnitude relative to the 0% crosstalk base case decreases as the crosstalk level increase. Moreover, for a fixed value of crosstalk, the degradation effect seems to be more pronounced as the disparity increases. This effect is stronger on the thin objects as compared to the wider ones. One of our initial hypothesis suggesting that the perceived depth magnitude might not be degraded once the ghost and the object separates completely was also proven to be wrong as the results clearly shows degradation even in those cases. In order to justify these results, we have to delve into the theories regarding how the HVS extracts depth from disparity.

There is evidence to suggest that the HVS uses the cross-correlation between horizontally displaced patches on the two retinal images to obtain the disparity of objects.[6][11].

The disparity, once the cross-correlation is performed is extracted by locating the peaks in the resultant correlation profiles [5]. It is easy for the HVS to identify sharp clear peaks compared to broad noisy ones as shown in figure 3.2. Since adding crosstalk additively to an image effectively reduce the global contrast and severely reduces the local contrast around object, it is obvious that HVS will have difficulty in resolving the proper disparity hence the depth degradation. Also it is believed that the patches chosen for inter-ocular cross-correlation are two dimensional isotropic Gaussians[6] called the Gaussian windows. It is not clear what the size (constant or variable) of those windows is.

If the HVS could somehow match the patch containing the ghost-object pair in one retinal image to the other, then according to windowed cross-correlation theory disparity computed would either be zero or the actual disparity without any degradation. However, we think that the HVS in case of stereo only uses the object-containing patch in one retinal image to obtain the horizontal disparity based on correlation with the other image. One of the reason for this is that HVS has a certain limitation and it can not fuse two objects together if the disparity gradient (defined as the ratio of disparity difference between two objects and their cyclopean angular separation) is greater than 1-1.5 [8] [11]. In case of stereo where the objects in both images has a crossed disparity, their ghosts have an uncrossed and equal disparity relative to the plane of focus. This in terms of geometry is only possible if the ghost is located exactly behind the object (similar to the double nail illusion as illustrated in [25] [14]) making the disparity gradient ∞ . In such cases, the stimulus with higher luminance (the actual object) is fused leaving the ghost in diplopia state. The other reason is that the HVS also takes into consideration the polarity of the luminance changes between patches in order to find a correct match. This means that an object who's left side is black and right side is white will not be matched to the object in the other retinal image who's left side is white and right side is black [8]. In case of stereoscopy with added crosstalk, the polarity of the ghost-object luminance change in one retinal image is the opposite of the other. Hence it is reasonable to assume that a patch that only contains the object of interest from one retinal image is chosen to compute the horizontal interocular cross-correlation with the other. We tried simulating the disparity estimation via interocular cross-correlation using the model proposed in [6] and found that the crosstalk had no effect of the computed disparity. **show the diagram of cross-correlation profile. and also mark the different slopes and one peak in case of overlapping ghost..**

For the x, y position of an object in one of the stereo image, the ghost in the other image is present at the exact same location while the actual object is located at some horizontal disparity ‘d’. Computing the cross-correlation in this case would result in two peaks i.e one at zero disparity and the other at disparity ‘d’. Hence the HVS might apply some averaging in order to obtain a disparity. This however is only possible when

the disparity is large enough to separate the ghost from the object completely. As seen in figure [The diagram above](#), this is not the case when the ghost is not fully separated from the object. In this case the correlation will result in one peak. Considering the correlation profile, we observe that there is difference between the slope around zero disparity (location of the ghost) and the actual disparity ‘d’. ?? performed experiments that suggested that the HVS also uses the first derivative of luminance in order to find matching portions of stereo images. In that case the HVS can still isolate two distinct peaks in the cross-correlation profile where one peak results at zero disparity due to ghost and the other at disparity ‘d’. Since the HVS gives preference to lower disparities [14], if the averaging is performed based on the heights and the distances (relative to the zero disparity) of the peaks, then this might explain the loss of perceived depth magnitude that is proportional to the crosstalk level. This would also explain why at some crosstalk level threshold (16% in our experiments), the ghosts are matched to the original objects and the viewer perceive two copies of the object side by side (double nail illusion) located at the plane of focus. However, this will still not explain why wider objects result in lower loss of perceived depth magnitude as compared to the thin objects.

In our experiment results, we also noticed that the perceived depth magnitude remains unaffected for some small disparities even when the crosstalk level is at 14%. For 3% crosstalk, this threshold is the angular disparity of 5.25 arc min (1.75 cm depth) where as for the crosstalk level of 7% and 14% these thresholds seems to be 4.2 arc min (1.5 cm) and 3.15 arc min (1.18 cm). This suggests that the HVS probably does not average the disparities at locations of interocular cross-correlation peaks as that would have resulted in a degraded perceived depth at every disparity. Our proposed modified windows interocular cross-correlation model explained in chapter 5 might explain these results.

Our results are consistent with the current literature and shows a clear degrading effect on the perceived depth that increases with the increase of crosstalk level and the decrease of object’s width. Kooi and Toet [13] showed that as low as 5% crosstalk can result in reduced visual comfort. Considering that and based on our results, we recommend that the crosstalk levels in stereoscopic 3D displays should not exceed more than 3%. At this level we found that the perceived depth is not significantly degraded for all the objects.

4.6.2 Automultiscopic

Even though, at first impression it might seem like the crosstalk should have a greater effect on the observed depth in automultiscopic scenes for a simple reason that the number of ghosts per image are greater (one on each side of the object as opposed to only one ghost in case of stereo). Our results indicate that there was no substantial effect of crosstalk on the perceived depth magnitude in automultiscopic environment. We believe that the HVS in case of automultiscopic environment matches the patches containing the tuple of left-ghost, object and right-ghost in one retinal image to the similarly appearing patch in the other one. One reason for this as mentioned in the previous section is that the HVS considers the polarity of luminance changes in the object. The tuples in both the retinal images have the same luminance profiles. The other reason is that matching the tuples containing patching in this way will not violate any disparity gradient which was the case with the ghosts in stereoscopic environment.

TABLE 4.3: Description of the of ghosts and objects seen in an automultiscopic environment according to equation 4.3

Image	Stimulus	Location(disparity)
Left Eye Image	Left ghost	0
	Object	$\frac{d}{2}$
	Right ghost	$2 \times \frac{d}{2}$
Right Eye Image	Left ghost	$2 \times \frac{-d}{2}$
	Object	$\frac{d}{2}$
	Right ghost	0

It can be seen from table 4.3 that the tuple in the left eye is located at a disparity ‘d’ in the right eye image. And since matching tuple containing patches will not cause any confusion, it is clear why the viewers were able to report the proper depths (in most cases) for the objects despite of raising the crosstalk level to 14%. Based on our results we can conclude that crosstalk does not have any significant effect on the observed depth in automultiscopic displays. However, since the number of ghosts are double the amount found in stereoscopic screens, we can predict that crosstalk in automultiscopic screen will affect the viewers visual comfort to a greater extent. Our experiments simulated only for the sweet spot of an automultiscopic screens. It should be noted that even though amount of light leakage from neighboring views will change as the viewer moves away from the sweet spot, the pattern of the luminance changes throughout the objects will remain the same. Hence the observed depths of the objects will not be affected. The observed geometry of the objects however might change (depending on the scene) due to crosstalk if the viewer is not located in the sweet spots.

Given the fact that the amount of crosstalk changes as the viewer moves his/her viewing position, and the fact that crosstalk might change the observed geometry of the objects in the scene while viewing from a non-sweet spot position, it is difficult to recommend a minimum level of crosstalk that ensures a pleasant and comfortable viewing experience. We know that as low as 5% of crosstalk in a stereoscopic screen is enough to result in visual discomfort. We can predict that this threshold would be much lower for an automultiscopic screen. However, further research must be carried out in order to provide such objective measurements.

Chapter 5

Applications

In the previous chapters we learned that other than viewer's discomfort, reduction of contrast, reduction of stereo acuity and reduction of overall image aesthetics, the crosstalk in stereoscopic screens also has a substantial effect on the observed depth of the desperate objects (i.e. the objects not at the plane of focus). The general rule is that the observed depth for any object not lying on the plane of focus will tend to fall back to the POF (loosing depth) as the crosstalk level increases or as the disparity of an object increases. The effect seemed to be more pronounced for objects with narrow width compared to the objects with comparatively wider width. The reason being that the ghost separation (which causes the confusion for HVS) for thin objects is larger for any given disparity. We also learned that contrary to our intuition, the crosstalk in an automultiscopic screen has little to no effect on the perceived depth for objects of any width for even the most extreme level of crosstalk (14%). The main reason why crosstalk did not affect the observed depth might be that in an automultiscopic case, there are two similar ghosts present on each side of the object in both retinal images. This makes the ghost-object combination in both eyes very similar and the HVS might consider them as the same object. Hence there is nothing to confuse the HVS in estimating the correct disparity between two retinal image patches.

We also learned that to the best of our knowledge, the current literature seems to agree with the theory that HVS resolves the estimated disparities of objects in a binocular scene by computing the cross-correlation of several patches located at different positions in between two perspective retinal images. Finally, we learned that in order to reduce the viewers crosstalk, most of the current state of the art techniques rely upon preprocessing the stereo images in such a way that when viewed on a stereoscopic or automultiscopic screen, the system crosstalk added images resembles the actual images. Most techniques subtract the pre-calculated system light intensity leakage between views

from the actual images in addition to using some perceptual measured in order to mask the ghosting that still persists due to the limited dynamic range of the screens.

Observed depth reduction due to crosstalk is a serious problem which might alter or degrade the artistic viewing experience for a scene. Just like we have image quality metric e.g. SSIM [29], MSE[33] or VDP[18] etc that are used to calculate the effects of noise in an image on its perception by a human observer, it would be useful if we have a quality metric that is able to predict the observed depth of objects of interest in a 3D scene based on the crosstalk level of the display along with the dimensions and disparity of the object. Once this prediction is available, the scene artists can then alter the theoretical depths of the objects in order to bring the observed depths as close to the original as possible. For this to work however, we should have a good understanding of how the HVS estimates the depth from disparity between two retinal images. Moreover, reducing the viewers crosstalk for any given display is also as important if not more for a better viewing experience. During our research, we learned that the most promising technique to achieve that used complex optimizations to be performed in order to pre-process the images[26]. It would be helpful if the similar effects can be achieved without the mentioned complex and time consuming optimizations.

In this chapter, we will look into a proposed modified HVS depth from disparity resolution model that provides good approximation (not ideal but promising) to the observed depths obtained from the experiment results discussed in the previous chapter. We will also propose two new crosstalk reduction techniques along with there pros/cons and results.

5.1 Observed depth prediction

Filippini et al [6] proposed a model that simulated the disparity estimation of the HVS via disparity. In short, this model computes the local cross-correlation that is defined by eq 5.1

$$c(\delta_x) = \frac{\sum_{(x,y) \in W_L} [(L(x,y) - \mu_L)(R(x - \delta_x, y) - \mu_R)]}{\sqrt{\sum_{(x,y) \in W_L} (L(x,y) - \mu_L)^2} \sqrt{\sum_{(x,y) \in W_R} (R(x - \delta_x, y) - \mu_R)^2}} \quad (5.1)$$

where

$$W_L = W_R = e^{-\left(\frac{x^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2}\right)} \quad (5.2)$$

are anisotropic Gaussian windows (patches) in the left and the right stereo images. The window W_L is fixed in one image while W_R is displaced horizontally while keeping the vertical position constant. For each displacement, $c(\delta_x)$ is computed that results in a

value of +1 if the patches are perfectly correlated or -1 if the patches have no correlation at all or a value in between +1 and -1. The ' δ_x ' for which the maximum cross-correlation is attained is considered to be matching pixel (or patch) in the right image w.r.t the left image. The process is repeated for all the pixels in the left image. This model was tested on random dot stereogram consisting of saw-toothed corrugation and the resulting computed disparities for each part of the stereogram matched the results obtained via experiments on human observers. The random dot stereograms used however were devoid of any crosstalk.

We tested the same model on our stimuli (Chapter 4) and found that this model always resulted in the correct disparity of the objects between a stereo image pair. I.e the crosstalk had no effect on the estimated disparity. This did not match the results we obtained for the human observers. The reason being that even though the areas on the images where the ghosts are present will show some positive correlation, the maximum correlation is always obtained at the location where the actual object is located.

Hence it is clear that the HVS does not simply estimate the depth from disparity via local cross-correlation only and some kind of pre-processing or post-processing is performed. It is believed that the HVS, while matching patches between retinal images, prefers lower disparity over higher disparity. This means that for any patch in say left eye retinal image if the HVS finds two matching patches in the right image, it will choose the one that is closest to the location of the left image patch. Recall from the previous chapter that in case of stereo displays with some level of crosstalk, for a desperate object in the left image, the same object is located at some horizontal disparity 'd' whereas the ghost is located exactly at zero disparity (same location as the location of the object in the left image). Computing a cross-correlation in this case would result in some positive correlation because of the ghost at zero disparity and a highly positive correlation at disparity 'd'. To match the results from human observers, the disparity estimator model should

- Select a disparity 'd' based on where the cross-correlation results in a maximum value.
- Estimated disparity 'd' should shift towards zero disparity gradually as the actual disparity increases some threshold.
- Estimated disparity should be estimated as 0 if the crosstalk level increases some threshold.

Hence we have to weigh the resulting cross-correlation profile for all disparities. We observe that weighing the said cross-correlation profile with a Gaussian centered at the

location of object in the left eye image fulfills the above mentioned requirements as seen in fig [insert the figure for](#) .

Chapter 6

Conclusion

6.1 Summary

6.2 Future Work

experiments with variable widths to see how the hvs coup with that. experiments where the disparity gradiant between two objects is greater than 1. TO check if the ghost diplopia is really the factor causing the depth degradation or it can be any object. mention the proposed optimizations for automultiscopic screens as well.

6.3 Open Questions

Bibliography

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