How can hyperspectral projection enhance chromostereoscopic perception?

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Abstract

Chromostereopsis is an optical illusion that allows 2D images to simulate depth based on color. For example, red is perceived to be closer than blue, when displayed on a black background. This effect is present because of the slight chromatic aberration caused by the eye lens, and it can be strengthened by the use of ChromaDepth® glasses. This research looks into how the chromostereoscopic effect can be enhanced by precisely controlling the used color spectra by simulating the effect with the use of stereo projection. It was concluded that hyper-spectral projection can yield a stronger chromostereoscopic effect and better depth resolution of the image, but its full potential is still limited by the visible spectrum of light.

1 Introduction

Chromostereopsis is an optical illusion in which colors are used to simulate depth in 2D images [1]. This effect has been used both in art, for example in the 1971 film UFOs by Lillian F. Schwartz [2, 3], in which she uses colors in order to create a depth effect to express artistic intent, and in scientific visualisation methods [4].

The chromostereoscopic effect can be made stronger with the help of special glasses, which use prism-like films as lenses to increase the chromatic aberration at the base of the effect. During this research, ChromaDepth® glasses were used which use prisms-like films in front of both of the eyes. These films diffract light, most light being diffracted towards the inside of the face, thus enhancing the chromostereoscopic effect [5].

The chromostereoscopic effect is created by colors, and because of this, it is also limited by the color gamut of the viewed media. In the case of common displays and projectors, this limitation is caused by the limited array of colors RGB LED's are capable of outputting, thus creating interest in the interaction between ChromaDepth® and projections capable of showing a wider range of color.

Alongside the ChromaDepth® glasses, during this research a 3D projector was used, in tandem with a pair of active shutter 3D glasses. The projector displayed two images on top of each other (internally represented as a left and right image), on complementary time intervals. The active shutter 3D glasses synchronize with the projector to show a 60 frames per second stream to only one eye separately, i.e. the left eye will only see the left image and the right eye will only see the right image.

This paper presents how a wider array of colors can be simulated by the presented projector and glasses, and how the simulated results can be used to draw conclusions in regards to the influence a wider color gamut can have on viewing chromostereoscopic images. The simulation was done by spatially shifting the color primaries of the projected image, in order to enhance the depth effect, e.g., red pixels can be slightly shifted towards the direction the ChromaDepth® glasses will shift them, thus increasing the strength of the illusion. The 3D projector was used to display the shifted images to each eye individually, with their corresponding shift. These images were viewed while wearing both the active shutter glasses and the ChromaDepth® glasses.

The simulation was used in a small scale user study to find a spatial shift that can be attributed to the strongest depth perception of the image. The experiment consisted of asking participants to repeatedly choose between pairs of images where the shift was applied with different intensities, starting from the same original. The participants had to choose the images which they considered to have a strong depth effect, that didn't compromise the viewing clarity of the image, i.e., without the disparity between the images perceived by each eye being strong enough to cause a blurry perception of the image.

The test results were aggregated to obtain the spatial shift value that was preferred by the participants. The shift value was then used to compute the wavelength of light that would produce an equivalent depth effect, and the relevance of the findings in regards to hyper-spectral projection was then discussed based on the calculated wavelength.

The paper is structured as follows: Section 2 will cover the background a reader should have to properly follow the content, together with works related to this one; Section 3 will describe the main experiment of the research and its results; Section 4 will discuss on a way to create the results simulated with that experiment via purely chromostereoscopic means; Section 5 will cover the ethical aspects that went into the research; Section 6 will be reserved for conclusions.

2 Background and related works

2.1 Background

Chromostereopsis is an optical effect that causes different colors to be perceived at a different distance in regards to the viewer[1]. While a similar effect is perceivable with only one eye, the term chromostereopsis is reserved for the effect caused by binocular vision. The effect is generally attributed to the chromatic aberration caused by our eye lens which refracts different wavelengths of light at different angles on our retina. Specifically, the longer wavelengths of light (e.g. red light) are refracted at a greater angle than the short wavelengths of light (e.g. blue light).

A previous article looked into how viewing of chromostereoscopic images can be enhanced by intensifying the chromatic aberration effect with the use of prisms in front of the eyes of the viewer [6]. The same article compares two different ways of diffracting the color spectrum to increase the chromatic aberration that causes chromostereopsis. The first setup consisted of glasses using prisms instead of lenses, meant to enhance depth. The second one used two prisms overlapping each other for every eye, one low dispersion prism and one high dispersion prism. While both options intensified chromatic aberration, the two prism setup was deemed superior, since this setup presented the viewers with an enhanced depth perception of the image, while resulting in a relatively low amount of side effects, such as visual disorientation. The described system allowed for tuning of the two prisms, in order to allow the user to set a depth level of the image. In the scope of the research presented in this paper, a pair of glasses that use non-adjustable prisms was used, a commercial product aimed at creating an improved perception of chromostereoscopic images: ChromaDepth® glasses [7]. The glasses make use of a special film constructed in a way which diffracts light with the help of a prism-like structure. The film shifts light towards the inner part of the face, with red light getting shifted the most, while blue light gets shifted the least (see Figure 1). This optical effect enhances the chromatic aberration already created by the lenses of our eyes, thus intensifying the chromostereoscopic effect. The windows of the ChromaDepth glasses are made out of a glazed grating, that is built in a specific manner that diffracts most light into the first order of diffracted light [5]. A visual representation of the grooving is present in Figure 2.

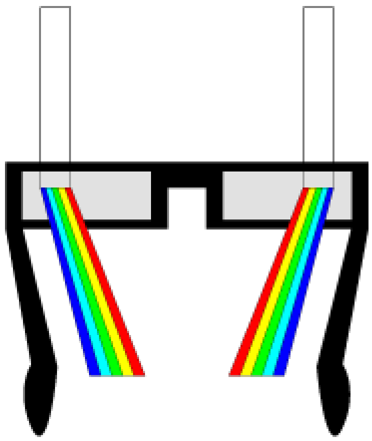


Figure 1: ChromaDepth® glasses.

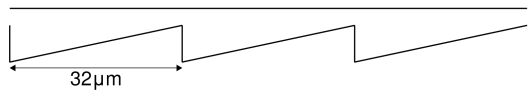


Figure 2: ChromaDepth glasses grooving.

Another method of displaying 3D images to a viewer is based on displaying two separate images to each eye, thus allowing the viewer to perceive depth caused by the differences in the two images. One way to achieve this is by using special 3D projectors with a synchronized pair of active shutter 3D glasses. The projector displays images for the left eye and right eye on top of each other, on complementing time intervals. The special glasses match the frame rate of the projection, allowing the images to only be perceived by the desired eye. This is achieved by having the lenses of the glasses contain a liquid crystal layer, which turns opaque when an electric current is passed through it, at a frequency at which the projector displays the images (see Figure 3).

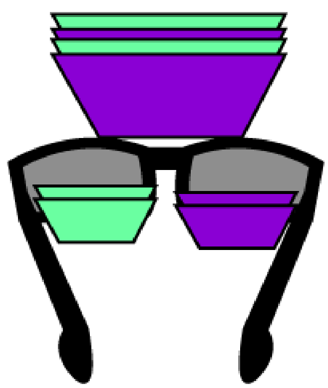


Figure 3: Active Shutter glasses.

2.2 Related Works

This research was done on chromostereoscopic images viewed as projected by an RGB projector. This implies that the projected image is displayed as an addition of three different light frequencies, each corresponding to one of the three color primaries of an RGB projector. While chromostereopsis can be observed on colors in the whole visible light spectrum, in the case of trichromatic displays, such as a projector, a better color encoding of depth has been found, which makes use of a red to white to blue gradient to encode the depth from close to far [4]. Furthermore, the images were displayed on a black background, as according to the same paper using other colors as a background requires a change in the gradient used for encoding. In consequence of these findings, this research was focused on displaying images encoded in a red to white to blue gradient(red being the closest and blue the furthest) on a black background. While the research was focused on the impact a wider range of color can have on chromostereoscopic perception, the images were projected by an RGB projector, so this color scheme was assumed as appropriate.

RGB projectors and displays are limited in the regards to the color gamut they can put out. This limitation is caused by the RGB primaries they use, each of which projects light corresponding to a range of wavelengths, compared to more specialized setups, such as laser projectors which have a clearer control over the wavelengths they project. This has caused interest in seeing how the spectra that the RGB primaries produce can be manipulated in order to obtain a better result in regards to fidelity of the color displayed and the range of colors that can be displayed [8, 9]. This paper will look into how wavelengths not in the color gamut of a projector can be simulated in the context of viewing chromostereoscopic images while wearing ChromaDepth®. The simulation will artificially intensify the refraction of the glasses by spatially shifting certain wavelengths of light projected by the RGB projector to cause the rays of light to be diffracted in a manner equivalent to different wavelengths of light. It will further be used in an experiment to derive which the shift that creates the strongest depth perception of the images without compromising on perception quality, based on the responses of study participants. Lastly, this shift will be used to compute an equivalent wavelength of light and discuss the implications of the found wavelength.

3 Experimental Setup and Results

A small scale case study has been performed on five bachelor students to decide on the intensity of the spatial shift that can be applied to the red component of chromostereoscopic images, in order to improve the quality of their depth perception. In the context of this experiment, the quality of the chromostereoscopic depth perception is defined by a strong depth effect that does not reduce the viewing clarity of the image (i.g, the image becomes too blurry to the viewer).

The hypothesis was that the wider range of color would be able to intensify the chromostereoscopic effect by displaying wavelengths of light that will cause objects to appear closer to the viewer. Alongside this, the experiment looked into simulating the wavelength of light at which the refraction would be too strong, thus causing an unclear perception of the viewed image.

The ChromaDepth® glasses diffract light at an angle depending on the wavelength of the light itself. Because of this, a wavelength of light that will be diffracted at a certain angle, can be simulated by a wavelength of light that will get diffracted less by shifting the image on the screen to compensate for the angle difference. In the case of ChromaDepth®, the image needs to be shifted separately, and oppositely, for each eye since the glasses diffract most of the light towards the inner side of the face [5]. While performing the experiment, a setup consisting of a pair of ChromaDepth® glasses, a 3D projector, and its afferent active shutter glasses was used to display pairs of chromostereoscopic images was used to display the test images to the test participants individually to each eye.

This section will describe the experimental setup that was used in order to draw a conclusion in relation to what amount of shifting is necessary to obtain the strongest depth effect that doesn't disregard the viewing experience of participants.

3.1 Experimental setup

For the experiment, an application was written that allows users to pick between two images. The application is made out of two parts, the first part creates the image set used for the choices, and the second part allows the users to make said choices.

In order to generate the images, the program receives an image meant to be viewed with ChromaDepth® glasses as input. A copy of the image is made and these images are then split into their three color primaries: red, green, and blue. The red component of the image was spatially shifted left in one copy and right in the other, the shift being a percentage of the width of the original image in the following domain:{-15%, -13%, -11%, -9%, -7%, -5%, -3%, -1%, 0%, 1%, 3%, 5%, 7%}. This array of intensity levels was further used to classify the images during the experiment, with negative values representing the shifts that were expected to create more depth in the image. This effect was meant to replicate the effect ChromaDepth® glasses have on the image, as they shift most of the red light stronger towards the inner part of the face.

The two resulting images were then projected on top of each other by a 3D projector and viewed with the both ChromaDepth® and active shutter glasses at the same time, alongside another overlapping pair of images, in order to be compared. The active shutter glasses served to show just the image corresponding to the effect meant for each eye out of each pair, and the ChromaDepth® glasses were further intensifying the effect. While the effect of ChromaDepth® glasses could have also been simulated with the shift in the image, this wasn't done because the goal of the case study was to serve as an experimental start to reasoning in regards to the wavelength of light that would produce the best results while viewed with the glasses, the glasses being the common denominator of the two situations. During the experiment, the viewers were seated approximately 3 meters away from the projection, with the projection size being $\sim$1.07 m by $\sim$0.6 m. This setup is also visually represented in Figure 4.

The pictures used can be divided into two categories: abstract images, where the only depth cue present was the color of the objects on the screen, and concrete images, which were color mapped to the red-white-blue scheme based on their depth, thus having both our perception and understanding of the images and the color map as depth cues. This division was made for the purpose of checking if other depth cues than color will influence the result. Examples of the two types of images can be seen in Figure 5.

3.2 Experiment

The experiment consisted of presenting test participants a randomly generated array of pairs of pictures with their goal being selecting the most qualitative one of the pair, with quality being defined as a strong depth effect that does not reduce the viewing clarity of the image. The lack of clarity would be caused by shifts in the image that would create too large of a disparity between the images perceived by the two eyes. The images in the pair differed from each other in terms of the intensity of the applied effect.

On each pair they had to choose which image had the strongest depth effect without giving up on a sharp perception of the image. In the background, the program holds the two effect intensity levels of the two displayed images, without showing them to the user.

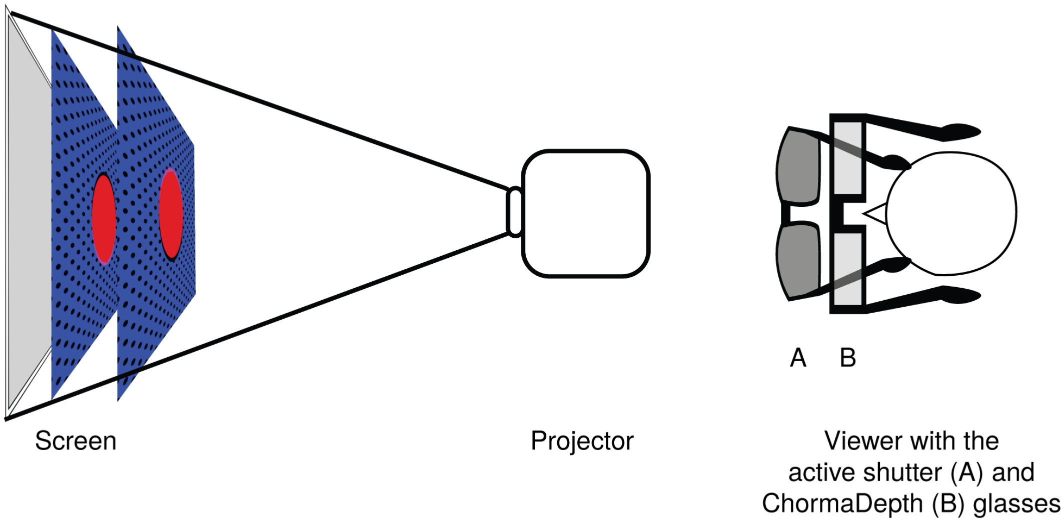
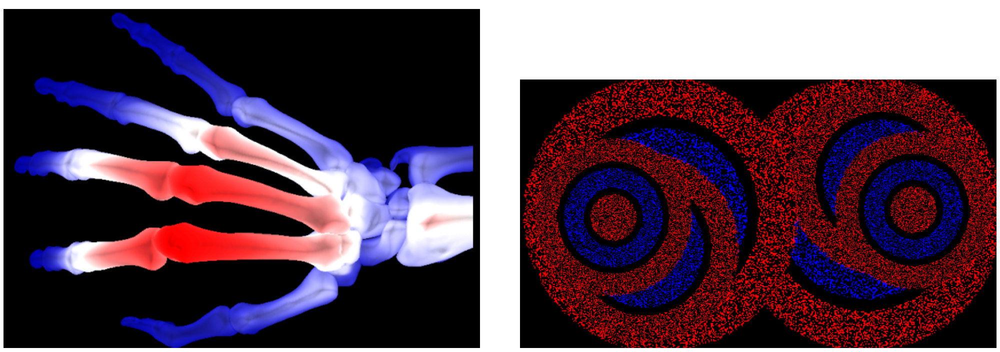


Figure 4: Projector setup used during the experiment.



((a)) Concrete Image
Source: [4]

((b)) Abstract Image
Source: [10]

Figure 5: Examples of images used during the experiment

After they made their choice, they are presented with a new pair of images and the cycle continues. After 300 repetitions, the cycle stops, and the results are stored in order to be further aggregated and displayed in a manner that allowed for further conclusions to be drawn from them. The following aspects of the experiment were recorded in terms of shift intensity: the preference of the participant on each choice, what said preference was chosen over, and if the images being displayed were either an abstract or a concrete image to check if a trend difference can be observed between the two types of images.

3.3 Results

The choices were counted in terms of the offset that was applied to the original image in the shown image, and the results are displayed as a ratio of the times the option was chosen out of the times it appeared as an option (i.e. times selected/times chosen). Figure 6 shows the choice distribution of the participant preferences. The plot shows a trend indicating a distribution centered around the value -5 (with -1 and 1 being outliers), which corresponds to a -5% shift in the red component of the image, which implies that this shift was the most preferred between the participants. When accounting for the distance between the viewer and the screen, and the size of the projection this shift is equivalent to an angle $\theta = -0.411°$.

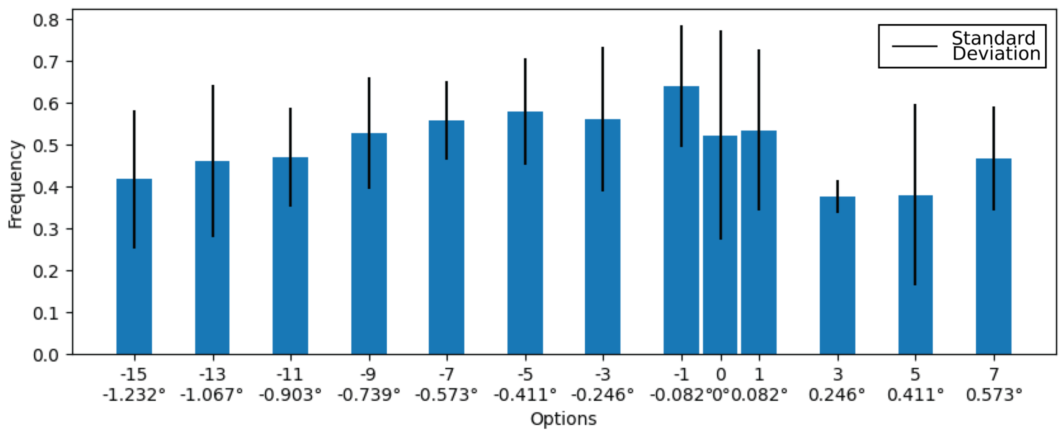


Figure 6: Offset preference of participants in both concrete and abstract images.

Some of the experiments also recorded the nature of the picture being compared. Figure 7 shows the preferences of the subjects with the results being separated into the two types of images. It can be seen that the two types of images peak around a similar value, and follow vaguely similar curves, so while not identical, the angle $\theta = -0.411°$ was used as a reasonable result for both types of images.

Another insight that can be obtained from Figure 6 is the slight increase in the preference on the right side of the effect intensity spectrum. The increase on the value 7, corresponding to an angle $\theta_1 = 0.573°$ can be caused by a reversal in the depth perception effect, i.e., blue color being perceived in front of red. One reason for this happening would be that, in order to avoid bias, the participants were not told what color should appear closer, thus an inverse effect could still get a relatively high score.

4 Achieving the simulated effect by purely chromostereoscopic means

Following the experimental results, which served to display the shifting effect in the image causing an optimal depth perception, effort was dedicated into researching if the observed results could be replicated by only using the ChromaDepth glasses and a normal projector, eliminating the need for a 3D projector and the attached 3D active shutter glasses. The way this was going to be achieved is by making use of the diffracting properties of the ChromaDepth® glasses, which refract different wavelengths of light colors at different angles, with the longest wavelengths being refracted the most. Since the visible spectrum of light

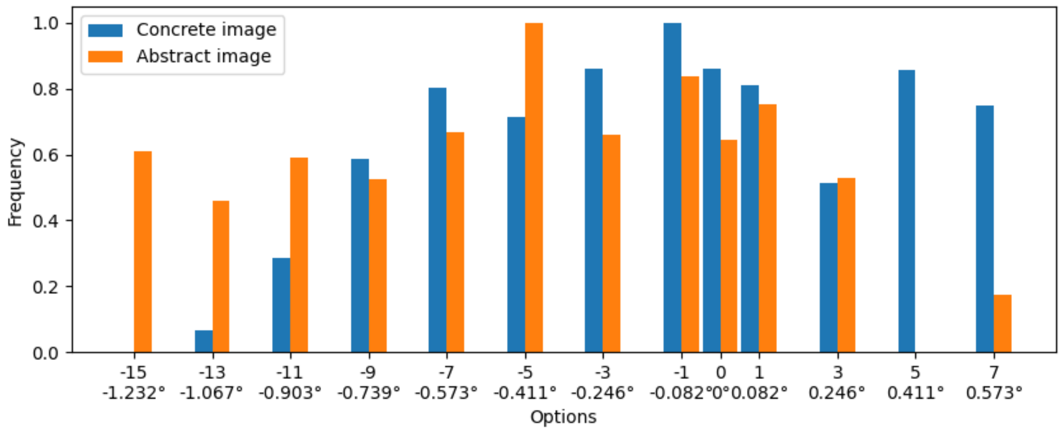


Figure 7: Offset preference of participants in each type of image images.

lies between 380 nm and 750 nm, and the peak wavelength of the red color of the RGB projector is 640 nm, this leaves us with around 100 nm of different wavelengths that could cause a stronger effect than the light displayed by the projector, without the need to shift the image.

From the experiment, we know that the found shift corresponds to a 2.14 cm shift in the actual image, which corresponds to a 0.411° angle, from now on angle α (see Figure 8). We then compute the refraction angle of a 640nm wavelength ray (called ray R1) coming in at angle α compared to the normal of the glasses the point at which this lands on the eye. We then assume another ray R2 of unknown wavelength, which is perpendicular to the glasses. The goal is to compute which wavelength corresponds to the angle of refraction which would have ray R2 intersect R1 on the retina, thus causing the same depth effect, without shifting the image. We assume that the glasses are placed ∼2.5 cm away from the eye lens, and that the eye depth of the eye in the sagittal plane (i.e., from front to back, from cornea to retina) is ∼2.5 cm [11], totalling to a ∼5 cm distance from the glasses to the retina. For the sake of this calculation, we also ignore the prismatic effect of the eye lens, as it is significantly weaker than the effect of the ChromaDepth glasses. The refracted rays, and other aspects of the following calculations, are represented in Figure 8.

The windows of the ChromaDepth glasses are made out of a glazed grating [5]. Because of this, when doing calculations related to the ways in which they refract light they can be treated as a diffraction grating with a grating period of 32 µm [12]. The angle at which they refract the light can be described by Equation (1) [13].

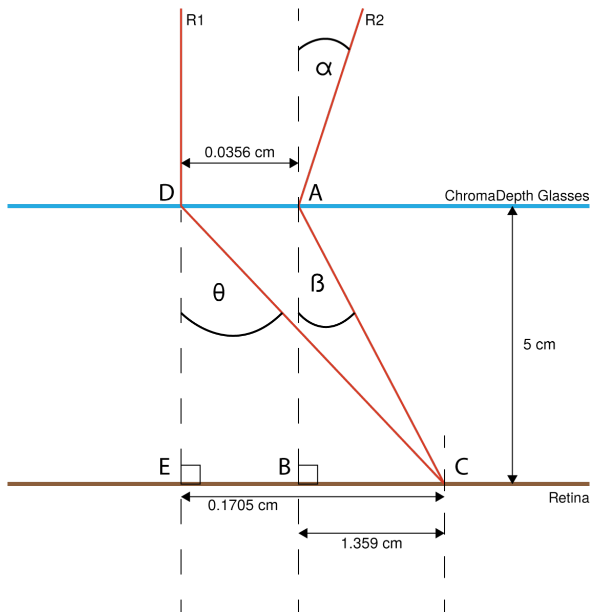


Figure 8: The environment.

$$d(sin\alpha - sin\beta) = m\lambda \quad (1)$$

where:

α = the incident angle
β = the diffraction angle
d = the grating period
λ = the wavelength of the ray
m = order of diffraction $(0, \pm 1, \pm 2, etc.)$

Replacing the known values for R2 in equation (1) we get the following:

$$32\,\mu\text{m} * (sin(0.411°) - sin\beta) = (-1) \cdot 640\,\text{nm}$$

$\Leftrightarrow$

$$-sin\beta = -640\,\text{nm}/32\,\mu\text{m} - sin(0.411°)$$

$\Leftrightarrow$

$$sin\beta = 0.02717$$

$\Leftrightarrow$

$$\beta = 1.55691°$$

After computing the angle β, we can then compute the lengths of the edges in the triangle ABC, with the β, $\angle ABC$ and length AB, yielding us the length of BC edge, $BC = 0.1359\,cm$. This gives us $EC = 0.1359 + 0.0356 = 0.1705\,cm$, which allows us to calculate the angle $\theta = 1.953°$. We can then replace these in Equation (1) in order to compute the wavelength of ray R1.

$$32\,\mu\mathrm{m} * (sin(0^\circ) - sin(1.953^\circ)) = (-1) \cdot \lambda$$

$\Leftrightarrow$

$$32\,\mu\mathrm{m} * -0.03407 = (-1) \cdot \lambda$$

$\Leftrightarrow$

$$\lambda = 1090.24\,\mathrm{nm}$$

The found wavelength is outside the visible spectrum of light by a significant margin (>200 nm). Two conclusions can be derived from this.

Considering both the experiment and the performed calculations the following findings can be derived. On one hand, a very strong effect cannot be a achieved by purely chromostereoscopic means, even while using hyper-spectral projections. The results of the experiment indicate that the wavelength of light that creates the strongest depth effect that still provides a sharp perception of the image lies outside of the spectrum of visible light. This can indicate that while displaying 3D images in this manner can be a useful technique in certain context, displaying stronger effects can be better achieved by other means, such as stereoscopic projection. On the other hand, while chromostereoscopy cannot create strong depth effects, it can help with displaying smoother depth in 3D images based on the fact that each wavelength of light will create an effect of a different intensity.

5 Responsible Research

5.1 Reproducible Research

Most of the reproductibility of the research lies in creating similar testing environments in which a similar target group can be evaluated. Both the environment and the target group has been described in order to allow other researchers to replicate the findings. One of the pressing concerns with this research is the small amount of participants that can lead to a sub-optimal sample of results. While the small sample size was still able to display a trend in the collected information, more information should be gathered in future research in order to verify these findings.

5.2 Ethical Research

During the experimental part of the research, human participants were included. This means that certain requirements imposed by the TU Delft Human Research Committee had to be followed in order make sure that participants were in no danger and that their data is used in a responsible. The participants had to read and sign an Informed Consent form, which detailed what the experiment entailed, what information was going to be stored and that they can withdraw from the experiment at any point during it, thus removing their data from the results. During the research, the only personal data stored was the name of the participants, for the sole reason of them being able to provide informed consent. All the other data was made up of their choices during the experiment and was stored in a way that could not be traced back to the participant itself.

6 Conclusions and Future Work

For this research we looked into how a wider spectrum of color can enhance the chromostereoscopic experience when viewing images. This was achieved by simulating a wider spectrum of color by the means of spatially shifting the image in order for the observed colors to be perceived equivalently to colors that cannot be output by a normal RGB projector. The experiment and research found out that the whole array of visible light wavelengths can be used when viewing chromostereoscopic images while wearing ChromaDepth glasses, with the wavelength that would yield the strongest depth effect being in the infrared spectrum of light. The experiment also indicated a trend that a stronger depth perception is preferable to what an RGB projector paired with a pair of ChromaDepth® glasses can display. Even so, a finer control over the used color spectra can aid in displaying different depth effects, as the experiment showed a different depth perception between the simulated wavelengths.

As for future work, the simulation nature of the presented experiment leaves space for experimenting with hyper-spectral projectors, or RGB projectors equipped with special filters that allow them to display a larger color gamut. These kind of experiments can give a better idea of how different colors are perceived, and allow for more experimentation in terms of what can be achieved while using them, for example a stronger effect (the goal of this experiment) or smoother color gradients that can allow for smoother depth transitions. When considering simulations similar to the one presented in this research, one possible improvement is related to the way the projected images were created. The images displayed to each individual eye were the result of a mirrored effect, effectively doubling the effect. This can be approached in a different way in the future, in which the effects for each eye are independent, thus allowing for more degrees of freedom in the depth resolution.

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