Using Chromostereopsis to Enhance Depth Perception in Photos by changing the Hue

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June 19, 2022

A Dissertation Submitted to EEMCS faculty Delft University of Technology,
In Partial Fulfilment of the Requirements
For the Bachelor of Computer Science and Engineering

Abstract

The following paper explores the use of chromostereopsis for the purpose of enhancing the perceived depth in photos. Contrary to previous work, this is achieved by using a continuous depth map as input and creating a natural-looking photo with enhanced depth even when viewed without any type of three dimension technology. This is the first algorithm to achieve this effect by shifting the hue and shows that it is possible to exploit chromostereopsis for depth enhancement by solely changing the hue values. We perform a user study to examine the properties of naturally occurring chromostereopsis, with focus on the reversal effect caused by the lightness of the background. The results of the user study are used in the algorithm, which can be applied to any photo with a depth map. We show the results and analyse them on six example images that highlight limitations and strengths of the algorithm.

1 Introduction

There are several depth cues that can be exploited to enhance depth perception in a 2-dimensional image. With the rise in popularity of 3d technology, a lot of progress has been made in the process of capturing the depth of a scene, which can be applied for this purpose. Such cues include perspective, shading and lighting, defocus blur and aerial perspective. A factor of different nature that also affects the depth perception of an image is chromostereopsis. It describes the optical illusion that causes colors of different wavelengths to be perceived at different depths. Typically, red is perceived as closer than blue, but the effect is reversed when the background is lighter [1]. However, because this effect is subjective and changes based on outside circumstances such as pupil size [2], it is not commonly recognized as a depth cue.

In recent years, the idea of using chromostereopsis to portray depth has gained some traction [3, 4, 5, 6]. Through the use of ChromaDepth glasses, which contain small prisms that bend the light in opposite directions for each eye, the effect is exaggerated [7]. Researchers have developed several algorithms to make use of this effect for depth enhancement, both for use with and without the glasses. Out of the two solutions that were developed without ChromaDepth glasses in mind, both of them avoid having to change the hue of pixels in the image. Instead, they modify the lightness, intensity and chroma [5, 6]. From past research we know that changing the brightness of the background can contribute to depth enhancement without using the theory of chromostereopsis [8]. This makes it difficult to tell whether chromostereopsis actually lies at the root of these algorithms. S.W. Jung et al. observe that "a more improved solution can be devised from better understanding of the color stereopsis" [6]. This paper explores point by answering the following question: Is it possible to create an algorithm that uses color hues as a depth cue in photos by changing them on the basis of chromostereopsis?

The research was conducted in three steps. First, we explored existing literature to gain a better understanding of the science behind chromostereopsis and the solutions that exist. As a next step we held a user study in order to find out the properties of using chromostereopsis as a depth cue. Based on the results of the user study we propose an algorithm that takes an image and a depth map is input and enhances the perceived depth through the use of chromostereopsis. This is achieved by shifting the hue of pixels according to their depth and the lightness of surrounding areas. The algorithm is able to enhance the depth perception especially well in landscape photos and in photos where some areas stand out in front of the background.

This report discusses related work in Chapter 2. It includes a problem description in Chapter 3, which contains background information on chromostereopsis and a description of experiments used to further explore the effect. Chapter 4 describes the proposed algorithm based on the experiments, and the result can be seen in Chapter 5. Chapter 6 contains an analysis of the ethics behind the research. The last two chapters contain a discussion (Chapter 7), and a conclusion and future work (Chapter 8).

2 Related Work

There have been several attempts to create algorithms that make use of chromostereopsis for depth enhancement of images [3, 4, 5, 6]. The following section discusses two implementations with the purpose of being viewed using ChromaDepth glasses. It also describes two algorithms that make use of the effect to enhance depth perception without needing glasses.

By mapping a depth value to a hue, it is possible to create images that can be viewed as 3d using the principles of chromostereopsis [3, 4]. This idea has been developed for the use of scientific visualization using ChromaDepth glasses [3]. These glasses contain tiny prisms which refract the light at opposite angles for each eye. Similar to when it is bent on the lens of the eye, light of different wavelengths has different levels of refraction, creating the illusion of depth [7]. The reason it works well for scientific visualization, is that the depth information is encoded in a single image, which can be viewed with or without ChromaDepth glasses. The idea was further developed by improving the depth to hue mapping for trichromatic systems [4]. To adjust to the properties of this type of display, the depth is mapped linearly from blue through white to red. In an informal user study, the proposed mapping gave a more linear perception of depth on a trichromatic display when using ChromaDepth glasses.

There have also been attempts to create algorithms which enhance images through chromostereopsis without the use of ChromaDepth glasses [5, 6]. One of these takes an image along with 3 depth masks as input [5]. The output is an image with an enhanced depth perception. It changes the lightness of the background based on the hue of the middle- and foreground. It does not, however, change the hue values of any of the layers. Additionally, the algorithm relies on a manual depth mapping of the three layers and cannot deal with continuous depths. Another algorithms deals with a continuous depth mapping as input [6]. It splits the image into local neighbourhoods, calculates weights based on the difference between local fore- and background and aggregates the results over the image using a gaussian kernels. By using local neighbourhoods, the researchers managed to create a more versatile algorithm. However, they solely make use of chromostereopsis by changing the intensity, not the actual hue of the image.

These examples illustrate the use of two extremes when it comes to hue: Either it is changed completely to enhance depth perception for ChromaDepth glasses, or it is not touched at all. In this paper we explore this gap in research and propose an algorithm that creates images to be viewed without ChromaDepth glasses. Contrary to existing solutions, the hue is changed slightly according to the principles of chromostereopsis in order to enhance the depth while keeping the image natural looking.

3 Problem Description

The following section gives a theoretical background on chromostereopsis and its cause. It then describes the experiments performed to test three factors that influence the effect: global background, local background and color hue.

3.1 Theoretical background on Chromostereopsis

Chromostereopsis is an optical illusion where different colours on a 2-dimensional image appear at different depths. It was first described by Bruecke and Donders in 1868, who both attributed it to the difference in accommodation by the eye when looking at different colors [9, 10]. However, this theory has since been disproven by the fact that the effect is only noticeable with binocular vision. The most recent theories relate the effect to two causes: A displacement of the pupil position relative to the lens and an off centered peak of light sensitivity in the eye, which is affected by the pupil size [11, 2]. These

two causes work in opposite directions, which is why the reversal effect can be triggered through a change in brightness [12].

Although the exact nature of the effect is still not confirmed, there is a consensus among researchers that the effect is caused by a difference in refraction between long and short wavelengths on the lens of the eye. In the general case (on a black background), red is seen as being in front of blue [13].

3.2 Effect of background on Chromostereopsis

In order to create an algorithm that enhances the depth effect based on color hues, the influence of the background needs to be investigated. The following section discusses the effect of the global background lightness, which we define as the overall lightness of the image. For the experiment, 5 participants were asked to observe images on a screen in a darkened room at a distance of 1.5 metres. They were then asked simple questions about their depth perception of the images. To avoid the influence of other depth cues, the experiment was conducted on simple shapes and colors. All experiments were approved by the Human Research Ethics Committee of the TU Delft.

Participants were shown images in a random order containing a red and blue square as shown in Figure 1. The background had 6 varying shades of gray ranging from white to black. They were then asked which colored they perceived to be closer to them. The results can be seen in Figure 2. For a sample size of 5, the number of successes needs to be 5 in order to show statistical significance. Because not everyone experiences chromostereopsis in the same way, there are too many outliers to show significance. However, the graph includes an 80% confidence interval to illustrate the trend.

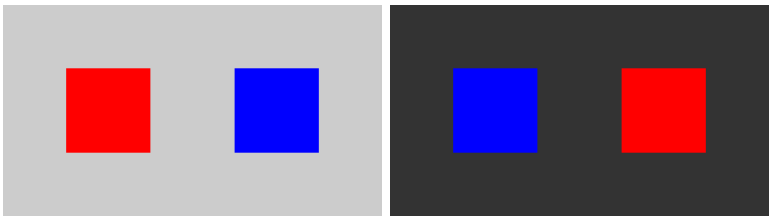


Figure 1: Examples of images shown during the first part of the user study. These were used to evaluate the influence of the background brightness on chromostereopsis.

These results demonstrate the inversion effect that is caused by a change in background brightness [1]. At low brightness (black - dark gray), red is most likely to be perceived as closer to the observer. As shown by the graph, we can say with 80% certainty that blue is perceived as closer than red most of the time at a brightness of 0.4 or lower. At high brightness (light gray - white) there are more outliers, but there is a trend of blue being perceived as closer. The 80% confidence interval shows that in a majority of cases, blue should be perceived as closer at a brightness of 1.

3.3 Effect of local background on chromostereopsis

Since it is still unclear what should be considered the background of an object when it comes to chromostereopsis, the effect of the local background also needs to be investigated. By local background we mean the immediate surroundings of a colored object. In order to investigate the influence of the local background, three different methods were used. The setup was the same as in the experiment on the global background, with 5 participants. The size of the local background is another factor that should be investigated, but due to limited resources it was not included in this study.

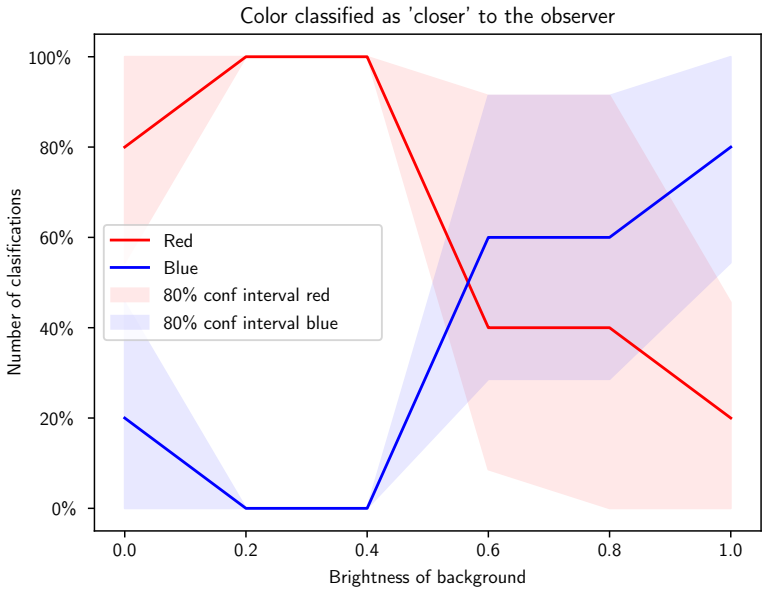
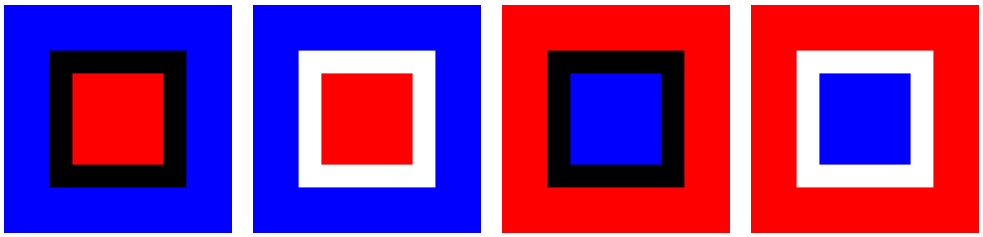


Figure 2: Result of the user study aimed to find the influence of the brightness of the background on chromostereopsis. The curves show how many times red or blue was classified as 'closer' to the observer and the shaded area shows the 80% confidence interval.

Method 1: Single square experiment

First, participants were shown an image with a blue or red background, a black or white frame and a single blue or red square. The images can be found in Figure 3. The participants were asked which color they perceived as being closer to them. When the frame was black, blue was perceived to be closer to the participant 6 out of 10 times. In the case that the frame was white, blue and red were both perceived as closer 5 times each. Neither of these results show statistical significance. However, from the fact that the results are much less conclusive than in the first experiment, it seems that the local background does affect the depth perception.



(a) (b) (c) (d)

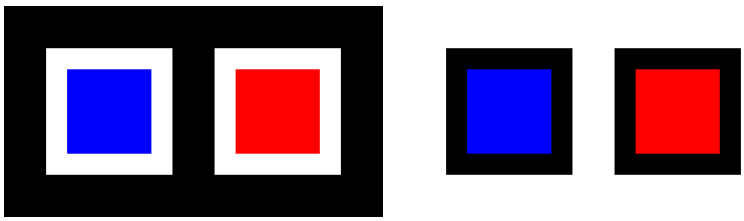
Figure 3: Images shown during the second part of the user study. These were used to evaluate the influence of the local background.

	a	b	c	d
With frame	1	4	5	2
Without frame	4	1	0	3

Table 1: Results of the frame/no frame comparison in the user study. It show the amount of times that the square with frame and the square without frame was classified as closer to the observer.

Method 2: Local/Global background comparison

Secondly, participants were shown images with a black or white background, black or white frame and one blue and one red square. The images used can be seen in Figure 4. The participants were again asked to classify which color was perceived to be closest to them. When the background was white and the frame was black, red was classified as closer 8 out of 10 times. When the background was black and the frame white, red was classified as closer 6 out of 10 times. These results again seem to indicate that the local background influences the inversion of depth perception caused by a change in background. None of the results show statistical significance. However, we can still reason that in the case of a white local background, the black global background seems to have a stronger effect on the inversion. In the case of a black local background, there is a trend in which the local background outweighs the influence of the global (white) background.



(a) (b)

Figure 4: Images shown during the second part of the user study. They contain a red and blue square with a local and global background. a. Black global background and white local background b. White global background and black global background.

Method 3: Frame/No frame comparison

Thirdly, the participants were shown an image with a blue or red background and two blue or red squares, one with and one without a frame. They were asked to classify which square was closest to them. The four examples presented can be seen in Figure 12. The results can be found in Table 1. From these results we can deduce that a local black frame enhanced the depth effect (red in front of blue) 7 out of 10 times, and a local white frame enhanced the inverted depth effect (blue in front of red) 9 out of 10 times. The latter of the two results shows statistical significance.

3.4 Optimal hue changing method for chromostereopsis

In order to bring out chromostereopsis in a photo, the algorithm changes the hue values according to depth. The following user study aims to find out which method creates the most accurate mapping from 'furthest back' to 'closest'. The setup was the same as for the previous experiments: 5 participants observed the images on a screen in a darkened room at a distance of 1,5m. The samples were picked with a range of factor which produced images with visually similar degrees of difference within the colors.

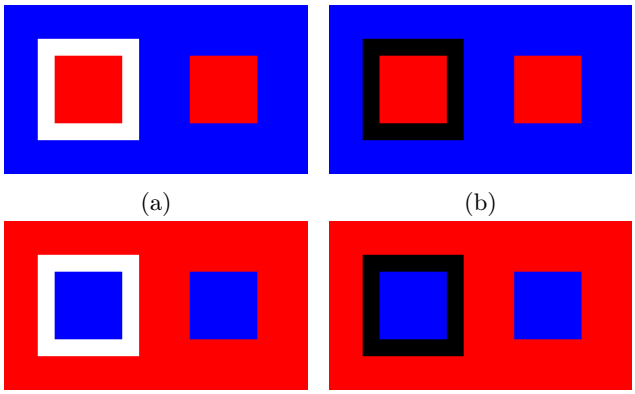


Figure 5: Images shown during the user study for frame/no frame comparison. a. Blue background, white frame, red squares b. Blue background, black frame, red squares c. Red background, white frame, blue squares d. Red background, black frame, blue squares

The following four methods were investigated for changing the hue according to a depth:

- **RGB shift**: The R and B values are changed relative to the depth of the pixel
- **Hue shift**: The image is converted to HSV format and the hue is shifted relative to the depth of the pixel
- **Heat - Depth mapping**: Each depth is mapped to a heat, which is then converted into RGB color
- **Hue - Depth mapping**: Each depth is mapped to a hue, ranging from red to white to blue

When using the last two methods, the resulting image is combined with the original image using alpha blending. The third method maps the depth value from 0 - 1 to 1000 - 11000 Kelvin, which is then converted to RGB values using an existing algorithm [14]. The fourth method is based on the scale described by Schemali and Eisemann [4] in a paper in which they investigate chromostereoscopy on trichromatic displays.

For each of these methods, participants were asked to rank patches of colors according to their depth. An example for each method can be seen in Figure 6. The results can be seen in Table 2. They were evaluated by calculating the similarity of each ranking to the original depth mapping. For this, the rank-biased overlap (RBO) was used due to it's robustness towards outliers in a dataset and the subjective nature of the study. The RBO works by comparing the overlap between the top - n choices and aggregating the results by weighing higher ranks stronger [15]. The table shows the RBO value when comparing the ranking the users gave with the original depths.

From the results of the user study in Table 2 it becomes clear that there is a difference in the mean RBO. This means that for certain methods, such as the RGB shift, Heat map and Hue map, the perceived depth after changing the hue was less accurate to the depth value. The Hue shift method stood out by receiving the highest mean RBO value by almost 0.1 while maintaining a relatively low variance. Based on these results the Hue shift method was was picked for the presented algorithm.

(a) (b) (c) (d)

Figure 6: Examples of images shown during the user study to compare the hue changing methods. The methods used are a. RGB shift b. Hue shift c. Heat map d. Hue map.

	A	**B**	**C**	**D**	**E**	Mean	Variance
RGB shift	0.44	0.57	0.72	0.92	0.80	0.69	0.05
	0.44	0.54	0.44	1.0	1.0		
Hue shift	0.44	0.76	0.62	0.96	0.83	0.78	0.03
	0.69	0.96	0.70	0.86	1.0		
Heat map	0.65	0.65	0.48	0.62	0.94	0.69	0.02
	0.71	0.65	0.65	0.58	1.0		
Hue map	0.38	0.86	0.62	0.44	0.38	0.67	0.05
	0.91	0.86	0.43	0.82	1.0		

Table 2: Results of the third part of the user study. It shows the RBO values for each participant and each hue changing method comparing their ranking with the original.

4 Algorithm to Enhance Depth using Chromostereopsis

The following section describes how the results of the user study were used to develop the algorithm. The goal of the algorithm is to take an image and depth map as input and return a depth enhanced image as output. First, the results of the user study are analysed, then the pipeline of the algorithm is presented, followed by an explanation of each of the steps.

4.1 User study result

The user study analysed the influence of the lightness of the global background and local background on the depth perception of certain colors. It also found the best method of shifting the hue to create an understanding of depth, which was the hue shift method.

For the global background, the user study indicated that a reversal of depth perception occurs as the background becomes lighter. From lightness 0 to 0.6, most participants classified red as 'in front' of blue. From lightness 0.6 to 1, blue was seen as 'in front' of red. We will make the assumption that these results can be generalized to a bigger sample size and take 0.6 as the cut-off for the reversal effect.

When it came to analysing the local background, the results of lighter and darker local backgrounds varied. When the global background was dark, there was no strong indication that a local white background caused a reversal. However, when the global background was light, it seems as though a dark local background does mitigate the reversal effect caused by the white background. For this reason, we split the algorithm into 2 cases. Only if the background is light do we analyse the local background to determine whether a reversal is necessary.

4.2 Algorithm Overview

The algorithm goes through five steps to output an image with enhanced depth 7. First, the depth map is adjusted using histogram equalization. Then, the global background lightness L_G is extracted by converting the image to HSL format. If the background is light ($L_G > 0.6$), the local backgrounds need to be considered. For this, the depth map is segmented into separate fields. Then, the local background lightness L_L is computed for each of these fields. If they are dark ($L_L < 0.6$), that field will not have a reversal due to the bright background. If they are not, then the order of depth is reversed. Finally, the hue of the image is shifted based on the reversal, the degree of depth and the factor given as input.

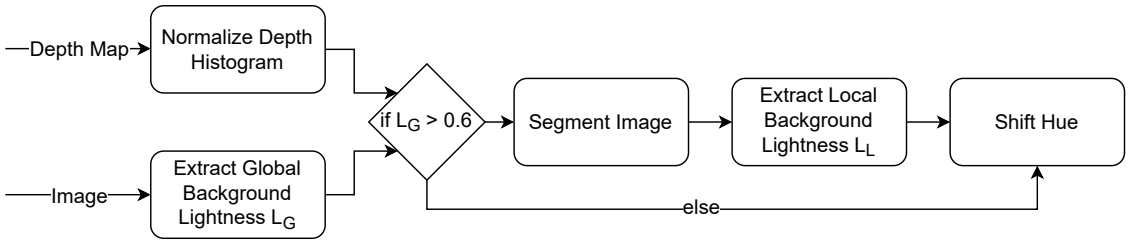


Figure 7: Pipeline of the algorithm used to enhance depth through the means of chromostereopsis.

Normalize Depth Histogram The depth histogram is normalized using histogram equalization. The purpose of this step is to make sure that the full range of depth enhancement is used by making sure the depth values are distributed uniformly between 0 and 1 and increasing the depth contrast. This also makes the result more accurate to the user study in Section 3.4, where depth values from 0 to 1 were used.

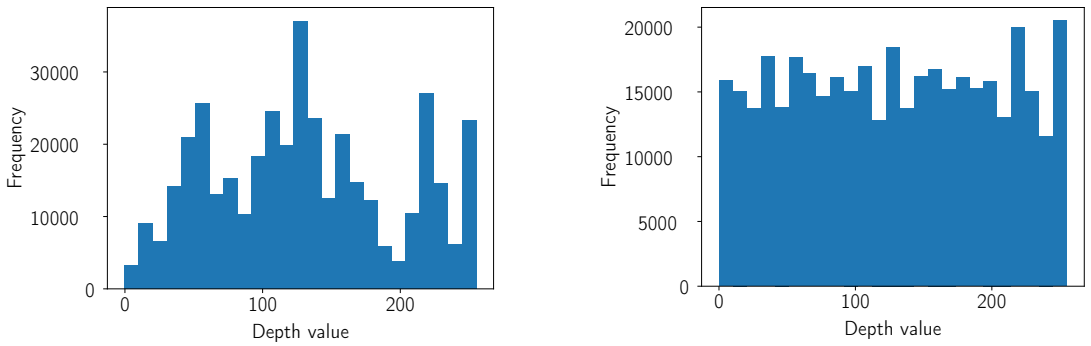


Figure 8: An example of the histogram of depth values before (left) and after (right) histogram equalization.

Extract Global Background Lightness The lightness is used to find out which color will be perceived in front and in order to know whether or not the local background plays a role based on the results of the user study in Section 3.2, and Section 3.3. For this, we convert the image to HSL format, which separates the color channels into Hue, Saturation and Lightness. Then, the mean lightness is computed. If the mean lightness is less than 0.6, that means that the background is dark and that a light local background will not make much of a difference. In this case, no reversal takes place. If,

however, the mean lightness is more than 0.6, the local backgrounds need to be further analysed and the color mapping is reversed.

Segment Image The image is segmented using k-means clustering on the depth map. This technique divides the existing values into k groups, such that the values within one group have as small of a variance as possible. Each value is then assigned the mean of the group it belongs to. This process is repeated for values of k between 2 and 10. For each of these values, we calculate the mean square error. With k-means clustering, the mean square error function usually produces an elbow like graph. We use the k at the elbow to minimize the mean square error while keeping the number of clusters as low as possible. An example of the segmented image can be seen in Figure 9.

Figure 9: Example of segmentation of depth map. The left image shows the original depth map and the right image shows the depth map segmented using k-means clustering.

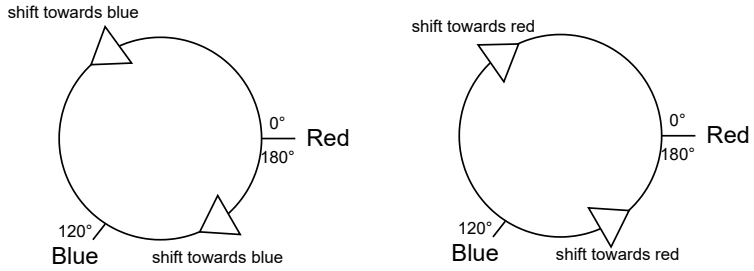
Extract Local Background Lightness This step is repeated for every cluster. The mask of the cluster is dilated by 10% of the size of the field (using the bigger value between width and height of the bounding box). These 10% make up the local background of the object. The original mask is subtracted from the dilated mask to produce the frame. Then, we mask the original image in HSL format using the frame and compute the average lightness. If the local lightness is higher than 0.6, the factor of shifting the hue is multiplied by -1. This is stored in a reversal mask containing the information on whether or not to reverse each pixel.

Shift Hue Based on the results of the user study in Section 3.4, we use the hue shifting method. The shift hue function goes through each pixel and uses the hue h, depth d, factor f and reversal values r to calculate the new hue. The normalized depth value d and the factor f both lie between 0 and 1. The user gives the factor as input and can adjust it to fit the specific image. If the factor is 1, the hue is shifted all the way to red or blue in case of depth 0 and 1. At a factor of 0.5, the hue is only shifted halfway from the current hue to red or blue. The reversal value r can be either -1 or 1. The hue is represented on a wheel containing values from 0 to 180. Red hues are in the region of 0/180 degrees, while blue hues are centered around 120 degrees. The idea is to shift the hue of each pixel in the direction of red/blue, depending on the depth value.

First, the distance between the middle depth and d is scaled by factor f, and then multiplied by 2 in order to get a range between 0 and 1:

$$dist = abs((d - 1/2) \cdot f) \cdot 2$$

Then, we need to consider two cases, which are demonstrated in Figure 10:



(a) (b)

Figure 10: Visualization of the hue values of red and blue. (a) The direction the hue is shifted when it goes towards blue. (b) The direction the hue is shifted when it goes towards red.

(a) d **lies between 0 and 0.5 (or 0.5 and 1 with r = -1)**

In this case, the pixel is shifted towards blue. We calculate the total range between the hue and the extreme case (completely blue) as follows:

$$range = 120 - h$$

By keeping the sign of the range instead of taking the absolute value, we have already incorporated both cases where the hue is higher and lower than 120.

(b) d **lies between 0.5 and 1 (or 0 and 0.5 with r = -1)**

In this case, the pixel is shifted towards red. We now calculate the total range between the current hue and the extreme case (completely red) as follows:

$$range = \begin{cases} -h & \text{if } h \leq 120 \\ 180 - h & \text{otherwise} \end{cases}$$

Lastly, the hue is shifted by the range and scaled by the distance:

$$h_{new} = dist * range$$

5 Results

The following chapter examines the results of the algorithm analytically. Figure 11 demonstrates the results on six examples using factors 0, 0.3, 0.6 and 1. The images are taken from the ReDWEB dataset which inlcudes RGB images along with a grayscale depth image [16]. Examples a and f have a high brightness and therefor contain a reversal. Below, the scenarios in which the algorithm works particularly well are outlined and some limitations are explained.

From a qualitative analysis it becomes apparent that changing the hue increases the depth perception. However, different images seem to perform better at different factors. Examples b and e still look natural and can therefor use factor 1 for an optimal depth enhancement. Examples a and c, however,

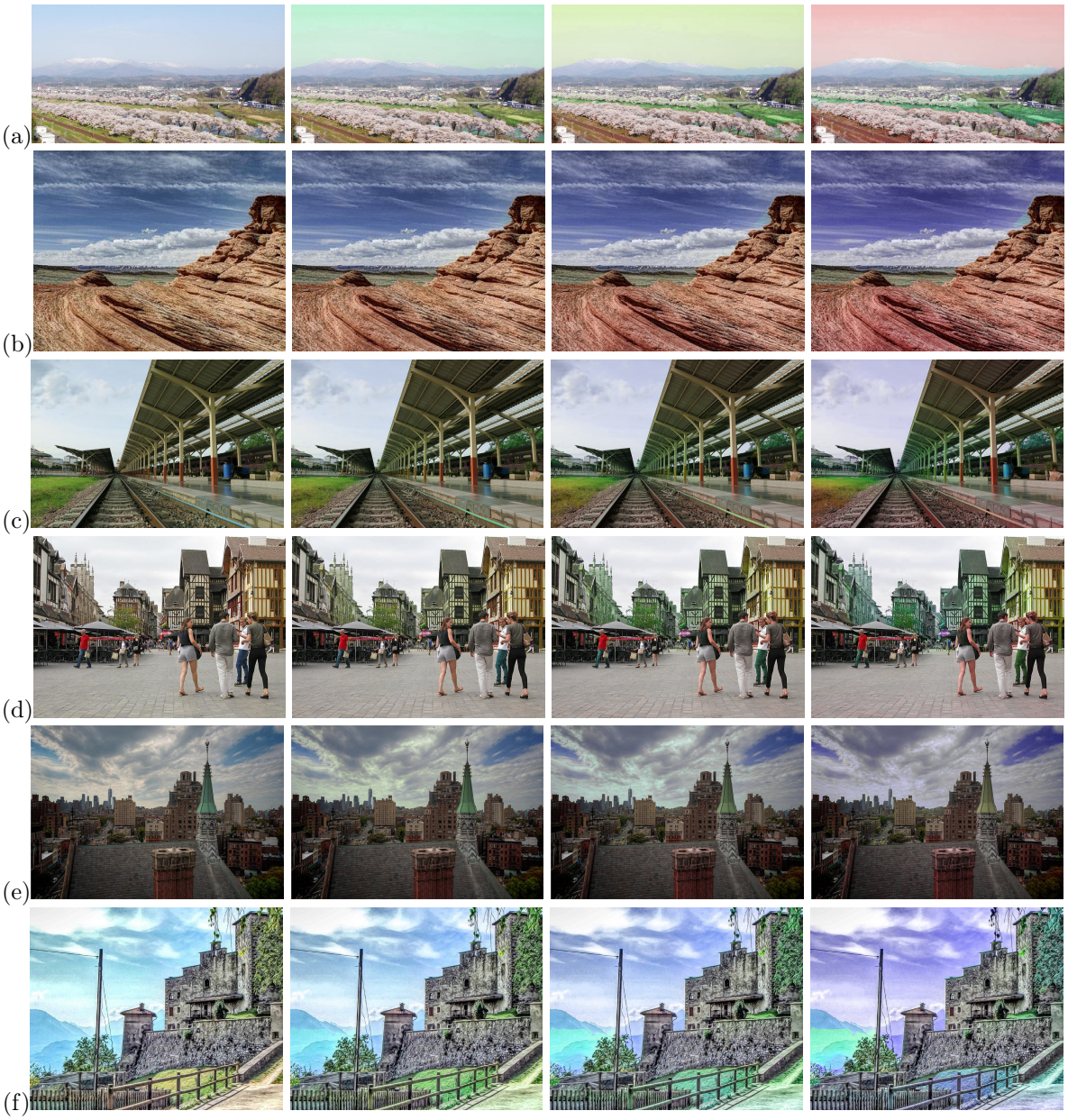


Figure 11: Six examples of results using the depth enhancement algorithm on images with a depth map. From left to right the factor used is 0 (original image), 0.3, 0.6 and 1.

start looking unnatural at factor 0.6 and should therefor only use a low factor. Deciding this factor has a lot to do with the human perception of an image and is therefor difficult to automate.

In the examples that contain a reversal (a, f), the depth effect is not as apparent. This observation is in-line with the results of the user study, where a light background produced more uncertain results. In addition, the reversal is more likely to produce strange looking artifacts because it doesn't correspond to the natural composition of a lot of images (eg. a blue sky in the background).

The algorithm works particularly well in situations where the chromostereopsis emulates natural

colours. Through aerial cues, far-away mountains may appear in a bluish tint. This is a separate effect from chromostereopsis, but (perhaps by chance) plays perfectly into the color scheme that enhances an image according to the principles of chromostereopsis. Examples that demonstrate this are example b, e and f. Another situation where the algorithm performs strongly is the case where some objects stand out in front of a background. An example is d, where the people walking are clearly stand out from the rest of the scene as the factor increases.

There are a couple of limitations to the algorithm. One of those is the fact that shifting the hue can lead to unnatural looking results. This can be seen in example a, where the sky (which is originally blue) is shifted towards red and therefor has extreme shifts in hue. This issue occurs when the colors in the image are far from the colors that would enhance depth perception. Another limitation arises when there are continuous depths such as in example c. In this case, the grass which should be a uniform color shifts from red to green as the depth increases. This could be mitigated by clustering regions in the depth map that have similar colours in the original image.

6 Responsible Research

The following chapter analyses the paper in terms of responsibility of the provided research. It discusses replicability and integrity of the user study, the reproducibility of the algorithm, and ethical implications in the field of image enhancement.

6.1 Replicability and Integrity

Due to the small amount of participants in the user study, repeating the study could yield different results. The confounding variables that might have impacted the result include: Room brightness (although all studies were performed in dim conditions), personal differences in perception and the degree of changing the hue and original color. The latter two variables were picked semi-randomly. On a big enough sample size, this should eliminate bias, but at 5 samples this can not be guaranteed. It is important to note that most of the findings of the first two parts of the user study have already been verified by existing research [17, 18, 13]. Therefor, the study mostly served the purpose of verifying that these effects exist under the given circumstances such as the screen display used, the natural (dimmed) lighting, the viewing distance and so forth, so that the results of the algorithm could be analysed under these conditions.

During the user study several assumptions were made. Firstly, related to the replicability, one assumption was that the result from the 5 participants can be expanded to the general public. Due to the limited size of the group (5 participants) and age range (21 - 25), this is quite a broad assumption to make. This assumption had to be made due to the limited resources and time for the project. Because the effect of chromostereopsis varies from person to person, it was not possible to draw statistical significance from a lot of the results. Another assumption made, was that the fact that the researcher conducted the user study did not influence the result. There is always a chance that preexisting expectations by the researcher had an effect on the participants. To mitigate this, a neutral tone was used when asking questions and the order of images was randomized.

6.2 Reproducibility

Due to the fact that the algorithm is described in detail, the results of the study are reproducible. All the tools that were used are specified and publicly accessible. The variables introduced are named and motivated. In addition, the code can be found online and used on new inputs. Anyone who wishes to can try out the algorithm on their own examples (given an image and a depth map) and draw their own conclusions about the effectiveness.

6.3 Ethical implications

As image enhancement techniques get more advanced, there are several ethical implications that should be considered.

Art and photography are skills that are difficult to measure objectively. However, for many people they are integral to their career and something they pride themselves on. As more image enhancement tools become available, it gets increasingly tricky to judge the 'natural talent' of a photographer or artist, as it becomes easier to edit content retroactively. This could be seen as deceptive and could influence the success of photographers and artists that do not use such techniques. However, art is always changing and developing, and so instead of seeing it as a challenge that these professions face, new techniques can also be viewed as opportunities that allow more space for creativity and improvement.

Another area that is affected by image enhancement techniques is social media. With apps such as TikTok and Instagram, the usage of real-time filters that modify footage have exploded. Some of these seem rather innocent, but a lot of times they enhance the video according to our standards of beauty. This can cause viewers to get a morphed sense of reality and set unrealistic standards cause body dismorphia, desire to undergo plastic surgery and other adverse effects [19]. While this is important to consider, the presented algorithm is not based on any beauty standards and was not developed with images of people in mind, so it does not contribute to this issue.

7 Discussion

The contribution made by this paper is an algorithm that adjusts the image according to the principles of chromostereopsis to enhance depth perception. This is a step forward, because it shows that this effect can be achieved solely by shifting the hue in order to bring out the chromostereopsis effect. The algorithm works especially well in cases where the natural composition of the image has a similar depth to color mapping which can be enhanced, such as through aerial cues.

There are some limitations to the research. Due to the limited resources, the user research could not be expanded to include more participants. The assumption had to be made that the results of the user study with five participants are applicable to the general public. With more resources available, the results of the user study might have been more conclusive. In addition, certain values that are used now could be investigated more clearly. One of these values is the degree of lightness that causes a reversal effect. The user study was conducted on a single laptop, so the results are consistent to one display, however, a display with different properties and brightness might have a different result. Therefor the threshold of 0.6 might not be accurate on a different device. Another value that should be investigated further is the effect of the size of the local background. The local background was set to 10% bigger (vertically or horizontally) than the object itself, but a better understanding of the effect of this border size could lead to more accurate results.

Another limitation to the algorithm is that it seems less effective in the case where a reversal occurs. From past research we know that the depth effect works differently when the background is lighter. However, more research would be necessary to find a more effective way to make use of the reversal effect, for example by finding alternative colors to use in the reversal case or combining the algorithm with previously suggested methods [5, 6] in order to obtain more natural-looking results. A better understanding of the cause of the reversal effect would useful should this point be pursued further.

A different area in which the algorithm might be applicable is when using ChromaDepth glasses. These enhance the naturally occurring chromostereopsis effect by increasing the angle at which in-

coming rays are refracted [7]. More research needs to be done in order to find out whether properties such as the reversal effect can be transferred to the chromostereoscopic effect achieved when using the glasses. My hypothesis would be that it is not that simple, since the refraction that occurs on the lens of the eye is overshadowed by the glasses. That way, it becomes less sensitive to factors such a pupil size.

8 Conclusion and future work

The paper presents further research into the areas of chromostereopsis. It includes a user study to explore the reversal effect caused by a change in lightness of the background. In addition, it proposes an algorithm which uses the results of the user study to enhance the perceived depth of photos. The research question of this paper is as follows: Is it possible to create an algorithm that uses color hues as a depth cue in photos by changing them on the basis of chromostereopsis? By presenting the results of the algorithm it has been confirmed that it is indeed possible.

The benefit of this algorithm over previous work is that it produces natural looking images with an increased perceived depth. The images do not need to be viewed through ChromaDepth glasses and the factor can be chosen such that the color shift does not affect the look of the photo too much. In addition, it works on a continuous depth map and does not affect the brightness of the image.

There are still areas that can be explored when it comes to chromostereopsis. For one, the actual cause of the effect is still just a hypothesis [12]. A better understanding of the cause could contribute to a more precise algorithm. One could, for example, reduce the human factor by running simulations of the effect on the eye. Another direction that would be interesting to explore are the extreme cases. From my own research is seems like the strongest effect can be seen when the image only contains red, black and blue. In this case, the objects on images actually appear to stand out of the image several centimeters. An example that I created of this kind of optical illusion can be found in Appendix A. While a good application for this does not immediately come to mind, it is still a fun feature to explore.

References

[1] F. Verhoeff, "An optical illusion due to chromatic aberration," *American Journal of Ophthalmology*, vol. 11, no. 11, pp. 898–900, 1928.

[2] J. M. Sundet, "Two theories of colour stereoscopy an experimental investigation," *Vision Research*, vol. 16, no. 5, pp. 469–472, 1976.

[3] M. Bailey and D. Clark, "Using chromadepth to obtain inexpensive single-image stereovision for scientific visualization," *Journal of Graphics Tools*, vol. 3, no. 3, pp. 1–9, 1998.

[4] L. Schemali and E. Eisemann, "Chromostereoscopic rendering for trichromatic displays," in *Proceedings of the Workshop on Non-Photorealistic Animation and Rendering*, NPAR '14, (New York, NY, USA), p. 57â62, Association for Computing Machinery, 2014.

[5] J. Hong, H. Lee, D. Park, and C. Y. Kim, "Depth perception enhancement based on chromostereopsis in a 3d display," *Journal of Information Display*, vol. 13, 09 2012.

[6] S.-W. Jung and S.-J. Ko, "Depth map based image enhancement using color stereopsis," *IEEE Signal Processing Letters*, vol. 19, no. 5, pp. 303–306, 2012.

[7] "Chromadepth technical explanation." `https://chromatek.com/what-is-chromadepth/chromadepth-technical-explanation/`, 2015.

[8] T. Luft, C. Colditz, and O. Deussen, "Image enhancement by unsharp masking the depth buffer," *ACM Trans. Graph.*, vol. 25, p. 1206â1213, jul 2006.

[9] E. Bruecke, *Über asymmetrische Strahlenbrechung im menschlichen Auge.* 1868.

[10] F. Donders, "Invloed der accommodatie op de voorstelling van afstand," *Wetenschappelijke bijlage bij het jaarverslag van het Nederlands Gasthuis voor Ooglijders*, pp. 111–113, 1868.

[11] W. Einthoven, "Stereoscopie durch farbendifferenz," *Albrecht von Graefes Archiv für Ophthalmologie*, vol. 31, no. 3, pp. 211–238, 1885.

[12] J. J. Vos, "Depth in colour, a history of a chapter in physiologie optique amusante," *Clinical and Experimental Optometry*, vol. 91, 2008.

[13] B. Kishto, "The colour stereoscopic effect," *Vision Research*, vol. 5, no. 6, pp. 313–IN4, 1965.

[14] T. Helland, "How to convert temperature (k) to rgb: Algorithm and sample code," 2017.

[15] W. Webber, A. Moffat, and J. Zobel, "A similarity measure for indefinite rankings," *ACM Trans. Inf. Syst.*, vol. 28, p. 20, 11 2010.

[16] K. Xian, C. Shen, Z. Cao, H. Lu, Y. Xiao, R. Li, and Z. Luo, "Monocular relative depth perception with web stereo data supervision," in *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2018.

[17] J. Faubert, "Seeing depth in colour: More than just what meets the eyes," *Vision Research*, vol. 34, no. 9, pp. 1165–1186, 1994.

[18] J. Faubert, "Colour induced stereopsis in images with achromatic information and only one other colour," *Vision Research*, vol. 35, no. 22, pp. 3161–3167, 1995.

[19] A. Perkins, "Body dysmorphic disorder the drive for perfection," *Nursing*, vol. 49, p. 1, 03 2019.

Appendix A

Figure 12: Image of tree with extreme chroma colors. For some people, this causes an optical illusion where some parts appear in front of others. The original photo was uploaded by @gillystewart and can be found at https://unsplash.com/photos/boE2xft0cAo.