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OmniColor - Google Glass app for colorblind individuals and people with impaired vision

Master's Thesis

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Graz, April 2016

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Thanks

First, I would like to thank and express my gratitude to my supervisor Martin Ebner, for supporting me all along the whole master thesis process and giving me the necessary motivation to create this great work at the the end of my computer science study. I'd also like to thank Thomas Pock from the Institute of Computer Graphics and Vision of the Technical University of Graz for his useful informations and comments regarding the implementation of the Google Glass application. Furthermore, I'd like to thank my parents Elisabeth and Dieter for giving me the possibility to make my dream come true to become a computer scientist and for giving me the strength and endurance to complete my study. I wouldn't have finished without your help. I want to thank my sweetheart Stefanie for always be willing to listen to my ideas and problems, for keeping me harmonious and support me by all available means. You were always there for me and I will never forget that. Last but not least, I'd like to thank the participants that were envolved in the evaluation of my work and all of my great friends.

Abstract

Colorblind people or people with a color vision deficiency have many challenges in their daily activities. Color perception plays a major role in everyone's life such as recognizing traffic lights while driving a car or proofing the rareness of meat while cooking, but also limit the career chances. However, due to the wide distribution of smartphones, applications that offer the possibility to manipulate or correct an image or a video stream in a way that colors can also be distinguished and recognized by colorblind users are available. Smartglasses on the other hand are relatively new devices and not as wide distributed as smartphones, but offer exciting new possibilities to overcome certain problems colorblind people or people with a color vision deficiency have to deal with every day and provide a whole new user experience. Hence, this work presents a Google Glass based prototype called OmniColor, which can be used to correct images according to the specific color vision impairment of the user. Evaluation has shown how colorblind people or people with a color vision deficiency can benefit from the usage of the application by passing a standard test for color vision impairment called the Ishihara color plate test. OmniColor reflects the great potential of a head-mounted device to support colorblind people on their daily tasks.

Farbenblinde Personen oder Personen mit einer Farbsehschwäche müssen viele Herausforderungen bewältigen. Die Farbwarnnehmung, wie das Erkennen von Lichtsignalen beim Autofahren oder die Bestimmung des Gargrades von Fleisch während dem Kochen, aber auch bei der Berufswahl, spielt eine wichtige Rolle im Alltag jedes Menschen. Mit Hilfe von Smartphones und Applikationen können Manipulationen oder Korrekturen von

Bildern und Videostreams durchgeführt werden um farbenblinden Personen und Personen mit einer Farbsehschwäche eine Unterscheidung von Farben zu ermöglichen. Bei Smartglasses handelt es sich um eine neue Art von Geräten, die zwar nicht so weit verbreitet ist wie Smartphones, aber interessante Methoden mit sich bringt um Probleme zu lösen mit denen farbenblinde Personen oder Personen mit einer Farbsehschwäche täglich konfrontiert werden. Diese Arbeit präsentiert den Prototypen einer Google Glass Applikation mit dem Namen OmniColor, welche Bildkorrekturen für die jeweilige Farbsehschwäche des/der Benutzers/Benutzerin vornimmt. Die Evaluierung hat gezeigt, dass farbenblinde Personen oder Personen mit einer Farbsehschwäche von der Applikation profitieren können. In diesem Zusammenhang wurde ein Standardtest zur Feststellung der Ausprägung der jeweiligen Farbsehschwäche mit Testpersonen durchgeführt. OmniColor zeigt auf, welches große Potenzial in Smartglasses steckt um farbenblinden Personen oder Personen mit einer Farbsehschwäche in deren Alltag zu unterstützen.

Contents

Abstract	vii
1 Introduction	1
2 Related Work	3
2.1 Chroma	3
2.2 ColorSnap Glass	7
2.3 Colorizer	8
2.4 DanKam	10
2.5 EnChroma	11
3 Theory	15
3.1 Color blindness and Color Vision Deficiency	15
3.2 Diagnosing Color Vision Deficiency	19
3.2.1 Ishihara Color Test	19
3.2.2 Nagel Anomaloscope	22
3.2.3 Color Arrangement Test	23
3.3 Color-correction Methods	25
3.3.1 Daltonization	25
3.3.2 Color Contrast Enhancement	27
3.3.3 LAB Color Correction	28
3.3.4 Color-via-Pattern	29
3.3.5 Empirical Methods	30
3.4 Augmented Reality	31
3.4.1 Definition	31
3.4.2 Comparison with Virtual Reality	33

Contents

3.4.3	History	34
3.5	Head-Attached Displays	40
3.5.1	Headmounted Displays	40
3.5.2	Head-Mounted Projectors	42
3.5.3	Retinal Displays	42
3.6	Smartglasses	43
3.6.1	Types	44
3.6.1.1	Google Glass	44
3.6.1.2	Epson Moverio BT-200	45
3.6.1.3	Recon Jet	47
3.6.2	Properties	48
3.6.2.1	Privacy	48
3.6.2.2	Performance	49
4	Implementation	53
4.1	Google Glass Development	53
4.1.1	Timeline	53
4.1.2	Glass-styled cards	53
4.1.3	Live cards	54
4.1.4	Immersion	54
4.1.5	Menus	55
4.1.6	Voice input	55
4.1.7	Gestures	55
4.1.8	User Interface	55
4.1.8.1	Card regions	56
4.1.8.2	Colors	57
4.1.8.3	Typography	58
4.2	Development Tools	59
4.3	OmniColor Prototype	60
4.3.1	Graphical Userinterface (GUI)	60
4.3.2	Libraries	63
4.3.2.1	OpenCV	63
4.3.3	Camera	64

Contents

4.3.4 Daltonization	67
5 Evaluation	73
5.1 Setup	73
5.2 Results	74
5.3 Discussion	76
6 Conclusion and Outlook	81
Bibliography	85

1 Introduction

Nowadays, people with colorblindness or having a color vision deficiency facing many challenges in their every day life such as cooking or driving. Not only daily tasks are affected, but also the career choices of such people are restricted due to their limited color perception. Whenever there is a high importance of recognizing or distinguishing color signals, it's often not possible to staff jobs with people affected by colorblindness or a color vision deficiency. As smartphones and tablets became more and more important, the number of applications for people with coloblindness or a color vision deficiency for those devices highly increase over the past years. However, although a smartphone or a tablet is much more handier than a laptop or a computer, it's still necessary to take out the smartphone from a pocket, unlock it, open the smartphone application and so on. Hence, color information need to be accessible as far as possible when the user needed it. Due to the variety of the new wearable devices such as smartglasses and smartwatches, new ways of user interaction and possibilites come into being. However, those devices are not as widespread as smartphones and also come up with some new challenges that need to be considered when choosing them as target platform. While there exists a moderate amount of applications for people having a color vision deficiency on smartphones, there are only a handfull applications available for smartglasses. This master thesis tends to improve the life for these people by introducing a prototype of a Google Glass application called *OmniColor* that can be used to distinguish colors. According to the different color vision deficiency types, the application provides the functionality to take a snapshot of the real world and perform a color shifting method called *Daltonization*. This makes it possible for people

1 Introduction

with a color vision deficiency to better distinguish confusing colors (e.g. red and green for Deutanopes and Tritanopes). To test the usefulness of the application, an *Ishihara Test* consisting of colored plates with numbers on it where performed. The first time without the support of *OmniColor*, the second time with the support the application. Finally, limitations and problems are discussed together with a outlook of future work.

2 Related Work

In recent years, a bunch of new algorithms and approaches to help colorblind people in their every day life have been developed. On the one hand, physical approaches such as the wearing of lenses can be used to improve color vision, but on the other hand, electronic devices in combination with implemented algorithms can augment or recover missing color information for colorblind people. This section tries to give an overview of state-of-the-art solutions for colorblind people.

2.1 Chroma

Tanuwidjaja et al. (2014a) presented *Chroma* as a wearable system based on Google Glass that allows users to see a filtered image of the current scene in real-time. Depending on the type of color blindness, the application automatically adapts the scene-view. To do so, different algorithms are used to help the user distinguish colors. The problem with current solutions is that they are even very limited in terms of scope and functionality or unpractically to use. For example the *Ishihara Color Vision Test* can't be passed by colorblind people with the aid of actual tools. Hence, *Chroma* focuses on real-life issues of colorblind people, providing realtime color detection. Rather than changing the whole scene-view, colorblind people are assisted to distinguish colors by letting the user choose a color of interest (typically the confusing colors according to the specific color vision deficiency type). Due to certain advantages such as the natural affordances and the minimization of the process when compared with the usage of a typical smartphone

2 Related Work

application, Google Glass is chosen to be the target device.

After opening and initializing the Chroma application, a video stream from Google Glass's camera is brought to the user. The application can be controlled via touchpad gestures or voice input commands. In the Settings View, a list of Chroma's modes are presented to the user and can be chosen by selecting a specific item of the list according to the user's needs.

Basically, Chroma provides 4 modes to improve the color perception for colorblind people:

- *Highlight Mode*: The highlight mode is used to highlight a specified list of colors in the scene-view e.g. highlight the colors red and pink. To get a good contrast, the application uses white as highlighting color by default. However, the highlighting color can be modified by the user. This way, the rawness of meat can easily be determined by the user.
- *Contrast Mode*: One of the main problems of colorblind people is to distinguish certain colors e.g. red and green. For this purpose, Chroma's contrast mode can be used. By selecting a predefined pair of colors, the scene-view will be modified in a way such that those colors are exchanged with another. Therefore, a configurable pair of colors can be selected by the user, which makes it easier for him to distinguish certain colors. Other colors in the scene-view are darkened to enhance the attention of regions containing color confusing information.
- *Daltonization Mode*: Colorblind people lost information according to their color vision deficiency type. This makes it hard or even impossible to distinguish shades of a certain color for the user. To overcome this, Chroma provides a *Daltonization Mode*, which makes it possible to perform color shifting. The original color spectrum is mapped to a new color spectrum where it's easier for the user to distinguish confusing colors. Hence, it enables the user to recover lost information of a scene.
- *Outlining Mode*: The main purpose of the *Outlining Mode* is to assist

2.1 Chroma

the user in daily activities or simply when he's wandering around - according to the color vision deficiency type, areas of interest are outlined. The key idea behind this mode is that colorblind people often do not know that they are in a color aware situation.

To evaluate Chroma, Tanuwidjaja et al. (2014a) introduced three general tests, which were performed with all the participants as well as three specialized tests that were only performed by people that were active in particular fields (e.g. electrical engineering for the resistor test). To get meaningful results, the participants have to perform the tests twice. The first time without using Chroma, second time with the assistance of Chroma.

The general tests involved an Ishihara color blindness test, a blackboard test where different colored bars and line graphs are analysed as well as a picture test. The specialised tests, which are not performed by all participants involve an arts test, where unlabelled crayons on a coloring book must be used to color a scene and label each color they choose to use as well as a ph strips test (the task was to differ colors of the ph stripes after they were treated with different chemicals) and a resistor test (recognizing the colors on a resistor).

The results had shown that overall, the major part of the participants derived a benefit from the usage of Chroma. Especially on the three general tests performed by all participants, significant improvements were achieved. The specialized tests that were performed by only a small group of participants only brought slightly improvements. Figure 2.1 shows the Chroma Google Glass application, which is used in highlight mode to determine the colors of a resistor.

2 Related Work

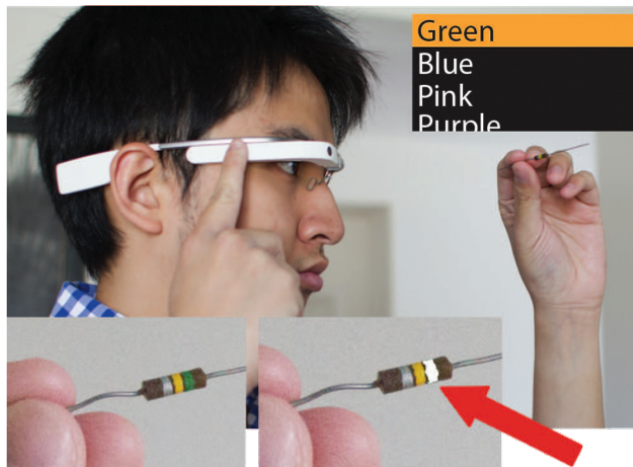


Figure 2.1: *Chroma Google Glass Application used to determine colors of a resistor* ²

Chroma is in theory by far the most powerful and comprehensive application that is available for colorblind people or people having a colovision deficiency that runs on smartglasses. Sadly, there is no possibility to download the implemented prototype. *Chroma* is neither on the website nor in the Android glassware store available. Nevertheless, the provided features are well described and useful to overcome common problems that colorblind people have to deal with every day. Instead of providing a single approach for colorblind people, the application comes with four different modes to overcome different kind of problems. However, the more functionality and features are provided by the application, the more attention in terms of usability has to be given, since the complexity increases parallel to the functionality.

As all participants of the evaluation group have done the general tests and the picture test, the number of participants decreases from 23 to just six. Therefore, increasing the number of participants would have lead to more meaningful results.

²<http://chroma-glass.ucsd.edu/> (last visited May. 02, 2016).

2.2 ColorSnap Glass

The *ColorSnap Glass* application provided by the company Sherwin Williams was not especially developed for colorblind people. The developers mentioned, that people are often inspired by scenes they see while on vacation, food preparation or simply flowers and other things when they're out. Later, they want to replicate those seen colors but don't know how. By using the Google Glass built in camera combined with the Sherwin Williams's color recognition, the user is able to determine the primary and complementary colors within a scene. However, since the color recognition algorithm is very complex and performance intense, a taken image is first sent to server where it is processed, which means that there must be a network connectivity to use the application. Next, a set of colors containing the primary identified colors is sent back to the user and displayed on the Google Glass device. The ColorSnap application was available on most smartphone platforms before it was available for Google Glass.^{3 4}

Although the Google Glass application is not intended to be used for colorblind people, it presents an intuitive and creative way to extract color information out of an image. It's important to mention that the application doesn't pursue the goal to extract all color information provided by an image, but rather determines the predominant colors of a scene. Hence, given an image presenting a street with a yellow car, the algorithm is intelligent enough to provide two shades of yellow (direct and indirect sunlight regions of the car), two shades of red (direct and indirect sunlight regions of the taillights) and grey (street in the background) instead of selecting different shades of grey contained in the background of an image. For example, colorblind people could take a picture of clothes while they are shopping. The application analyzes the taken images and provides information on the actual photographed clothing item. Of course, the supposed color identifica-

³<http://adage.com/article/digital/sherwin-williams-debuts-glassware/244477/> (last visited May. 02, 2016).

⁴<https://www.youtube.com/watch?v=Hzsc1Jx6ldc> (last visited May. 02, 2016).

2 Related Work

tion heavily depends on the taken scene e.g. if the image of a blue coat is taken, while there are a bunch of different colored shirts in the background of the image and the amount of pixels presenting a different color is greater than the amount of pixels containing the blue coat's color, this may lead to unsatisfactory results. Therefore, the algorithm must be taught on the objects depth of an image (which object(s) are in foreground and which are in background). Demonstration videos show how *ColorSnap Glass* identifies colors in real-life scenes.⁵ Sadly, no information about Sherwin-Williams's color recognition algorithm can be found at the time of writing.

2.3 Colorizer

Popleteev, Louveton, and McCall (2015) presented *Colorizer*, „a smartglasses application for helping colorblind people to distinguish problematic colors in daily life“ (p. 7). For this purpose, a live video stream of the smartglasses built in camera is used. By processing each frame of the live video stream, confusing colors are modified according to the color vision deficiency of the user. The prototype was implemented on a Epson Moverio BT200 smart-glasses device. The application provides basically two modes according to the display type of the used device:

- *Full image recoloring mode*: This mode implements the *Jefferson's color transformation method* and is more likely to be used on side-view displays like Google Glass. After increasing the color contrast of an image due to the contained confusing colors, the recolored image is presented to the user.
- *Partly image recoloring mode*: Rather than the first approach, the second approach is well suitable of see-through displays such as the Epson Moverio BT200. Instead of recoloring the whole scene, only problematic and confusing colored image areas are highlighted by using high-contrast overlays. For example, a person suffering under

⁵<https://www.youtube.com/watch?v=Hzsc1Jx6ldc> (last visited May. 02, 2016).

2.3 Colorizer

Protanomaly (red weakness) sees a red object by highlighting those pixels with another, well distinguishable color like blue. Hence, unconfusing color regions remain unaffected.

A disadvantage of both presented methods would be the ambiguity if a color in the scene is highlighted as such or represents the original color e.g. is blue really blue or highlighted red? The authors overcome those problems by displaying the modified image only on one eye. Furthermore, the authors mentioned that the usage of voice commands or touch gestures can disturb a conversation. According to this, the application can be controlled via head gestures by the user to overcome this problem. In terms of performance, smartglasses have very limited battery life and processing power. Colorizer uses a precomputed small look-up table to enhance performance when processing all pixels of an image independently. The evaluation of the prototype implementation will be handled in a future work.

As many other applications, Colorizer pursues the goal to provide a real-time solution for colorblind people. What's really interesting is the separation of modes according to the display type. Although the underlying two methods are briefly described, there's no described reasoning why on one hand the Jefferson's color transformation method works better for side-view displays, while on the other hand the high-contrast mode fits better for see-through displays. Also, information and implementation details, especially according the high-contrast mode are insufficient available (e.g. visual alignment). However, applications for colorblind people on see-through devices such as the Epson Moverio BT200 are rare at the moment and therefore leads to interesting new approaches like presenting the modified live video stream on just one eye to distinguish highlighted colors from real colors. Sadly, there is no evaluation of the Colorizer application at the time of writing. The implemented modes are likely to improve both daily activity tasks as well as specialised tasks colorblind people have to deal with every day.

2.4 DanKam

DanKam is an „augmented reality app for iPhone and Android that uses unique, configurable color filters to make the colors and differences between colors in images and videos readable to colorblind people“ (n. p.).⁶ Currently, the application is optimized for most common color blindness types (Deuteranomaly, Protanomaly), although it can be configured according to the users needs and therefore it can also theoretically be used for tritanopes when right configured. The key idea behind the development of *DanKam* is that the human color vision system registers only relatively few hues. According to the shift of the photoreceptor cells towards red, these people having problems to distinguish red and green colors. By adjusting the hue of a color wheel representing the RGB color model, colorblind people are able to clean up the colorspace to improve or reveal the colors of an image or a video. The field of application is widespread ranging from the selection of cloths to correctly recognizing light signals right up to managing parking structure.⁷

Figure 2.2 shows the DanKam iOS application which uses hue quantization to make it easier for people with a color vision deficiency to distinguish certain colors (in this case, the Ishihara color plate test is performed).

In contrast to other available smartphone apps that are following non-real-time, asynchronous approaches (e.g. ⁸ (last visited May. 03, 2016).), DanKam uses a real-time approach to overcome the problems of colorblind people.

⁶<http://bigthink.com/design-for-good/dankam-iphone-app-corrects-colorblindness> (last visited May. 03, 2016).

⁷<http://www.gizmag.com/dankam-smartphone-app-helps-color-blind/17451/> (last visited May. 03, 2016).

⁸<http://www.huevue.com> (last visited May. 03, 2016).

2.5 EnChroma

However, adjusting the color wheel enable those people to distinguish certain colors but affect not only problematic and confusing colors, but rather all colors. Another problem is the smartphone platform, which results in inconvenient usability on daily activity tasks of colorblind people. For example, to determine the rawness of meat while cooking, one hand must always hold the smartphone. In terms of availability, the choice of using smartphones as target platform has an important disadvantage when compared with smartglasses. While the user has to take the smartphone out of the pocket, unlock it, open the desired application and use it, smartglasses are already worn by the user and therefore accelerates the process.

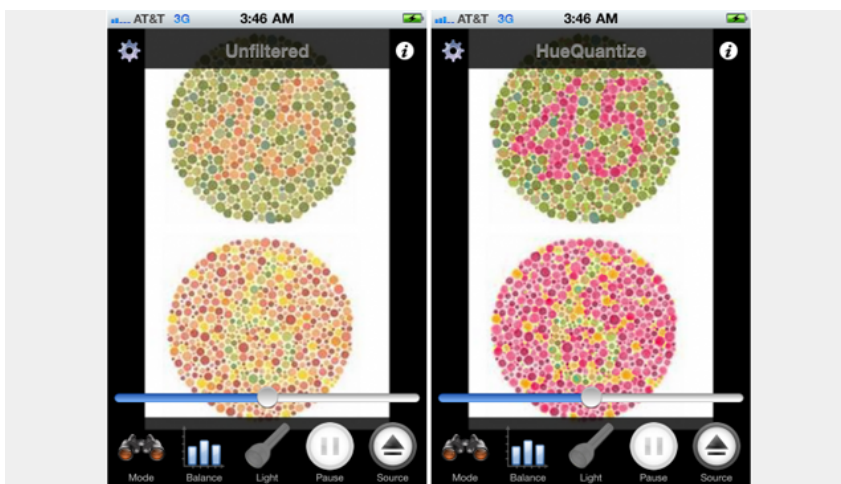


Figure 2.2: *DanKam smartphone application for iOS* ⁹

2.5 EnChroma

EnChroma is an optical assistive device that looks like normal sunglasses with tinted lenses, which is used to recover color information for colorblind

⁹<http://bigthink.com/design-for-good/dankam-iphone-app-corrects-colorblindness> (last visited May. 03, 2016).

2 Related Work

people. The cone cells of an eye (l,m,s) are responding to different wavelengths, making it possible to perceive blue, red and green colors. Red and green colors are more likely to be harder distinguishable than blue ones, due to the fact that red and green cones may overlap and therefore affects the perception of certain colors. When a pair of different cone cells overlap too much, the user has problems perceiving colors right. To overcome these problems, EnChroma „places a band of absorption on glasses that captures light pushing the cones away from each other and reestablishing the normal distribution of photons on them“ (n. p.). However, this approach has also the limitation that it can't be used for people having a lack of specific cone cells type. Hence, for people suffering under Deutanopia, Protanopia and Tritanopia, the glasses won't improve the color vision system. Also, actual glasses are intended to be used outdoors and may lead to insufficient results indoors. However, a indoor version of color correcting glasses is advertised.^{10,11}

Figure 2.3 shows how the EnChroma glasses filter out specific wavelengths to make it easier for people with a color vision deficiency to see certain colors.

Due to Tanuwidjaja et al. (2014a), EnChroma changes the whole scene-view of colorblind people. This means that not only confusing colors are affected of the color transformation, but rather all colors in the scene are modified. Therefore, while the glasses make it possible to recognize certain colors better for colorblind people, real-life scenarios are not likely to be better handled than without the glasses e.g. pass the Ishihara Colorblindness Test.

¹⁰<http://www.smithsonianmag.com/innovation/scientist-accidentally-developed-sunglasses-that-could-correct-color-blindness-180954456> (last visited May. 03, 2016).

¹¹<http://enchroma.com/technology/> (last visited May. 03, 2016).

2.5 EnChroma

As stated in the FAQ of EnChroma¹², the glasses are designed to be worn outdoor like a normal sunglass. For the use with a computer display, the glasses might be too dark, resulting in insufficient improvements. Also, this product focuses primarily on Deuteranomaly and Protanomaly (confusing red-green) rather than Tritanomaly (blue weakness). Although the manufacturer promises to enhance all primary color simultaneously by wearing the glasses, there are no significant studies or statistics for tritanopes at the moment of writing.

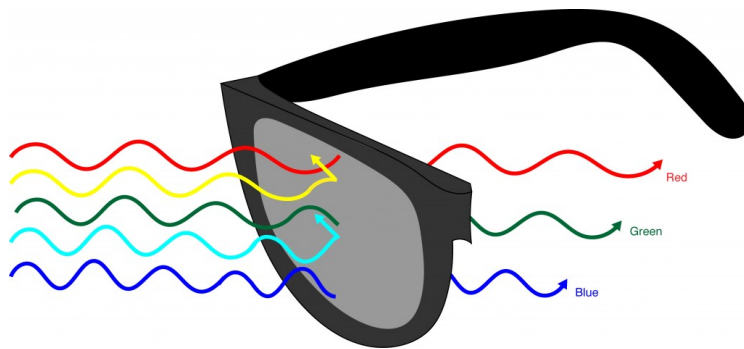


Figure 2.3: *EnChroma glasses*¹³

¹²<http://enchroma.com/> (last visited May. 03, 2016).

¹³http://sitn.hms.harvard.edu/wp-content/uploads/2015/03/Foster_Fig_4_draft_2-1024x468.jpg (last visited May. 04, 2016).

3 Theory

3.1 Color blindness and Color Vision Deficiency

In recent years, the utilization of colors became more and more important for effective visual communication. Multimedia contents use color to enrich visual information. Due to the huge amount and availability of display devices such as smartphones or tablets, but also printers, the distinction between colors play a major in the process of gathering information in everyone's life. (Huang et al., 2009)

People with color blindness suffer under a vision impairment that inhibits the ability to understand colors. Color blindness itself isn't classified as a hard disability, but has an significant impact on daily activities. (Tanuwidjaja et al., 2014a)

The difficulties are widespread and range from buying fruit and cooking meat over getting dressed right up to decorating. (D. R. Flatla and Gutwin, 2012)

In terms of visualization and displaying information, color is used in graphical interfaces as well as specific visualization applications. This involves the encoding of categories, the encoding of continuous variables and the highlighting of specific items. (D. R. Flatla and Gutwin, 2010)

Huang et al. (2009) stated that normal color vision is based on the absorption of photons, which are processed by the three different types of fundamental

3 Theory

photoreceptor cells, which are called *cone* cells. *Cones* can be classified in three different types, according to their different spectral sensitivities: The long-(L), middle-(M) and short-(S) cones. Each of them have a peak response in different wavelength regions of the spectrum.

Thus, according to Wakita and Shimamura (2005), light is perceived as a triple l,m,s , where the values of l , m and s represent the number of photons absorbed by the L, M and S cones. „More formally, color stimulus (S_i) for a light can be given by a numerical integration over the wavelengths λ :

$$S_i = \int \phi(\lambda)l_i(\lambda)d\lambda, \quad (i = L, M, S) \quad (3.1)$$

where ϕ stands for spectral power distribution of the light, l_L , l_M , and l_S for spectral sensitivity for L-, M-, and Scones. “ (p. 159)

Beside cones, there is also another type of grid cells called rods. While cones can be seen as the color receptors in the eye, rods are not color sensitive but very sensitive to low light levels. The human eye consists of plenty more rods than cones. With the discovery of visual pigments in the nineteenth century, it was founded out that rods and cones contain a light-sensitive protein called rhodopsin, which allows color vision. Even before the discovery of cones and rhods, Thomas Young comes up with the proposition that the human eye sees only three primary colors. By overlapping and combining those colors, the visible spectrum of the human eye is covered. (Oliveira, Ranhel, and Alves, 2015)

D. R. Flatla and Gutwin (2012) argue that a color vision deficiency can be caused by internal and external factors. Internal factors are defined to be intrinsic to the user (e.g. genetic causes and acquired color vision deficiency), whereas external factors care caused by environmental or situational issues outside the user (e.g. lightning levels). *Genetic color vision deficiency* is caused if someone doesn't have specific cone types, which are contained in the human X chromosome. While men have only a single X chromosome, women have two X chromosomes. Therefore, males are more likely to be colorblind than females - around eight percent of the male and 0.5 percent of the female world population are affected by a color vision deficiency.

3.1 Color blindness and Color Vision Deficiency

If the vision system is damaged by an event such as an accident, a disease or harmful chemicals, one speaks of an *acquired color vision deficiency*. In this case, because the number of short-wavelength cones is relatively small compared to the number of long and medium sensitive cones, a color perception that is similar to tritanomaly is more likely than deuteranomaly and protanomaly. (D. R. Flatla and Gutwin, 2012)

According to Jefferson and Harvey (2007), the three main types of abnormal color vision system are anomalous trichromatism, dichromatism and monochromatism. Anomalous trichromatism embraces protanomaly, deuteranomaly and tritanomaly, depending on whether the L, M or S cones have been affected. In such case, the peak sensitivity of one of the fundamental cones is shifted.

When compared with non colorblind people, colorblind people perceive a narrower color spectrum. (Tanuwidjaja et al., 2014a)

Figure 3.1 illustrates the comparison of the color spectrum according to non colorblind people and the three main color blindness types.

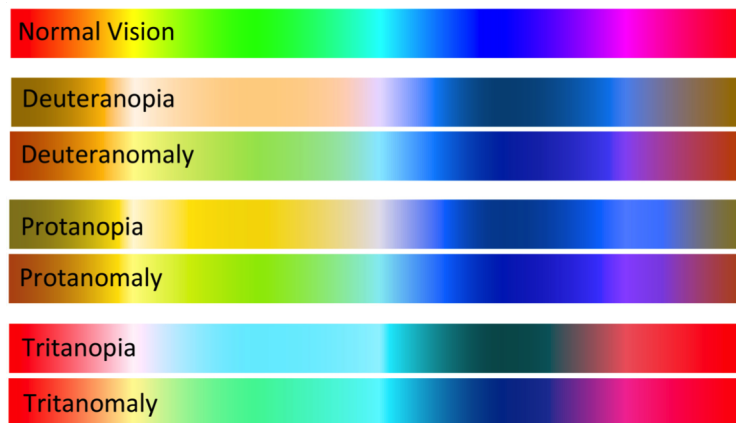


Figure 3.1: Color spectrum of non-colorblind people compared with the three main color-blindness types, from Tanuwidjaja et al. (2014b)

According to MailOnline¹⁴, color blindness and color vision deficiencies can

¹⁴<http://www.dailymail.co.uk/sciencetech/article-3145736/Are-colourblind->

3 Theory

be categorized in three categories:

- **Protanopia/Protanomaly:** Protanomaly describes the disfunction of the long wavelength cones (L). Protanopia is the lack of the long wavelength cones, making it hard to distinguish between colors in the green, yellow and red spectrum. Therefore, protanopes are more likely to confuse black with many shades of red, dark brown with dark green, dark orange and dark red, some sorts of blues with some reds and purples with dark pinks. This affects around five percent of males and 0.1 percent of females according to the world population.
- **Deuteranopia/Deuteranomaly:** Deuteranomaly describes the disfunction of the middle wavelength cones (M). Deuteranopia is the lack of the middle wavelength cones, which affects the same part of the spectrum as Protanopia. Deuteranopes are more likely to confuse mid reds with mid greens, blue-greens with grey and mid pinks, bright greens with yellows as well as pale pinks with light grey.
- **Tritanopia/Tritanomaly:** Tritanomaly describes the disfunction of the short wavelength cones (S). Tritanopia is the lack of the short wavelength cones. Tritanopes are more likely to confuse light blues with greys, dark purples with black, mid greens with blues and oranges with red. This color vision deficiency only affect 0.003 percent of males and females. Thus, tritanomaly/tritanopia is by far the rarest kind of colorblindness/color vision deficiency.

Dichromatism is a concrete form of color vision deficiency, where one of the fundamental cones is missing. Monochromatism describes the inability to distinguish colors, which is typically caused by a complete lack of cone receptors in the retina. Those people only see black, white and shades of grey. (Jefferson and Harvey, 2007)

This master thesis focuses on anomalous trichromatism and dichromatism

[Interactive-test-reveals-normal-rainbow-vision-living-murky-world.html](#) (last visited May. 05, 2016).

3.2 Diagnosing Color Vision Deficiency

rather than monochromatism.

Figure 3.2 shows a simulation of each colorblindness type.

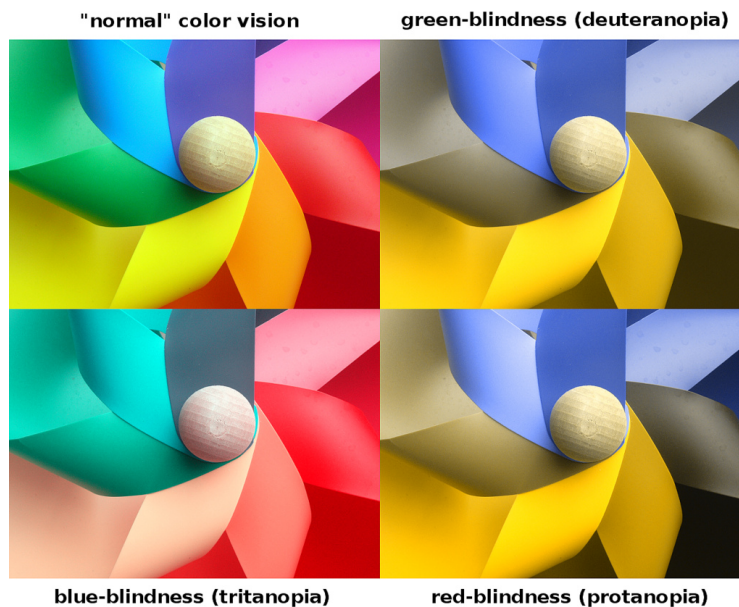


Figure 3.2: Simulation of different color blindness types, taken from Johannes Ahlmann (2011)

3.2 Diagnosing Color Vision Deficiency

3.2.1 Ishihara Color Test

The Ishihara color test described by Semary and Marey (2014) consists of a set of pseudoisochromatic plates. It is more likely to be used for diagnosing red-green color vision deficiencies rather than blue-yellow color vision deficiencies. It was first presented by Dr. Shinobu Ishihara and published in 1917.

3 Theory

Typically, the Ishihara color test comes in three common brands according to the number of color plates used: either 14, 24 or 38 plates. There are basically two different types of plates, one type contains numbers and the other one contains graphical patterns. All plates have a circle on it consisting of colored dots that have a random size.

As its name implies, numerical plates contain a different colored number centered inside each circle. While it's easy for people with a normal color vision to extract the number of the plate, people having a color vision deficiency are not able to extract certain numbers according to their color vision deficiency type. For example, people that are only able to extract less or equal to 13 plates out of 21 numerical plates would be classified as having a color vision deficiency (in case of 38 plate Ishihara color test brand).

The second type of plates are the ones having graphical patterns. Two points are connected by at least one path. People who can't read English numbers are forced to track the different colored linepath through the circle.

Each brand consist of different plates:

- *Introductory plate*: A *introductory plate* is used for explaining the testing process, with pattern visible to everyone
- *Transformation plate*: A *transformation plate* combines two patterns. While people without a color vision deficiency can clearly extract the given number, people with a color vision deficiency perceive another number.
- *Vanishing figure*: Plates with a *vanishing figure* contain a pattern that can be recognized by people having no color vision deficiency, whereas people with a color vision deficiency can't.
- *Hidden digit*: These plates are also called *reverse plates*. *Hidden digit* plates are basically the opposite of plates showing a vanishing figure. While people with a normal color vision can't see something on these plates, people having a color vision deficiency perceive information.
- *Qualitatively diagnostic*: These are plates with a *vanishing figure* on it which make it possible to determine the color vision deficiency type of a person e.g. deuteranomaly.

3.2 Diagnosing Color Vision Deficiency

Although there are plenty more tests to determine a color vision deficiency by the use of pseudoisochromatic plates, the Ishihara color test is by far the most commonly used.

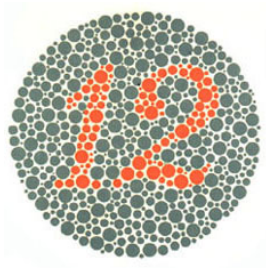


Figure 3.3: Introductory Plate

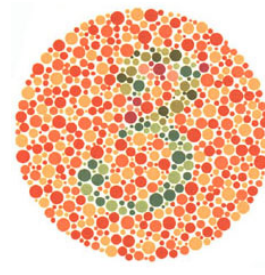


Figure 3.4: Transformation plate

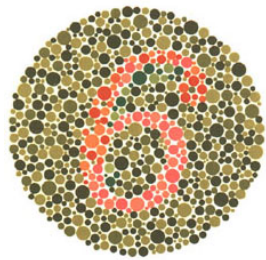


Figure 3.5: Vanishing Figure

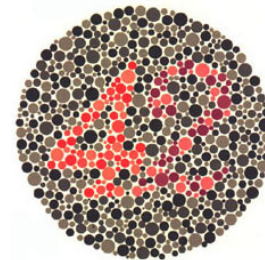


Figure 3.6: Qualitatively Diagnostic

Regardless if there's a color vision deficiency or not, Figure 3.3 shows the number twelve. For figure 3.4, people with normal color vision should see the number three whereas people with a color vision deficiency should see the number five. For figure 3.5, people with normal color vision should see the number six whereas people having a color vision deficiency can't extract a number. Figure 3.6 presents a qualitatively diagnostic plate: While people with normal vision see the number 42, the number which is recognized by people having a color vision deficiency depends on the specific color vision deficiency type (protanopes would see the number two and deuteranopes the number four).

3.2.2 Nagel Anomaloscope

According to Scheffrin (1994), there are also other methods that can be used to diagnose a color vision deficiency such as the *Nagel anomaloscope* beside the Ishihara color test. It is primarily developed to diagnose protan and deutan color vision defects rather than tritan color vision defects. Furthermore, the test method also makes it possible to distinguish dichromats from anomalous trichromats and determine the degree of the color vision deficiency. The *Nagel anomaloscope* avoids the use of color naming, light adaptation and calculation of an anomal quotient. Due to the given advantages, this test method is often used in clinical trials.

First, the instrument is presented to the subject by an examiner. The subject is instructed to look through the eyepiece of the instrument where a test field is shown (normally a circle). The instrument provides two wheels, one on the left to change the color of the top half of the test field (red-green mixture), whereas the other one is placed on the right side to change the luminance of the lower half of the test field. The goal is then to adjust the wheels till the two sides of the test field match. In the meantime, the examiner watches the adjustment of the red-green mixture wheel to get information about how far the subject's matching range differs from the normal matching range. In case of a match, the examiner checks if the scale is within the normal matching range or not. The first match of the subject is ignored due to demonstration purposes. After that, the subject is instructed to record three further matches (from red to green). Depending on the normal match range, the results reported by the subject are compared against the normal observed ones. If all three results lie within the normal color range, there's no color vision deficiency. On the other hand, if at least one result doesn't lie within the normal matching range, further examination follows. The subject is then instructed to only adjust the right wheel of the instrument (luminance) and tell the examiner if an exact match can be achieved (either *yes* or *no*). This enables the examiner to determine the limits of the matching range.

Figure 3.7 shows an anomaloscope instrument.

3.2 Diagnosing Color Vision Deficiency

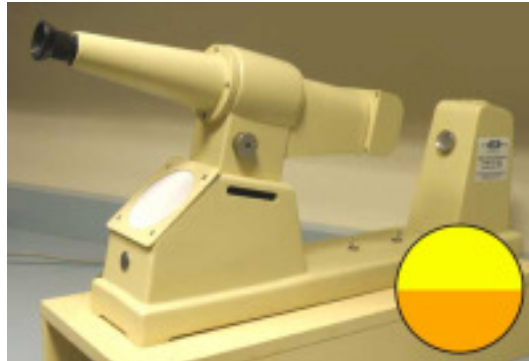


Figure 3.7: Anomaloscope, from color-blindness.com¹⁵

3.2.3 Color Arrangement Test

Another well known color blindness tests are hue discrimination or arrangement tests. Color blind people often mix up colors along a confusion line, making it impossible for them to distinguish certain colors. One famous form for a color arrangement test is called *D-15 dichotomous test* introduced by Farnsworth in 1947, which consists of two parts: A given, fixed color in the first row and below of that, a pallet of colors. The task is now to arrange the provided colors in the correct order by picking the most similar color to the previous ones. This color test makes it possible to divide people in two groups, on the one hand those people who are slightly colorblind and on the other hand not colorblind people. „Colorblind people will arrange the colors not in the correct order but parallel to one of the three confusion lines: protan, deutan and tritan“ (n. p.). According to the color arrangement test, a scoring method based on color difference vectors was presented by Vingrys and King-Smith, which made it possible to quantify the the type of

¹⁵<http://www.color-blindness.com/2010/03/23/color-blindness-tests/> (last visited May. 08, 2016).

3 Theory

color blindness using a personal confusion angle and the severity through the confusion index.¹⁶

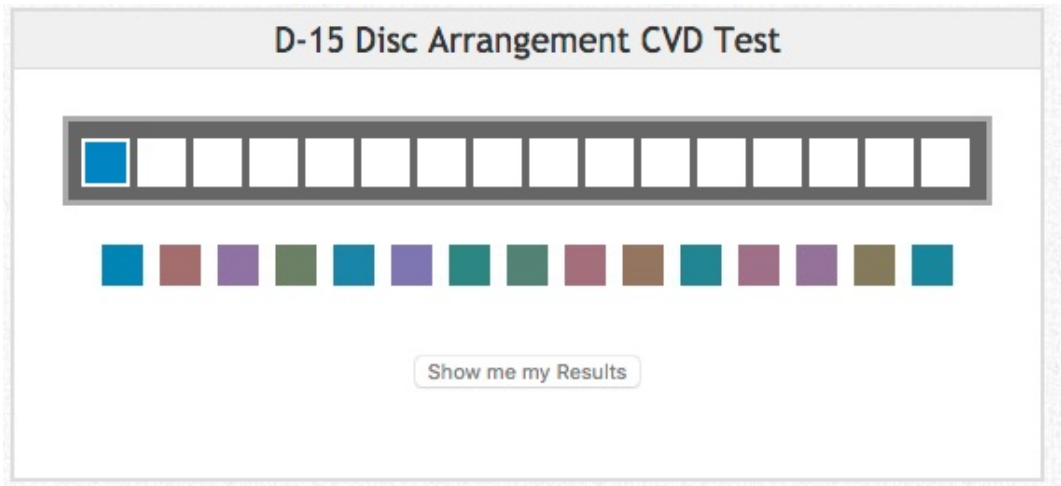


Figure 3.8: Online implementation of the D-15 color arrangement test, taken from colorblindor.com¹⁷

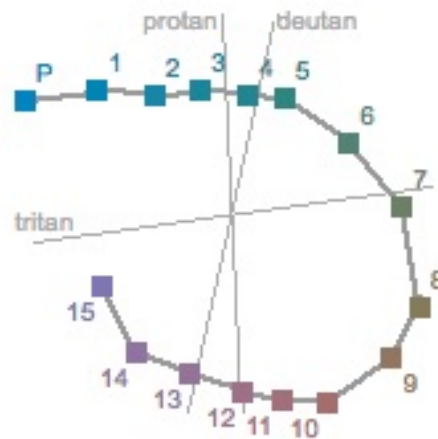


Figure 3.9: Result of the color arrangement test (normal color vision), taken from colorblindor.com⁴

¹⁶<http://www.color-blindness.com/color-arrangement-test/> (last visited May. 08, 2016).

Figure 3.8 shows a online implementation of the D-15 color arrangement test, while figure 3.9 shows the result of the D-15 color arrangement test performed by a person with normal color vision. The colors are drawn in the order given by the user. Normal visioned people order the colors in form of a circle. Whenever crossings arise in the result of the test, this indicates a possible color blindness or color vision deficiency. „Parallelism of crossings to a confusion line (protan, deutan, tritan) is a clue for the specific type of color blindness“ (n. p.).¹⁸

3.3 Color-correction Methods

There are different kinds of algorithms and approaches to correct an image, such that colorblind people can distinguish color according to their color blindness type. This section gives an overview of the three most common used approaches.

3.3.1 Daltonization

According to Christos-Nikolaos Anagnostopoulos (2007), daltonization describes a procedure for adapting colors in an image or a sequence of images for improving the color perception by a color-deficient viewer. Khurge and Peshwani (2015) stated, that *daltonization* uses the information lost by a specific colorblind simulation (deuteranopia, protanopia, tritanopia) in order to improve the original image.

The algorithm¹⁹ basically consists of four steps:

¹⁷<http://www.color-blindness.com/color-arrangement-test/> (last visited May. 08, 2016).

¹⁸<http://www.color-blindness.com/color-arrangement-test/> (last visited May. 08, 2016).

¹⁹<http://www.daltonize.org/2010/05/lms-daltonization-algorithm.html> (last visited May. 09, 2016).

3 Theory

1. First, the RGB coordinates are converted into the LMS color space, which is a color space suitable for calculating color blindness represented by the three different types of cones of the human eye.
2. Next, a simulation of color blindness is achieved by reducing the colors along a dichromatic confusion line, the line parallel to the axis of the missing photoreceptor, to a single color.
3. Then a compensation for color blindness is accomplished by shifting wavelengths away from the portion of the spectrum invisible to the dichromat, towards the visible portion.
4. At last, the LMS coordinates are converted back to RGB color space by using the inverse matrix of step one.

For deuteranopes, this means that *daltonization* doesn't affect the blue and red components of each pixel. Furthermore, the lost green component is shifted partially into red and partially into green. A big advantage is that *daltonization* only marginally affects the original image. This means that for both, colorblind and non colorblind people, the adjusted image require close inspection to notice differences (also from non colorblind people). (Khurge and Peshwani, 2015)

Simon-Liedtke and Farup (2015) presented two methods for better daltonization solutions using *Spatial Intensity Channel Replacement (SIChaRDa)*. The key concept is to replace the intensity channel with a grayscale version of an image. This makes it possible to translate color contrasts into lightness contrasts and therefore translate color edges into lightness edges. Thus, an integration of the red-green information into the intensity channel can be achieved.

The *SIChaRDa* algorithm works as following:

1. The original image is translated into a perceptual pathway image. This image consists of three layers corresponding to the three perceptual pathways of the human visual system - a lightness, a red-green and a yellow-blue layer.

2. Second, a grayscale image of the original RGB image is produced. This process primarily focuses on preserving color edges and/or color contrast.
3. Next, the lightness channel of the perceptual pathway image obtained in step one is replaced by the grayscale image obtained in step two.
4. Finally, the adapted perceptual pathway image is converted back to RGB color space.

The second presented method basically differs from the first one by including information from the P-channel obtained in step one into the newly computed gray channel.

The results by applying these algorithms strongly depend on the type of an image. While good results can be achieved with real-life images, e.g. an image with baseball caps on it, composed artificial images with borders of white space between color such as the Ishihara Test plates leads to unsatisfactory results.

3.3.2 Color Contrast Enhancement

The *Color Contrast Enhancement* approach presented by Khurge and Peshwani (2015) works by adjusting the RGB values of an image in order to enhance the contrast between confusing colors. For deuteranopes, this means that green pixels appear to be more blue. The basic idea is to first halving the pixels to provide the room for pixel values (increase the pixel information of the original image).

Basically, the approach consists of three steps:

1. First, the red component of the RGB values is increased relative to pure red. Reds that are further away from pure red are increased significantly, while reds that are close to pure red are only increased marginally.

3 Theory

2. Second, the green component of the RGB values is increased relative to pure green. Therefore, the same procedure is applied with green as with red in step one.
3. Finally, more contrast is produced by reducing the blue component for pixels that are mostly red and increasing the blue component for pixels that are mostly green.

3.3.3 LAB Color Correction

The *LAB Color Correction* approach on the other hand mentioned by Khurge and Peshwani (2015) forces to increase the color contrast by manipulating the confusing color components (e.g. for deuteranopes this would be red and green). It works similar to the *Color Contrast Enhancement* approach described before, but uses the LAB color space to achieve a better color contrast.

LAB Color Correction is applied by using the following steps:

1. First, the RGB values of the original image are converted to the LAB color space.
2. The algorithm starts with the manipulation of the A component. Based on the sign of the specific component of the LAB color space, the contrast is enhanced. Pixels with a positive A component indicate that they are closer to red, whereas pixels with a negative A component indicate that they are closer to green. According to the *Color Contrast Enhancement* approach, a better contrast is achieved by increasing the positive A components (making them more red) while decreasing the negative A components (making them more green).
3. Next, the blue and yellow hues of an image are enhanced by adjusting the B component of each pixel relative to how green or red they are.
4. Due to each pixel's A component, the L component is adjusted to improve the brightness of the image.

5. Finally, the LAB color space image is converted back to RGB. Since RGB colors take values from zero to 255, all values below 0 are set to 0 whereas all values above 255 are set to 255.

3.3.4 Color-via-Pattern

The method presented by Herbst and Brinkman (2014) follows another approach to address the problems of colorblind people. While other implementations tend to distort the hue and the brightness of colors, the *Color-via-pattern* approach focuses on distinguishing only the hues rather than significantly changing the color brightness or saturation of an image. Color shifting algorithms typically act by changing the hue and/or luminance of confusing colors. However, this can still lead to the problem of confusing colors after the color shifting algorithm is applied. Although only red-green color deficiencies are considered, this approach also works similar for yellow-blue deficiencies. To highlight colors, lines are drawn by alternately darkening and lightening colors. Depending on how the lines are orientated, one can draw conclusions about the color information. For example, greenish colors have left-right stripes while reddish colors have right-left stripes (considering the start and endpoint of the line). Tests had shown that the *Color-via-Pattern* approach is good for hue tests, but have no significant advantages on color brightness tests.

Figure 3.10 shows the *Color-via-pattern* approach presented by Herbst and Brinkman (2014). While yellow colors are neutral and aren't denoted with stripes, greenish colors are characterised by left stripes and reddish colors are characterised by right stripes.

3 Theory

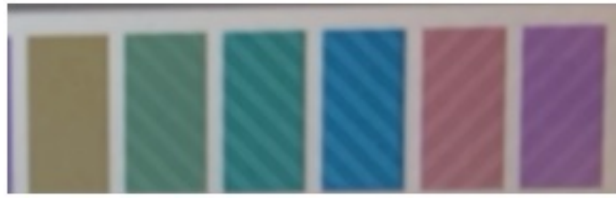


Figure 3.10: Color-via-Pattern, from Herbst and Brinkman, 2014

3.3.5 Empirical Methods

D. Flatla and Gutwin (2012) describe a recoloring tool called *SSMRecolor* that is based on *Situation-Specific Models (SSM)* to differentiate confusing colors. Because recoloring tools in general only work for a small amount of color vision deficiencies, a more personalized solution to overcome an acquired color vision deficiency, a situation-induced color vision deficiency and other types of congenital color vision deficiencies is needed. The key idea is to let the user perform a two-minute color calibration before using the tool to build a SSM depending on the users color-differentiation abilities. With the aid of the SSM, the recoloring tool determines confusing colors and corrects them. „The modified colors are then used to replace the problem colors in the image to produce a differentiable version of the image“ (p. 2297). While differentiable colors are maintained, only problem colors are modified. According to the evaluation of the speed, the color replacement take a few seconds on a standard desktop computer, making it impossible to use it for real-time applications such as live video or 3D gaming. However, this limitation will be improved in future work.

D. R. Flatla and Gutwin (2010) also brought another empirical approach, which also uses individual model of color differentiation. The major part of the existing solutions is using re-coloring, that is, changing color(s) in a visualization in a way such that the color(s) can be differentiated by the user. Typically, a predefined model is used to simulate the user’s color perception and subsequently re-color regions with confusioning colors. Hence, the selected model is very important for such approaches. The problem remains

that those models don't cover all certain forms of color vision deficiency. While people with a color vision deficiency that is close to the standard models work well, the usage of standard models can lead to unsatisfying results the more the color vision deficiency deviates from it. Factors like lightning, monitor settings or fatigue are also not taken into account by this solutions. To overcome these problems, D. R. Flatla and Gutwin (2010) developed a technique called individual color differentiation (ICD). The user has to perform certain differentiation tasks to build an individualized model. This has certain advantages: It doesn't require any knowledge of the user's color vision deficiency (model is build upon empirical test), all types of color vision deficiencies can be handled and envirointment factors are taken into account.

3.4 Augmented Reality

Colorblind people have a limited or damaged vision system. By means of visualization that involves color as an information medium, this results in an information loss. Nevertheless, approaches for improving the lost information exist and provide the possibility to correct color information in a way such that colorblind people can overcome their limited color vision system. In this section, Augmented Reality (AR) is presented according to its benefit for colorblind people.

3.4.1 Definition

Azuma (1997) stated that many researchers think that head-mounted displays are required to define AR. Instead of limiting the term to specific technologies, they describe AR by the following technology independent characteristics:

- Combines real and virtual

3 Theory

- Interactive in real time
- Registered in 3D

According to their definition, films and 2D overlays are not included, but allows monitorbased interfaces, monocular systems, see-through HMDs, and various other combining technologies to be considered as AR. Hence, AR let the observer see the real world which is augmented with virtual objects and hasn't the goal to completely replace the real world. Furthermore, AR combines Virtual Reality (VR) with the real world.

Furht (2011) define AR as „a real-time direct or indirect view of a physical real-world environment that has been enhanced/augmented by adding virtual computer-generated information to it“ (p. 3). The goal is to simplify the user's life by enhancing the perception of the user and interaction with the real world. This can be achieved by extending the real world with visual information or simply provide the possibility to let the user take an indirect view of the real-world environment such as live-video stream. Unlike AR, that „augments the sense of reality by superimposing virtual objects and cues upon the real world in real time VR completely immerses users in a synthetic world without seeing the real world“ (p. 3). AR is not limited for only displaying additional information, but can apply to more or even all senses of a user including smell, touch and hearing. A common use is also to augment or substitute the missing senses of users, e.g. augmenting the sight of blind users by using audio cues.

As a consequence, colorblind people or people with a color vision deficiency take benefit of AR. Audio cues can help distinguishing colors or real-world scenes can be modified in a way such that confusing colors are modified, e.g. by highlighting those or increasing the contrast of an image.

Furthermore, Furht (2011) stated that another use case of AR is to add virtual objects or remove real objects. The latter implies that the removed object is filled with virtual information to convey an impression that the real object isn't there. The information given by adding virtual objects to the real world result in an information gain for the user e.g. providing information the user can't recognize with his senses. Therefore, „information passed on

3.4 Augmented Reality

an virtual object can help the user in performing daily-task work“ (p. 4). For colorblind users, challenging daily task involve cooking (proofing meat rawness), buying fruits (determining ripeness of a fruit), buying and selecting cloths as well as carrer dependent skills like determining the colors of an resistor.

Figure 3.11 shows how AR is provided by Google Glass.



Figure 3.11: AR provided by Google Glass²⁰

3.4.2 Comparison with Virtual Reality

Azuma (1997) describes Virtual Environments (VE) or Virtual Reality (VR) as „technologies that completly immerse a user inside a synthetic environment“ (p. 2). While AR combines both, virtual objects and the real world, VR completly immerses the observer which doesn't make it possible to see the real world respectivly.

Milgram et al. (1994) confirmed that the concepts of AR and VR are related. Therefore, rather than defining a virtual reality environment as an environment in which the observer is surrounded by a completly synthetic world

²⁰<https://www.marsdd.com/news-and-insights/opportunities-augmentation-become-reality/> (last visited May. 12, 2016).

3 Theory

independent if the laws of physics governing or not, the two concepts can be viewed as „lying at opposite ends of a continuum, which can be referred to as the Reality-Virtuality (RV) continuum“ (p. 283). While the environment located on the left side (Real Environment) consists of real objects or an observed real-scene and the right environment consists of virtual objects such as computer graphic simulations, another environment called mixed reality (MR) environment located between the real and virtual environment exists. This environment combines real objects and virtual objects within a single display.

Figure 3.12 illustrates the described continuum defined by Milgram.

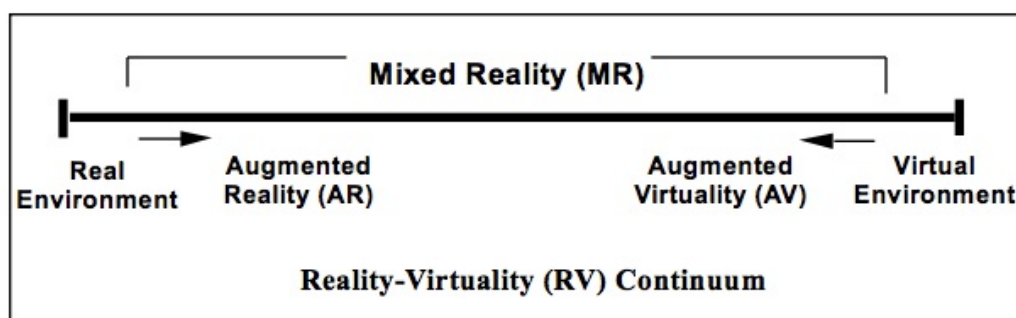


Figure 3.12: Reality-Virtuality continuum defined by Milgram et al. (1994)

3.4.3 History

The term AR often refers to head-mounted displays, but isn't really limited to those devices. The following section gives a short overview of the historical background of AR. However, describing all important stations will go far beyond the scope of this master thesis. Therefore, only important milestones regarding head-mounted displays (including smartglasses) are taken into account and are shortly described.

The first AR system is presented by Sutherland (1968). It is also known as the first virtual reality system. The original paper describes a optical

3.4 Augmented Reality

see-through head-mounted three dimensional display. To change the perspective when the user moves his head, special spectacles containing two miniature cathode ray tubes are attached to the user's head, which can be seen as a stereoscopic display. Furthermore, mechanical and ultrasonic trackers are used to determine the position of the user's head. A computer is then used to process the measured position of the user's head and transforms room coordinates to eye coordinates. The presented virtual image seems to be around eighteen inches away from the user's eyes. Because this head-mounted system was very heavy and uses a fixed arm construction, the device was limited to be used in laboratories rather than for mobile outdoor applications. Since processing power is very low in 1968, the virtual environment consists basically of wireframe rooms.

Later, the AR system presented by Sutherland got the name *Sword of Damocles*. „The formidable appearance of the mechanism inspired its name“ (n. p.).²¹

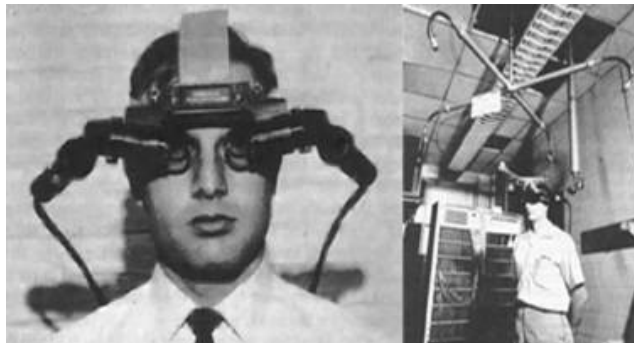


Figure 3.13: *The Sword of Damocles*, presented by Sutherland in 1968, taken from²²

Figure 3.13 shows the system presented by Sutherland in 1968.

²¹[https://en.wikipedia.org/wiki/The_Sword_of_Damocles_\(virtual_reality\)](https://en.wikipedia.org/wiki/The_Sword_of_Damocles_(virtual_reality)) (last visited May. 13, 2016).

²²<http://www.othercinema.com/otherzine/wearable-computers-augmented-reality-and-a-new-set-of-social-relations/> (last visited May. 13, 2016).

3 Theory

Caudell and Mizell (1992) coined the term AR by defining it as computer based material that overlays the real world. According to this, the authors present a design and prototype for a heads up, see through, head-mounted display which is shortly described as *HUDSET*. With the combination of head position sensing and a real world registration system, it is possible to superimpose the real world with computer generated objects where it's needed. Huge advantages of this new technology include cost reduction and efficiency optimization. For example, factory workers need to have assembly guides, templates and mylar lists etc. provided by engineers to correctly assemble an aircraft. This information is normally created and provided by a computer aided design (CAD) based system. This can lead to several problems during the manufacturing process like the requirement for *mirror changes* in the engineer design. However, by using the AR prototype, the real world can be overlapped with computer based content and therefore provide up-to-date information for the factory worker. For example, by wearing the heads-up, see-through display headset, factory workers get the information where a specific drill have to be placed along with some other usefull informations like the depth of the drill hole. The authors also differentate the terms AR and VR. Although their AR device is limited to display simple wireframes, template outlines and text, it has the advantage to use inexpensive microprocessors rather than using expensive desktop computer class processors as needed by VR devices. Thus, instead of processing each pixel of a scene (like it's usually done in VR environments), only about 50 lines have to be processed and superimposed with digital content. Beside those advantage, AR also comes with some problems. Accuracy plays a major role when superimposing the real world with digital information. Hence, „the location of the HUDset relative to the person's eyes and the workplace must be determined before work can begin“ (p. 660–661). Also, in some situations, an unethered system is necessary to avoid disturbing the worker (especially hard accessible places). The prototype presented uses a beam splitter to augment the real world with computer based material. Since the device should be lightweight because it's worn on the head, some components are outsourced to a belt pack like display system's processor, memory and the

3.4 Augmented Reality

power source. New digital material could be transferred while the device is attached to the battery station or alternatively via packet radio on the fly. To evaluate the demonstration system based on AR in the application of manufacturing, four applications have been developed such as connector assembly and maintenance or assembly. Although several weaknesses can be noted during the test of the demonstration system such as the fact that the presented system is not truly see-through which results confused many people because the brain tend to fuse the left eye real world scene with the digital content displayed on the right eye, it shows the great potential of AR in manufacturing applications.

In 1994, Steve Mann startet a project called *WearCam* which ended in 1996. In this time period, he had worn a mobile camera plus a display for every walk he has taken. The video stream was public available on the project's website²³. Visitors could see what Steve Mann could see and send text messages, which are then shown on the worn display. The goal was to have a near-realtime performance using a 64 bit processor. (Arth et al., 2015)

In 1997, Azuma (1997) presented the first survey on AR. The author clearly abstracts the term AR from the usage of underlying technologies (especially head-mounted displays). Instead, a technology independent definition is given. Furthermore, the term VR is delimited from AR.

For long time, ARs are limited to be indoor, more specific in a small area of a large room. In 1998, Thomas et al. (1998) presented a paper which describes the experiment to use AR techniques outdoors. Hence, the authors key objective was to extend an AR system from room size environments to large outdoor environments. For this purpose, a wearable computer together with a see-through display, digital compass and a differential GPS was worn by a user to provide visual navigation aids. The navigation software

²³<http://wearcam.org/> (last visited May. 15, 2016).

3 Theory

running on the device was specially created and is called *map-in-the-had*. The technical solution should cover a handfree navigation for the users. Rather than putting the wearable computer in a pocket like it's possible with smartphones today, they have to be worn elsewhere due to the fact that wearable computers weren't really compact at this time. In case of this prototype, it was even too large to carry on a belt. Therefore, the wearable computer together with the essential batteries and other extra peripherals had been put in a backpack. The user has to enter waypoints (latitude and longitude values) that lie between his position and the target position to start the visual navigation. Figure 3.14 shows the prototype device consisting of a wearable computer system (worn in the backpack), a see-through display and the GPS module worn on top of the head.



Figure 3.14: *Combining AR with a wearable computer system to achieve terrestrial navigation, taken from Thomas et al. (1998)*

Yohan et al. (2000) performed researches on the subject of a battlefield AR system (BARS). The key idea was to overcome certain problems a warfighter has such as the limited visibility, the unfamiliarity with the environment,

3.4 Augmented Reality

sniper threats, concealment of enemy forces and bad communication. Since situational awareness can't be achieved with radios or maps, more powerful display devices are needed. According to this, the used prototype consists of a wearable computer, a wireless network system and a head-mounted display. The system can be used either indoor or outdoor. The cumbersome parts of the construction such as the GPS module, the wearable computer and the battery packs were worn in a backpack. The head-mounted display enables the user to superimpose the real world with computer based material, for example a wireframe plan for a building or street names. In recent years, experiments with wearable computers in combination with GPS are performed by the military. However, certain disadvantages can be determined for those kind of approaches such as the fact that maps only provide 2D visualization and that the device using warfighter always have to look on the display (e.g. a laptop), making it harder to pay attention to the surrounding environment. The paper covers the research on the subject of tracking (location of the user) and user interface design (what the user sees) rather than the interaction with the device. Finally, the authors describe an information based filtering mechanism, which is needed to provide actual important information when it's needed. Figure 3.15 shows the developed prototype of BARS in 2000.



Figure 3.15: Battlefield AR system (BARS) developed in 2000, taken from Yohan et al. (2000)

In 2002, Kalkusch et al. (2002) presented an AR system that can be used to

3 Theory

guide a user to a target location in an unfamiliar building and is therefore used indoors. The user sees a wire framed model of the building through a see-through heads-up display and gets directional information where he has to go to get to the target location. The authors also describe a three-dimensional, World In Miniature (WIM) map on a wrist-worn pad that acts as input device for the AR system. For tracking purposes, a combination of wall-mounted ARToolkit markers that are recognized by a head-mounted camera and an inertial tracker is used. (Kalkusch et al., 2002)

Google Glass was first presented to the public in 2012. Google described the device as an optical head-mounted display that can be controlled via an installed touchpad located on the right hand side of the device or by using voice commands. The device triggered a major impact on research and brought AR to a new level. However, Google Glass wasn't available for developers in 2012. In 2013, registered developers were able to sign up and buy a device for development purposes. (Tobias Langlotz and Gruber, 2013)

3.5 Head-Attached Displays

3.5.1 Headmounted Displays

According to Bimber and Raskar (2006), the usage of video see-through and optical see-through head mounted displays for AR applications aren't something new. However, due to the fact that those devices have several technological and ergonomic drawbacks, they can not be used well for all kind of applications. In past years, new technologies came up which had taken AR to a new level that goes beyond traditional display methods such as hand-held displays. By using mirror beam-splitters, transparent screens, holograms or video-projectors, the field of application can be significantly increased. Those new technologies can be consolidated under a single term

3.5 Head-Attached Displays

called „Spatial Augmented Reality (SAR)“. Due to the decreasing costs of hardware such as projection technology, SAR systems are becoming more and more interesting for universities, laboratories and museums.

„Head-mounted displays (HMDs) are currently the display devices which are mainly used for AR applications“ (p. 3). They can be basically divided in two different types of display technologies:

- *Video see-through HMDs*: This display type typically uses video-mixing to augment the user's view of the real world. For this purpose, a video stream taken by the device (camera) is modified such that the merged images can be displayed by the device.
- *Optical see-through HMDs*: This display type makes use of optical combiners such as half-silvered mirrors or transparent LCD displays to produce augmented content. Hence, no video stream is needed, because the display directly overlaps the user's view of the real world.

Figure 3.16 presents an illustrated comparison of video see-through displays and optical see-through displays.

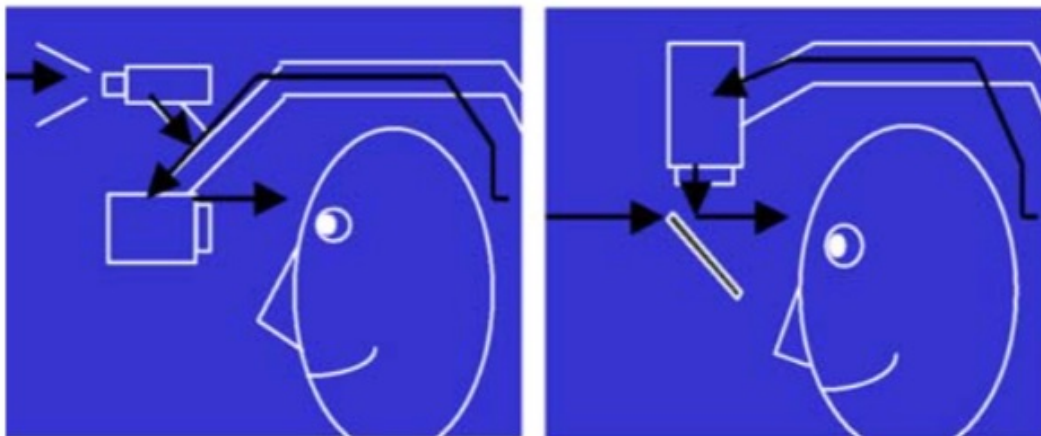


Figure 3.16: *Video see-through head mounted display (left side) and optical see-through display (right side), taken from Bimber and Raskar (2006)*

3.5.2 Head-Mounted Projectors

Bimber and Raskar (2006) describe head-mounted projective displays use a mirror beam-splitter to augment the user's view of the real world. For this purpose, images are beamed on retro-reflective surfaces, which are covered with micro corner cubes. These micro corner cubes have the property to reflect light. While normal surfaces reflect light in a diffuse direction, micro corner cubes reflect light along its incident direction. This results in a brighter image.

Beside head-mounted projective displays, there exists another display type called projective head-mounted displays. Instead of projecting the image on a retro-reflective surface, the image is projected on regular ceilings. This works by combining two half-silvered mirrors, which are used to project an image into the viewer's visual field.

Both, head-mounted projective displays and projective head-mounted displays have the positive property to decrease the effect of inconsistency of accommodation and convergence when compared with other head-mounted display types. Furthermore, they have the advantage to overcome the problem of the limited field of view with additional lenses that results in various distortions. Sadly, those display types also come with some shortcomings. The most important disadvantage is the cumbersomeness of those display types. Due to the usage of heavy optics resulting in poor ergonomics, those display types can barely be used outside laboratories.

3.5.3 Retinal Displays

While head-mounted displays typically consists of screens that are worn by the user in front of his eyes, retinal displays follow another approach. By using low-power semiconductor lasers, images are projected directly on the retina of the human eye. This approach has the advantage that the produced images are brighter, have a higher resolution, offer better contrast and take less energy than head-mounted displays. Hence, retinal displays suit very

well for mobile outdoor applications. However, due to their similarities to head-mounted displays, some problems are shared between those two display approaches. Furthermore, there are also some specific problems such as the fixed focal length and the existence of stereoscopic versions for retinal displays. (Bimber and Raskar, 2006)

3.6 Smartglasses

To help colorblind people, a couple of devices exist on the market. The *Oxy-IsoColorblindness Correction Medical Glasses* make it possible to only let red and blue colors through the lens. Therefore, it act as a passive filter for green colors. However, this can lead to the problem that users see a pink world. Beside the approach of using a passive filter to improve color vision for people with a color vision deficiency, electronic devices such as smartphones or tablets can be used for actively improving accessibility by manipulating electronic signal intensities. Electronic devices offer a huge amount of possibilites to help colorblind people e.g. provide a blinking function over the image areas containing confusing colors or enhance the object border of certain colors. (Oliveira, Ranhel, and Alves, 2015)

Today, mobile devices are widespread and indispensable in everyday's life. Nearly everyone owns a smartphone today. However, after the success story of the smartphone, new mobile devices such as smartglasses, smartwatches or smartclothing become more and more popular. With the appearing of Google Glass on the market, smartglasses have gotten an interesting platform for researchers and developers. However, those devices differ in terms of usability and use cases. Rather than using finger gestures, smartglasses usually provide handfree navigation via voice input or head gestures. Due to their limited computation performance and battery life, certain implementation aspects have to be considered when developing an application. While there exists already a bunch of applications for colorblind people or people with a color vision deficiency for smartphones and desktop computers, the number of applications for other mobile devices are relatively small. Hence,

3 Theory

smartglasses represent an interesting new platform to overcome the problems that colorblind people or people with color vision deficiency have to deal with every day. Instead of using the smartphone to take a picture or record a video, smartglasses are already worn by the user.

Oliveira, Ranhel, and Alves (2015) stated that „glasses could be manufactured with embedded correction algorithm with an undersized external camera to image capture, and Liquid crystal on silicon (LCoS) or RGB-LED screen on the inner face of the lens to the corrected image playback“ (p. 1).

3.6.1 Types

3.6.1.1 Google Glass

Google Glass is a head mounted wearable device manufactured by Google. Instead of using a display to show information such as smartphones, Google Glass projects information directly inside the person's field-of-view appearing in the corner of the right eye. Since the device is rich on sensors, growing API support and a compact design it's an exciting platform for researchers. However, Google presented the device to be primarily used as a notification device rather than a device that performs complex computations. It has a screen resolution of 640*360 pixels, which is equivalent to a 25-inch display from eight feet away. The capacitive touchpad is located on the right side of the device and makes it possible to control the device by swiping through so called Cards. As a wearable device that is worn like a normal pair of glasses, voice input is the second great method of input, making it possible to control device handfree. Head-gestures are the third way to control the device e.g. tilt the head backward to wakeup Google Glass. Beside an ambient light sensor, Google Glass owns an inertial and compass sensor as well as a proximity sensor. In terms of connection it offers Bluetooth 4.0 (with BLE support) and 802.11 b/g wireless module (internet connection is established via WLAN or smartphone tethering).

3.6 Smartglasses

The performance evaluation based on LinPack benchmark has shown that Google Glass can't compete with normal smartphones such as the Samsung Galaxy S2. Therefore, this underlines that the device is more likely to be used as an notification device rather than a computational rich platform. Tasks like image processing should be outsourced to a cloud or a cloudlet e.g. uploading a picture to cloud or cloudlet, perform tasks on it, returning a result back to Google Glass. Comparing with the Nexus 5 smartphone, the network throughput test performed with the iPerf benchmark test showed that Glass also has a significant lower TCP bandwidth. (Nguyen and Gruteser, 2015)

Figure 3.17 shows the Google Glass Explorer edition version 2 in black.



Figure 3.17: Google Glass Explorer Edition 2, taken from Techarx.com²⁴

3.6.1.2 Epson Moverio BT-200

The Epson Moverio BT-200 is a truly AR device, which is supposed to be used for enterprise purposes such as industry and medicine. The device integrates the digital projection wearer's immediate surrounding by using semi-transparency of projected image floating in space. Therefore, it can conceptually be placed between direct projection (like Google Glass did) and VR devices such as Oculus Rift²⁵. The device consists of a headset

²⁴<http://techarx.com/google-glass-will-get-a-complete-redesign/> (last visited May. 18, 2016).

²⁵<https://www3.oculus.com/en-us/rift/> (last visited May. 18, 2016).

3 Theory

and a control unit, which is connected via cable. While the headset is used for displaying information, the control unit is used for interaction and is equipped with a touchpad supporting multi-touch gestures and a bunch of buttons such as a menu button, a home button and power controls. Two micro projectors located on each side of the smartglasses project an image on the two small, 16:9 screens. The projection appears in the centre of the person's field-of-view. The built in camera on the front is more likely to be used for AR applications rather than taking photos or recording videos. Beside a compass, gyroscope and an accelerometer (built in both parts - smartglasses and controller) there is also a GPS module located in the control unit of the device. For connectivity, WIFI, Bluetooth 3.0 and a microUSB port can be used. The Epson Moverio BT-200 uses Android as operating system. The successor, the Epson Moverio BT-300 is already available for presale and appears on the market in 2016.²⁶

Figure 3.18 shows the Epson Moverio BT-200²⁷.



Figure 3.18: Epson Moverio BT-200¹⁴

²⁶http://skylla.ntc.zcu.cz/hcewiki/index.php/Epson_Moverio_BT-200 (last visited May. 18, 2016).

²⁷<http://www.epson.com/cgi-bin/Store/jsp/Product.do?sku=V11H560020> (last visited May. 18, 2016).

3.6.1.3 Recon Jet

Recon Jet provides a heads-up display fixed on a sunglasses frame with polarized lenses. The display is located in the bottom right corner of the smartglasses, while the battery is positioned on the left side (interchangeable). The device is primarily developed for sport activities, especially summer sports like cycling or running. Beside a GPS sensor, the Recon Jet device has built in sensors for metrics like speed, pace, distance and elevation. It also offers the possibility to pair other devices such as smartphones via Bluetooth, third party sensors via ANT+ and WLAN. Typically for smartglasses, notifications (phone calls, text messages) can be displayed on the device. It is suited with a 1 GHz ARM Cortex-A9 dual core processor, 1GB of RAM and 8 GB of storage. Recon Jet uses a custom operating system called Recon OS based on Android, optimized for small displays.²⁸ Figure 3.19 shows the Recon Jet²⁹.



Figure 3.19: Recon Jet Black¹⁵

²⁸https://en.wikipedia.org/wiki/Recon_Instruments#Jet (last visited May. 19, 2016).

²⁹<http://www.slashgear.com/recon-jet-takes-wearables-to-the-slopes-15282150/> (last visited May. 19, 2016).

3.6.2 Properties

3.6.2.1 Privacy

In recent years, *smartglasses*, especially Google Glass had often been examined for their privacy issues. Many people, including journalists mentioned that the camera can be used to observe people by recording a video or take a photo at all time. Hong (2013) argue that Google Glass is not the first wearable device having problems concerning privacy: In 1991, long time before ubiquitous computing plays a role in everyones life, wearable badges are developed by PARC researchers, making it possible to determine the location of a badge inside a building. Although the researches know that the development of those system has to pay attention on privacy concerns, they found no way to address the underlying issues and therefore they concentrated on the functionality and correctness of the system rather than addressing privacy concerns. This resulted of course in negative headlines. Furthermore, Hong (2013) statet that „when those who bear the privacy risks do not benefit in pro- portion to the perceived risks, the technology is likely to fail“ (p. 11). Based on the privacy concern of people in terms of beeing monitored by smartglass devices all the time, this means that the given value of this new technology must outweigh those concerns. Another interesting perspective is the one of expectations. Because of the lack of experience of how to use a wearable computer, many expectations will be off the mark. Also, expectations might change during over time, given that a real value is recognised for a new technology.

Singhal et al. (2016) presented „findings from an in-situ exploratory study that investigates bystanders reactions and feelings towards streaming and recording videos with smartphones and wearable glasses in public spaces“ (p. 3197). For this purpose, researchers simulate a recording video activity on campus with either a smartphone or a smartglass device (Google Glass). Another researcher observed the behavior of the bystanders and ask them for a short interview. They came to the conclusion, that participants react differently to

wearable cameras. While people clearly noticed the smartphone recording activity and react on them (e.g. pacing walking speed), no one noticed the Google Glass recording activity. Also, since nearly everyone owns a smartphone, people are less concerned about what happened with their personal information or data compared to Google Glass. Following the opinion of the authors, certain design considerations have to be taken e.g. „adding visual cues for the camera in order to make the camera activity recognizable“ (p. 3202).

3.6.2.2 Performance

Since smartglasses as any other mobile devices are very limited in terms of computation power and battery life, certain considerations have to be taken into account when developing applications for those devices.

Ha et al. (2014) presented a prototype implementation of an assistive system called *Gabriel* based on Google Glass for users in cognitive decline. Although their system focuses on people having a cognitive decline such as Alzheimer's disease or a traumatic brain injury, many of the given concepts are related to every kind of computational expensive applications running on a mobile device. Ha et al. (2014) described that the deep cognitive assistance remained an unattainable goal for the past years due to three main reasons:

- The speed and accuracy of many foundational technologies such as speech recognition and language translation have been steadily increased in the past years. Nowadays, the performance on mobile devices have become sufficient to overcome those tasks.
- The second important aspect is the fact that computing infrastructure is becoming more and more powerful. Hence, offloading strategies to overcome the problem of computational expensive tasks exist. Cloud computing is omnipresent nowadays.

3 Theory

- „Third, suitable wearable hardware was not available“ (p. 69). Head-up displays were formerly only used by the military and for researching activities. Today, mobile devices such as Google Glass offer an aesthetically elegant, product-quality hardware technology that provides many possibilities.

The offloading approach mentioned by Ha et al. (2014) can be described as the process of outsourcing the compute-intensive operations to powerful hardware such as a cloud service or another device e.g. notebook. Since wearable devices are primarily equipped with a lot of sensors to interact with the environment but only provide modest computing performance, whereas server hardware provides a huge amount of computation power but can't be used for mobile scenarios, offloading represents an interesting approach to combine the power of the two technologies. To show how offloading can improve the performance, Ha et al. (2014) have shown an experiment where the OCR³⁰ performance of Google Glass was measured, once without offloading and another time with offloading. Thus, in the first scenario, all computations for OCR are performed directly on Google Glass, whereas in the second scenario, the taken image is transmitted via WIFI to a server of modest capability. The results have shown that a significant improvement can be achieved with the usage of offloading. Although the experiment had only covered OCR performance, the benefit of offloading can be applied across the board a wide range of compute-intensive applications.

However, using offloading also leads to some disadvantages. The biggest problem is the availability of a network that is essential for this approach. In case of a network failure, server failure or any other disruption, the application can't be used as expected by the user which leads to frustration and discontent. In this case all computations have to be done on Google Glass, which results in poor performance and hurting the user's experience. For this purpose, fallback devices can be used e.g. a smartphone or a notebook. Hence, if the network service is temporarily unavailable, computations are

³⁰Optical Character Recognition https://en.wikipedia.org/wiki/Optical_character_recognition (last visited May. 19, 2016).

delivered to a fallback device.

Another problem is the high latency of normal network applications. Since Gabriel needed low-latency interaction to guarantee a good performance, the obvious solution of commercial cloud services over a WAN is unsatisfactory. To solve this issue, Gabriel uses so called cloudlets. „A cloudlet is a new architectural element that represents the middle tier of a 3-tier hierarchy: mobile device - cloudlet - cloud. It can be viewed as a data center in a box whose goal is to bring the cloud closer“ (p. 71). The process can be briefly described as follows:

1. First, the Google Glass application discovers the nearby cloudlet's. If no cloudlet cannot be discovered, the application tries to connect to a cloud service. If this fails too, offloading is performed on the fallback device.
2. Image is processed at the cloudlet, cloud service or fallback device, regarding of what is available (in this order).
3. The result is given back to the Google Glass device.

Due to the evaluation of Gabriel, a significant decrease in latencies can be noticed by using cloudlets over clouds.

To overcome the problem of queuing latency, the paper presents an „application-level, end-to-end flow control system to limit the total number of data items in flight at a given time “ (p. 74). The control system consists of a token-bucket filter, which is used to limit the amount of data items in the processing pipeline and therefore mitigate queuing. As it turned out, significant improvements are achieved regarding the latency by applying the described approach.

Furthermore, Ha et al. (2014) stated that offloading can be used to improve performance of compute-intensive operations. However, the design decision to perform offloading results in a strong dependence on network availability. The development of an assistive system such as Gabriel, who's requirement

3 Theory

is to provide a real-time solution with many compute-intense operations and high reliability, needs offloading due to the limited processing power and battery life of a smartglasses device such as Google Glass. OmniColor on the other hand doesn't need that high amount of reliability. Users often want to proof their assumption by using the application for a single scene-view, rather than wearing smartglasses all day long to correct their color vision deficiency. Thus, OmniColor is designed to perform all operations directly on Google Glass and renounced the usage of offloading.

4 Implementation

4.1 Google Glass Development

When developing an application for Google Glass, special considerations in terms of guidelines and coding styles have to be taken into account. This section describes the basic concepts and main UI elements needed for the development of a standard Google Glass application. (Tang, 2014)

4.1.1 Timeline

The timeline forms basically the central Glass UI, which consists of a set static or live cards (each of them having the size of 640*360 pixels). By swiping over the touchpad in either forward or backward direction, it's possible to navigate through the cards. The cards themselves can give information to the user or letting them perform certain actions on them. The home screen of Google Glass shows the current time and the text „OK, Glass“, located at the centre of the timeline. (Tang, 2014)

4.1.2 Glass-styled cards

Glass-styled cards are usually cards containing a main text, a left-aligned footer and one or more images displayed on the left side. Cards can be used in in various environments like activities and layouts. (Tang, 2014)

4 Implementation

4.1.3 Live cards

Live cards are located on the left side of the home screen and contain actual important informations. They make it possible to access low-level Glass hardware such as sensors and GPS. Live cards can be separated in two different types, according to their render time. While *high-frequency live cards* are more likely to be used for 2D and 3D applications that are needed to be rendered multiple times within a second, *low-frequency live cards* are usually rendered once every few seconds. Since live cards are part of the timeline, forward and backward swiping gestures can't be used due to their function of navigating through the timeline. (Tang, 2014)

Therefore, live cards are well used for ongoing tasks and applications that require a real-time interaction with the user or real-time updates. Live cards remain in the timeline, until they are closed explicitly by the user or the device is powered off. (Google, 2015b)

4.1.4 Immersions

*Immersion*s are designated for applications that must provide rich content or require high user interaction. They're usage is very similar to live cards. Hence, *immersion*s also provide the possibility to use low-level Glass hardware, but unlike live cards, forward and backwards swipe gestures can be used within the application. (Tang, 2014)

*Immersion*s allow the most custom experience when developing a Glass application. They are displayed outside the timeline to enable the complete control over hardware and processing of user inputs. However, a limitation in terms of user input still exists: it is not possible to use the swiping down gesture in the application, since it used to exit *immersion*s. (Google, 2015a)

4.1.5 Menus

All different types of cards, including static cards, live cards and immersions can contain menu items which are selectable by tapping on the touchpad or via voice command and therefore provide a way to perform actions by the user. (Tang, 2014)

4.1.6 Voice input

Instead of using gestures, user can perform voice commands which are accepted by Glass to either open a application or perform actions on specific cards after the application is launched. (Tang, 2014)

Therefore, *voice commands* enable hand-free navigation.

4.1.7 Gestures

The multitouch panel enable the users to use multitouch gestures such as one-finger, two-finger and three-finger swipe. Beside that kind of user interaction, Glass also provides the possibility to use head gestures such as head panning, look up and nudge. (Tang, 2014)

4.1.8 User Interface

The user interface of Google Glass is specific to the device and differs from user interfaces of smartphones. Therefore, there are different standard layout and margin guidelines according to the different types of timeline cards that need to be considered when developing a Glass application.

4 Implementation

4.1.8.1 Card regions

Cards can be divided in general regions, making it possible for developers to display cards consistently. Hence, the main card regions are:

- *Main content*: Bounded by padding, the main content is used to display various kind of informations and/or the title of the card.
- *Full-bleed image*: For image presentation, the whole space of a card should be used (640*360) without a padding.
- *Footer*: The footer can be used to show supplementary information about a card e.g. a timestamp.
- *Left image or column*: Make it possible to display an image in the left corner of a card, but requires modifications to padding and text content.
- *Padding*: To clearly present content, timeline cards normally should be padded with 40 pixels on each side.

The different regions are shown in figure 4.1. The main content is highlighted with red, the full-bleed image with grey, the footer with blue, left image or column with violet and padding with green.³¹



Figure 4.1: Card regions of Glass, taken from Google ³¹

³¹https://developers.google.com/glass/design/style#metrics_and_grids (last visited May. 22, 2016).

4.1.8.2 Colors

Colors play an important role to denote urgency or importance. While most text on Glass is displayed in white (provides also best contrast) there are also some other colors that can be used. These colors can also be used on timecards:

CSS Class	RGB Value
white	#ffffff
gray	#808080
blue	#34a7ff
red	#cc3333
green	#99cc33
yellow	#ddb111

Table 4.1: Different colors to be used by a Glass application

Figure 4.2 shows an example about train lines and their status which uses colors to denote important information.³²

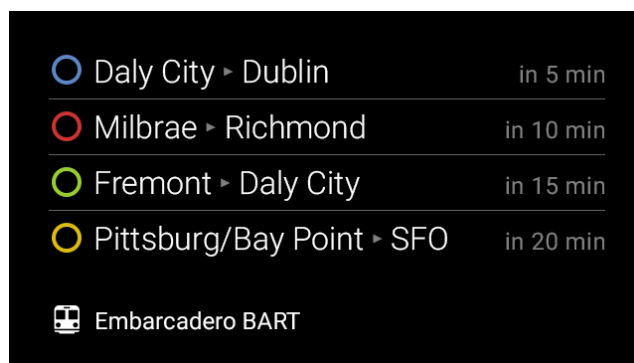


Figure 4.2: Recommended colors from Google for Glass development, taken from Google³²

³²<https://developers.google.com/glass/design/style#color> (last visited May. 22, 2016).

4 Implementation

4.1.8.3 Typography

Glass development usually plans to use a single typography. For displaying text on Glass, all system text use *Roboto Light*, *Roboto Regular* or *Roboto Thin*. According to the length and size of content, Glass decides which font has to be taken to ensure that it can be clearly read. This is called dynamic text resizing and is used on *Cardbuilder.TEXT* and *Cardbuilder.COLUMNS* layout. However, developers are not limited to use the suggested typography - they can use different typography on live cards and immersions.³³

Figure 4.3 shows a card containing text in Roboto light 32pt, figure 4.4 shows a card containing text in Roboto light 40pt, figure 4.5 shows a card containing text in Roboto light 48pt and figure 4.6 shows a card containing text in Roboto thin 64pt respectively.

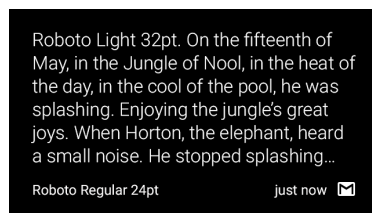


Figure 4.3: Roboto light 32pt³³



Figure 4.4: Roboto light 40pt³³

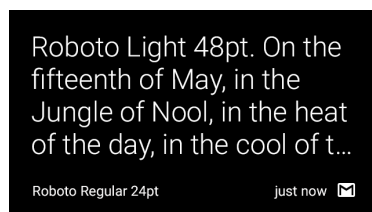


Figure 4.5: Roboto light 48pt³³



Figure 4.6: Roboto thin 64pt³³

³³<https://developers.google.com/glass/design/style#typography> (last visited May. 22, 2016).

4.2 Development Tools

Google Glass uses an Android based system. At the moment of writing the *OmniColor* application, two big IDE's³⁴ are well known for Android development. *Eclipse*³⁵ in combination with the ADT Bundle is the old standard to develop Android applications. This environment can be set up at most platforms such as Windows, OSX and Linux. However, since the first stable release of *Android Studio*³⁶ in December 2014, this IDE is becoming the standard IDE for developing Android applications.

Due to Rajput, 2015 there are a number of advantages to choose Android Studio rather than Eclipse for Android development:

- *Code Completion*: Although code completion is provided by both environments, the code completion of Android Studio works better, as Eclipse sometimes doesn't provide precise results.
- *System Stability*: When comparing Eclipse with Android Studio in terms of system stability, Eclipse needs overall more resources, due to the fact that it's a Java application. Therefore, Android Studio fares better and needs less time for building complex Android applications.
- *Project organization*: Often, projects have to be used at the same time. Eclipse can't handle this situation well, since other projects have to be merged in a single workspace. On the other hand, Android Studio uses modules and Gradle³⁷ build files to overcome those problems.

Both IDE's can still be used to develop Android applications. However, due to the specialisation on the Android platform and the given advantages, this prototype is developed with Android Studio v1.5.0.

³⁴Integrated Development Environment https://en.wikipedia.org/wiki/Integrated_development_environment (last visited May. 23, 2016).

³⁵<https://eclipse.org> (last visited May. 23, 2016).

³⁶<https://developer.android.com/studio/index.html> (last visited May. 23, 2016).

³⁷<http://gradle.org> (last visited May. 23, 2016).

4.3 OmniColor Prototype

4.3.1 Graphical Userinterface (GUI)

OmniColor is developed as an asynchronous, non-realtime Google Glass application. Since live cards are more likely to be used for 2D and 3D applications that need to be rendered multiple times within a second, they are not the best choice for this approach. Instead, Immersions were used due to their possibilities including the usage of forward and backward swipe gestures. The user has the possibility to either control the application by using the touchpanel of the Glass or via voice commands. The process can be explained as follows:

1. Starting at the Home screen of the Google Glass, one has to get to the application list by performing a single tap on the touchpad or use the voice command „OK, Glass“.
2. Next, The *OmniColor* application has to be opened by performing a single tap on the touchpad or use the voice command „OmniColor“.
3. Now that the application is opened and initialized, the menu to select the desired color vision deficiency has to be opened by performing a single tap on the touchpad or via the voice command „OK, Glass“.
4. With the menu being opened, the desired color vision deficiency is chosen by using the forward and backward swipe gesture and accepted by performing a single tap on the touchpad or using the voice command according to what color deficiency should be chosen (e.g. Deuteranopia).
5. The next screen shows a prompt to take a picture by performing a single tap on the touchpad or use the voice command.
6. After a few moments, the taken picture is shown to the user who has now the possibility to accept the image by performing a single tap on the touchpad or to get back by performing the swipe down gesture.
7. Since all computations are performed directly on Google Glass rather than use offloading to perform computationally expensive tasks in

4.3 OmniColor Prototype

the cloud or another device, the processing will take sometime. The user gets an hint that the device is now calculating the result image according to the previous specified color vision deficiency.

8. Finally, after the result image has been computed, it is shown the user. The user can now get back and take another picture without having to choose the color vision deficiency another time.

Figure 4.7 created with the Glassware Flow Designer ³⁸ provided by Google illustrates the process of the *OmniColor* application.

³⁸<https://developers.google.com/glass/tools-downloads/glassware-flow-designer#getting-started> (last visited May. 24, 2016).

4 Implementation

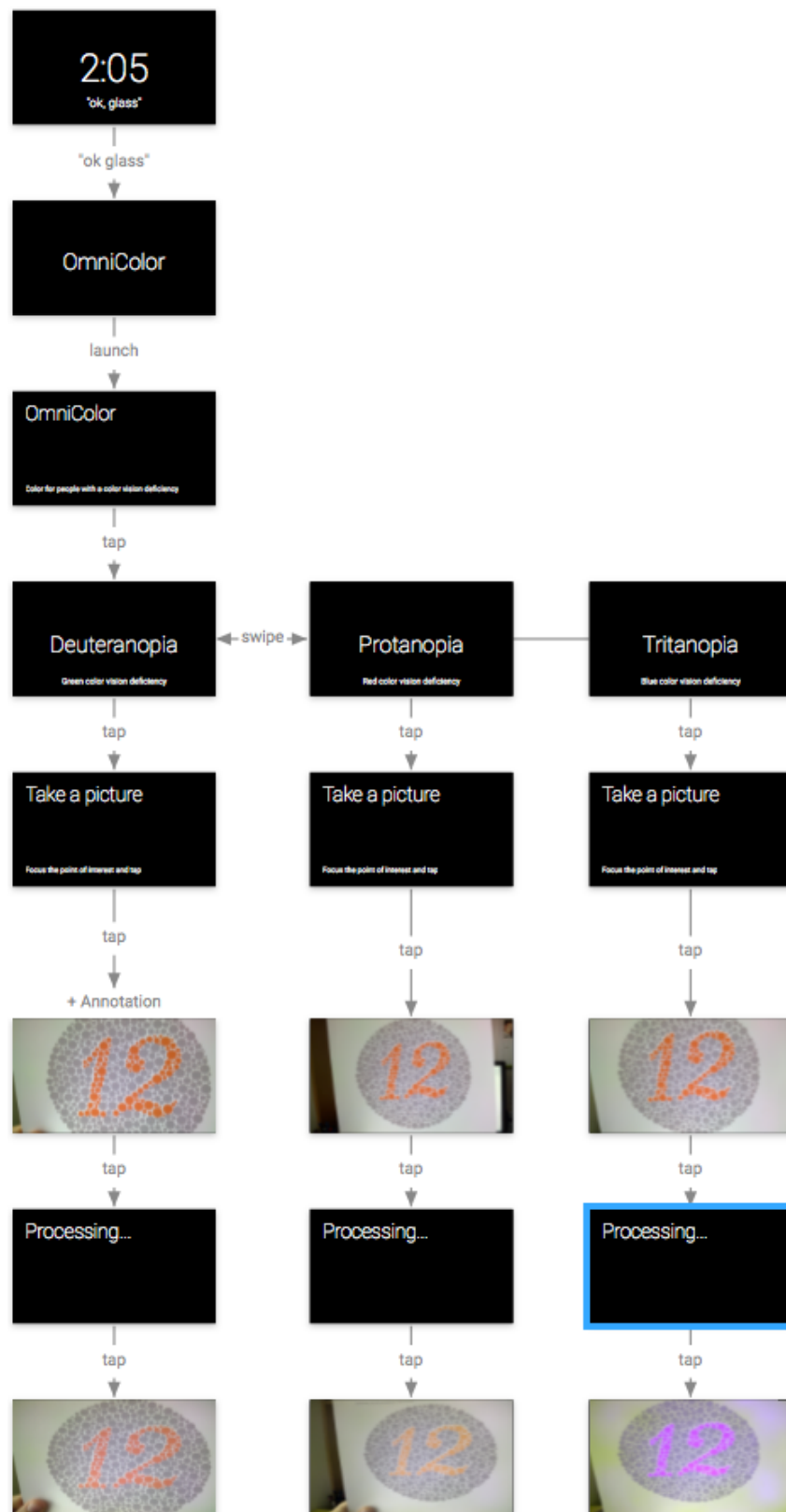


Figure 4.7: OmniColor Glassware Flowdesign

4.3.2 Libraries

4.3.2.1 OpenCV

OpenCV is basically an open source library for image and video analysis developed by Intel and officially launched in 1999. Due to the huge community and user group, the library is very powerful and contains over 2500 optimized algorithms. Since it is licensed under the BSD license³⁹, it can be used in academic and commercial applications. With *OpenCV 2*, many changes have been made to the interface. The library can be separated in different modules, each of them dedicated to a specific computer vision problem. Images are represented by matrices e.g. an empty image would have the dimension $o * o$. Pixels can be accessed by simply specifying the row and column of the matrix. The matrices can have different types according to the image type e.g. (*CV_8U*) would have one channel with each pixel stored in one byte, whereas *CV_8UC3* provides 3 channels for representing a colored image. *OpenCV* offer automatic memory management, therefore no manual allocation and deallocation is needed. Culjak et al., 2012

Google Glass runs Android, thus a library for this platform is needed. Fortunately, *OpenCV* is also available for Android⁴⁰, although some restrictions are given due to the fact that Android is not a desktop operating system.

In terms of performance, Hudelist, Cobârzan, and Schoeffmann (2014) stated that certain computation operations were only two to three times slower on a mobile device than on a consumer grade laptop computer. Although even high end mobile devices can't compete with the performance of typical consumer grade PC's, there exists certain scenarios where smartphones and tablets could match up to almost 60 percent of the power given by a PC. Sadly, this paper is limited to only smartphone and tablet devices brought by

³⁹<http://www.linfo.org/bsdlicense.html> (last visited May. 24, 2016).

⁴⁰<http://opencv.org/platforms/android.html> (last visited May. 24, 2016).

4 Implementation

Apple. It would be nice to include also other mobile devices such as smart-glasses, which are also able to run with the *OpenCV* framework. However, once installed, *OpenCV* offers many comfortable features and algorithms to manipulate Google Glass taken images according to the Daltonization algorithm. *OmniColor* uses *OpenCV* version 2.4.2.

Code listing 4.1 shows how the *OpenCV* library is asynchronous loaded before the result image will be computed.

```
// initialize OpenCv Manager
if (!OpenCVLoader.initAsync(
    OpenCVLoader.OPENCV_VERSION_2_4_2,
    this,
    mOpenCVCallback)) {
    Log.e("OpenCv", "Cannot connect to OpenCV Manager");
} else {
    Log.d("OpenCv", "Connected to OpenCV Manager");

    // load library
    try {
        System.loadLibrary("opencv_java3");
    } catch (UnsatisfiedLinkError e) {
        Log.v("ERROR", "OpenCV Error occured " + e);
    }
}
```

Listing 4.1: Asynchronous loading of the *OpenCV* library

4.3.3 Camera

Google Glass provides two main methods to use the camera for applications. The first method is to call the built-it camera activity with *startActivityForResult()*, which is recommended from Google to be used whenever it is

4.3 OmniColor Prototype

possible. The second method is to build a custom logic with the Android Camera API⁴¹.

For *OmniColor*, the first approach was chosen, since it already follows the guidelines provided by Google to handle camera activity. For this purpose, after selecting a color vision deficiency mode, a new activity will be started by calling *startActivityForResult(Intent, int)* with the action set as *ACTION_IMAGE_CAPTURE*. It's very important to know that even when the *resultCode* matches *RESULT_OK* and the image capture intent returns control to the calling activity again, the image might not be fully written to file. To overcome this problem, a *FileObserver* is used to verify if the file already exists. After the *FileObserver* determines that the file is correctly written, the taken picture is ready to be processed.

Code listing 4.2 shows the method *processPictureWhenReady* which is also used in *OmniColor* to determine if a taken picture is ready to be further processed.

```
private void
    processPictureWhenReady(final String picturePath) {

final File pictureFile = new File(picturePath);

if (pictureFile.exists()) {
    // The picture is ready; process it.
} else {
    // The file does not exist yet. Before starting
    // the file observer, you can update your UI to
    // let the user know that the application is
    // waiting for the picture (for example, by
    // displaying the thumbnail image and a progress
    // indicator).

final File parentDirectory =
```

⁴¹https://developers.google.com/glass/develop/gdk/camera#sharing_the_camera_with_the_glass_system (last visited May. 25, 2016).

4 Implementation

```
    pictureFile.getParentFile();

FileObserver observer =
    new FileObserver(parentDirectory.getPath(),
        FileObserver.CLOSE_WRITE |
        FileObserver.MOVED_TO) {

    // Protect against additional pending events
    // after CLOSE_WRITE or MOVED_TO is handled.

    private boolean isFileWritten;

    @Override
    public void onEvent(int event
                        ,String path) {
        if (!isFileWritten) {
            // For safety, make sure that the
            // file that was created in the
            // directory is actually the one
            // that we're expecting.
            File affectedFile =
                new File(parentDirectory, path);

            isFileWritten =
                affectedFile.equals(pictureFile);

            if (isFileWritten) {
                stopWatching();

                // Now that the file is ready,
                // recursively call
                // processPictureWhenReady again.
            }
        }
    }
}
```

```

        runOnUiThread(new Runnable() {
            @Override
            public void run() {
                processPictureWhenReady ( picturePath );
            }
        });
    }
}
};
observer.startWatching ();
}
}

```

Listing 4.2: File Observation of the camera activity

4.3.4 Daltonization

To overcome problems colorblind people have to deal with everyday, *OmniColor* uses a slightly modified *Daltonization* algorithm. The algorithm works by recoloring an image, but attempts to preserve color and information. There are several reasons why this algorithm has been chosen rather than another color correcting algorithm. First, the algorithm is by far one of the fastest algorithms that can be used to correct lost color information according to a specific color blindness type. Since *Google Glass* is very limited in terms of processing power and battery time, the usage of a fast algorithm is an important design decision. Furthermore, *Daltonization* can be used for all different types of colorblindness, regardless of whether the user has deuteranomaly, protanomaly or tritanomaly. Another advantage is that the original image is most widely unaltered, which means that the result image doesn't consist of only new colors. Hence, normal visioned people will only consider small changes and are also able to distinguish the colors after the algorithm is applied.

4 Implementation

Tanuwidjaja et al. (2014a) mentioned that they have modified the *Daltonization* algorithm for their Google Glass application „Chroma“ by precomputing a hash-map. Since the algorithm processes each pixel in each frame, it was needed to reduce computational time in order to reduce latency for their real-time approach. Therefore, each pixel of the original image is processed by looking into the hash-map and fetch the according *Daltonized* color. However, according to the results of the paper, colorblind people often only want to proof their assumption if an object such as a coat has a specific color. Thus, to satisfy those needs, no computation expensive and high-battery consuming real-time approach is required. Therefore it was obvious, that *OmniColor* uses a asynchronous, non-realtime approach.

The first step of the *Daltonization* algorithm is the transformation of RGB values which are ranged between 0 and 255 into the LMS color space. This can be done with a simple matrix multiplication as given by equation 4.1.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 17.8824 & 43.5161 & 4.11935 \\ 3.45565 & 27.1554 & 3.86714 \\ 0.02996 & 0.184309 & 1.46709 \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (4.1)$$

For each color blindness type, there exists an individual color deficiency matrix. Those matrices are respectively S_{deut} for deuteranomaly given by 4.2, S_{prot} for protanomaly given by 4.3 and S_{trit} for tritanomaly given by 4.4.

$$S_{deut} = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.494207 & 0.0 & 1.24827 \\ 0.0 & 0.0 & 1.0 \end{bmatrix} \quad (4.2)$$

$$S_{prot} = \begin{bmatrix} 0.0 & 2.02344 & -2.52581 \\ 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix} \quad (4.3)$$

$$S_{trit} = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 \\ -0.395913 & 0.801109 & 0.0 \end{bmatrix} \quad (4.4)$$

According to the type of color blindness, the right matrix is chosen for S_x and multiplied with the LMS transformed values. The result values $(L_{sim}, M_{sim}, S_{sim})$ represents the simulation of the pre-chosen color blindness type, given by 4.5.

$$\begin{bmatrix} L_{sim} \\ M_{sim} \\ S_{sim} \end{bmatrix} = S_x \times \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (4.5)$$

Next, the simulated LMS values are converted back to RGB values by using the inverse matrix of the LMS conversion matrix given in 4.1. This results in an equation given by 4.6.

$$\begin{bmatrix} R_{corr} \\ G_{corr} \\ B_{corr} \end{bmatrix} = \begin{bmatrix} 0.0809445 & -0.130505 & 0.1167211 \\ -0.0102485 & 0.0540193 & -0.113615 \\ -0.0000365 & -0.0041216 & 0.6935114 \end{bmatrix} \times \begin{bmatrix} L_{sim} \\ M_{sim} \\ S_{sim} \end{bmatrix} \quad (4.6)$$

With the information of the previous step, it's possible to calculate compensation values. This is done by calculating the subtraction of the original's image RGB values and the according to the color blindness type simulated RGB values, given in 4.7.

$$\begin{bmatrix} R_{err} \\ G_{err} \\ B_{err} \end{bmatrix} = \begin{bmatrix} R \\ G \\ B \end{bmatrix} - \begin{bmatrix} R_{corr} \\ G_{corr} \\ B_{corr} \end{bmatrix} \quad (4.7)$$

Now, the necessary shift is computed to make the color more visible for colorblind people, resulting in R_{shift} , G_{shift} and B_{shift} given in 4.8.

4 Implementation

$$\begin{bmatrix} R_{shift} \\ G_{shift} \\ B_{shift} \end{bmatrix} = \begin{bmatrix} 0.0 & 0.0 & 0.0 \\ 0.7 & 1.0 & 0.0 \\ 0.7 & 0.0 & 1.0 \end{bmatrix} \times \begin{bmatrix} R_{err} \\ G_{err} \\ B_{err} \end{bmatrix} \quad (4.8)$$

Finally, the resulting matrix of the *Daltonization* algorithm is calculated by multiplying the original RGB values with the shifted RGB values, as given in 4.9.

$$\begin{bmatrix} R_{dal} \\ G_{dal} \\ B_{dal} \end{bmatrix} = \begin{bmatrix} R \\ G \\ B \end{bmatrix} \times \begin{bmatrix} R_{shift} \\ G_{shift} \\ B_{shift} \end{bmatrix} \quad (4.9)$$

Code listing 4.3 shows an extract of the *Daltonization* algorithm as used in *OmniColor*.

```
for (int y = 0; y < image.cols(); y++) {
    for (int x = 0; x < image.rows(); x++) {

        double[] actRGBVal = image.get(x, y);

        // LMS transformation
        lmsVals[2] = (17.8824 * actRGBVal[2]) +
                    (43.5161 * actRGBVal[1]) +
                    (4.11935 * actRGBVal[0]);
        lmsVals[1] = (3.45565 * actRGBVal[2]) +
                    (27.1554 * actRGBVal[1]) +
                    (3.86714 * actRGBVal[0]);
        lmsVals[0] = (0.0299566f * actRGBVal[2]) +
                    (0.184309f * actRGBVal[1]) +
                    (1.46709f * actRGBVal[0]);

        // color defficiency calculation according
        // to type
```

4.3 OmniColor Prototype

```
colorDefficiencyVals [2] =
    cbTypeMat.get(0,0)[0] * lmsVals [2] +
    cbTypeMat.get(0,1)[0] * lmsVals [1] +
    cbTypeMat.get(0,2)[0] * lmsVals [0];
colorDefficiencyVals [1] =
    cbTypeMat.get(1,0)[0] * lmsVals [2] +
    cbTypeMat.get(1,1)[0] * lmsVals [1] +
    cbTypeMat.get(1,2)[0] * lmsVals [0];
colorDefficiencyVals [0] =
    cbTypeMat.get(2,0)[0] * lmsVals [2] +
    cbTypeMat.get(2,1)[0] * lmsVals [1] +
    cbTypeMat.get(2,2)[0] * lmsVals [0];

// transform back to rgb
rgbVals [2] =
    0.0809444479 * colorDefficiencyVals [2] +
    (-0.130504409) * colorDefficiencyVals [1] +
    0.116721066 * colorDefficiencyVals [0];
rgbVals [1] =
    (-0.0102485335) * colorDefficiencyVals [2] +
    0.0540193266 * colorDefficiencyVals [1] +
    (-0.113614708) * colorDefficiencyVals [0];
rgbVals [0] =
    (-0.000365296938) * colorDefficiencyVals [2] +
    (-0.00412161469) * colorDefficiencyVals [1] +
    0.693511405 * colorDefficiencyVals [0];

// daltonization
rgbIsolateVal [2] = actRGBVal [2] - rgbVals [2];
rgbIsolateVal [1] = actRGBVal [1] - rgbVals [1];
rgbIsolateVal [0] = actRGBVal [0] - rgbVals [0];

// shift colors to make them visible
```

4 Implementation

```
// for colorblinds
rgbCorrectedVal[2] = (0.0f * rgbIsolateVal[2]) +
                    (0.0f * rgbIsolateVal[1]) +
                    (0.0f * rgbIsolateVal[0]);
rgbCorrectedVal[1] = (0.7f * rgbIsolateVal[2]) +
                    (1.0f * rgbIsolateVal[1]) +
                    (0.0f * rgbIsolateVal[0]);
rgbCorrectedVal[0] = (0.7f * rgbIsolateVal[2]) +
                    (0.0f * rgbIsolateVal[1]) +
                    (1.0f * rgbIsolateVal[0]);

// compensate org. vals
rgbCorrectedVal[0] = rgbCorrectedVal[0] + actRGBVal[0];
rgbCorrectedVal[1] = rgbCorrectedVal[1] + actRGBVal[1];
rgbCorrectedVal[2] = rgbCorrectedVal[2] + actRGBVal[2];

// thresholding
for(int i = 0; i < 3; i++) {
    if (rgbCorrectedVal[i] < 0.0f)
        rgbCorrectedVal[i] = rgbCorrectedVal[i] = 0.0f;
    else if (rgbCorrectedVal[i] > 255.0f)
        rgbCorrectedVal[i] = rgbCorrectedVal[i] = 255.0f;
}

cbCorrectedMat.put(x, y, rgbCorrectedVal);
}
}
```

Listing 4.3: Daltonization algorithm used in OmniColor

5 Evaluation

5.1 Setup

To test the *OmniColor* Glass application, a standard Ishihara color test containing 14 color plates was performed. Other stages of the Ishihara color test that contain more color plates usually are used for people that don't know English numbers. Since there were no participants having issues to read numbers, the 14 plate Ishihara color test is sufficient. The participants had to do the exact same test twice. One time without the help of the *OmniColor* application and the second time with it. The test was performed individually by each participant rather than in a group of participants. First, all participants are introduced to the Ishihara color test. Therefore, the test was executed with printed color plates. They were informed that there isn't a time limit to take the test nor that there's any kind of help from the examiner. The participants were required to read the number of the actual color plate and report it to the examiner. The reported numbers are then recorded by the examiner. Actually, there are three possible options on each plate:

- If the participant is sure about the actual number, it is reported and recorded by the examiner.
- If the participant is not sure about the actual number, he/she can give two suggestions. Both are recorded by the examiner.
- If the participant can't see any number on the plate, he/she can skip it.

5 Evaluation

Next, the participants were briefly introduced to Google Glass and the *OmniColor* application. The examiner demonstrates the use of the application and showed a screencast on a Android phablet to the participant. For this purpose, the examiner presented the use of *OmniColor* on an introductory plate, which can be recognized by both groups of participants, people without color vision deficiency and people with color vision deficiency. Therefore, the introductory plate doesn't give information about a specific color vision deficiency. The participants were then required to perform the same scenario for the introductory plate again to get a feeling of how the application works. After this short introduction, the participants were asked to do the Ishihara color test again with the use of the *OmniColor* application. Since the processing time on each plate takes a non negligible amount of time, each participant had only to take 4 color plates. People having a color vision deficiency were required to take plates where it was hard or impossible for them to report a number while people without a color vision deficiency were able to decide which color plates they want to take. Of course, since people with a normal color vision don't belong to a specific color vision deficiency mode, they were recommended to choose the deutanopia mode, because the result image only change marginally. For the rest of the plates, previously taken images of the plates are shown to the participants by the examiner. Again, the reported numbers are recorded by the examiner (along with the information which color deficiency type the participant had). Finally, the Ishihara color test results were compared with the two performed stages of the test.

5.2 Results

Five out of the 14 participants have a diagnosed color vision deficiency. Due to the fact that males are more likely to have a color vision deficiency than females, all participants with a color vision deficiency are males. Also, since tritanopia is very rare, no participant can be found with this type of color vision deficiency. The age ranges from 28 to 48. While four of the

5.2 Results

five participants with a color vision deficiency are protans (one of them also stated that he has also a mild tendency for deuteranomaly), one participant doesn't know which type of color vision deficiency he had. For this participant, two qualitatively diagnostic plates were analyzed with the deuteranopia mode and the protanopia mode. This led to the obvious assumption, that the participant is more likely to be a protan than a deutan. The degree of the color vision deficiency of the five participants range from mild to strong. Every participant of the color vision deficiency group was able to significantly improve on the Ishihara color test with the support of the *OmniColor* application. The three strong protans all went from strong to mild, while one mild protan achieved a normal color vision on the test. After that, participants were able to report the number on the plate correctly. The last participant however only achieves a minimal improvement with the usage of *OmniColor*. All five participants stated that they found *OmniColor* useful and three of them could imagine to use it in everyday life. However, four out of five participants also criticized the performance of the application and the heat generation of the Glass device while using *OmniColor*. No one of the color vision deficiency group wears a glass, therefore, no concern about this limitation was expressed. Table 5.1 shows the Ishihara color plate test results for people with a color vision deficiency - either without and with the usage of *OmniColor*.

Participant age	Color vision deficiency	Without <i>OmniColor</i>	With <i>OmniColor</i>
36	protanomaly	7/17	12/17
48	protanomaly	2/17	11/17
37	protanomaly	3/17	12/17
28	protanomaly	7/17	13/17
41	protanomaly	8/17	14/17

Table 5.1: Ishihara color plate test results with and without the *OmniColor* application for participants with a color vision deficiency.

Nine out of 14 participants don't have a diagnosed color vision deficiency

5 Evaluation

with two of them being females and the other 7 males. The age ranges from 25 to 58. Although all participants of the non color vision deficiency group where able to pass the Ishihara color test already in the first run, two of them having problems on certain plates to report the correct number. As already stated, this group of participants where recommended to use the deutanopia mode within *OmniColor* for the second test run. All participants of this group noted that they could barely notice any difference to the original image for the deutanopia and protanopia mode provided by the application, whereas they noted a significant difference by the use of the tritanopia mode. Of course, the color corrected images strongly depend on the external factors such as ambient light and the field of view. Thus, in some cases participants ask to take a picture of a color plate again in order to get a better result in comparision with their first try. This goes back to the field of view of the camera. Although all participants are instructed how to use Google Glass for taking photos, they needed some tries to record the field of view they wanted to. Three of the nine participants are wearing glasses and end up by putting Google Glass over their glasses. Exactly those people don't explicitly mentioned the heat generation of the Glass device, this may be due to the fact that the temple stem act a seperator to the device. Similar to the participants having a color vision deficiency, also concerns about the overall performance of the applications are expressed. It was clear that *OmniColor* isn't as fascinating to people with no color vision deficiency than to those having a color vision deficiency. However, the fact that the result images barly comes with noticable differences to the original one can be positive admitted.

5.3 Discussion

The overall results had shown that the *OmniColor* Google Glass application indeed create added value for people having a color vision deficiency. However, in the course of this work only one problem of colorblind people was adressed by performing the Ishihara color test to demonstrate what

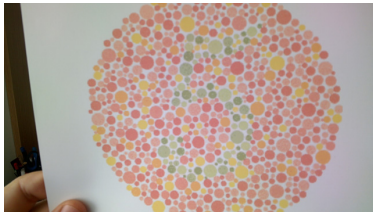


Figure 5.1: Original image

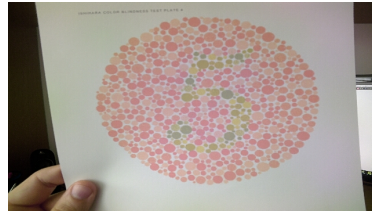


Figure 5.2: Daltonized image for deuteranopes

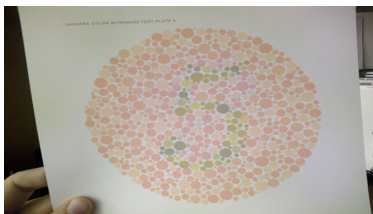


Figure 5.3: Daltonized image for protanopes

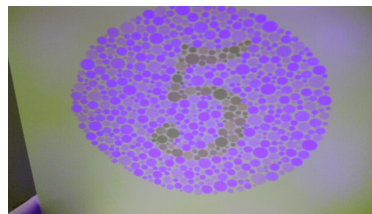


Figure 5.4: Daltonized image for tritanopes

the application can actually do improve the daily life of people with a color vision deficiency. Therefore, an extended test containing also practical reallife scenarios would be very interesting. Since Google Glass is also an experimental device, the practical use of the *OmniColor* application may not be sophisticated enough due to certain limitations. Nevertheless, *OmniColor* aroused interest of participants and presented that with smartglasses such as Google Glass an exciting new platform for people with a color vision deficiency is created. The demonstrated application may also add value to future related works.

Google Glass is primarily controlled via touchpad or voice control. Although participants are pointed out to either use voice commands or use the touchpad, all participants have used the touchpad to use *OmniColor*. One of the two participant was familiar with Google Glass and therefore also tested the voice commands, while the other one tested *OmniColor* in an environment with a high noise level. As two voice commands are not cor-

5 Evaluation

rectly processed by Glass, the participant went over to touchpad navigation. During the development and development test phase of *OmniColor*, voice commands had been processed almost perfect correctly. This showed that future, similar devices needed some sort of noise cancellation for loud environments. However, no participant had a problem to control the application via touchpad.

Most of the participants feel comfortable wearing Google Glass and perceive the platform to be positive for applications like *OmniColor*. Those participants that wear glasses had problems to adjust the Google Glass according to their needs. Since all of them have glasses with big dioptries, they ended up by putting Google Glass over their glasses. They mentioned that it's alright for them to take the test with Google Glass but couldn't imagine to wear Glass longer than a couple of minutes. While there are already devices out for glass wearers⁴², the Explorer Edition 2 used for this work doesn't provide prescription lenses.

Several participants expressed concerns about the heat development of Google Glass. Participants that doesn't wear glasses are more likely to notice the increasing heat produced by Glass during the test. This may be the case because the temple stems of the glasses act as a separator between Google Glass and the head. Since all computations of *OmniColor* are directly performed on the device without the use of offloading, Glass could get uncomfortable hot. Indeed, the heat development of Glass is a problem many Google Glass developers have already reported. If the device gets too hot, an alert pops up saying „Glass has to cool down“. In this case, the actual application is closed and needed to be started again by the user. However, this never happened during any test.

The most expressed concern is the computation performance of the *OmniColor* application. Although the implemented solution doesn't require a second device such as a linked smartphone or active network connectivity (either via WIFI or Bluetooth tethering), the computation of result images take too long for the participants. Google Glass has very limited compu-

⁴²<http://www.techradar.com/reviews/gadgets/google-glass-1152283/review/9> (last visited May. 28, 2016).

tation power and is often presented as a notification device rather than a device to perform complex computations. Ha et al. (2014) stated that the CPU of Google Glass can operate at several frequencies: either 300, 600, 800 or 1008 MHz. The higher frequencies are only used for bursts of time in order to limit the heat development of the device. However, according to the implementation of *OmniColor*, no CPU frequency measurement was performed. The coherence of heat development, cpu frequency and computation time would be interesting for future work.

Another important aspect is the limited battery life of Google Glass, which holds only 570 mAh. Performing one Ishihara color test takes about 30 to 35 percent of the battery life. Tanuwidjaja et al., 2014a stated that comparing Google Glass with a actual smartphone such as the Google Nexus 5, one can determine that there's a significant gap between those devices in terms of battery capacity. Due to the fact that compute intense operations also need more power, implementation specific concerns regarding power consumption must be involved. To overcome this problem during the tests of *OmniColor*, Google Glass is supplied with electricity by a powerbank if needed.

The camera provided by Google Glass also constitutes a limiting factor, because the image colors deviate from the true colors. While digital cameras often offer the possibility to calibrate the camera, it was not possible to modify the factory settings of the device. Although considerations about the usage of a white balance algorithm had been made, the implementation of *OmniColor* doesn't cover such an algorithm due to the fact that the algorithms couldn't improve the white balance of an image as good as the human eye. The Ishihara test was performed on different locations and light sources (natural light, artificial light). While most test locations had a good natural light source, the last test was performed in a poor natural light environment with artificial light source only. The participant found it hard to recognize the number on certain plates. However, he was able to recognize the number after showing him the pretaken image on the laptop. This may be affilitate to the light influence in this specific environment. Hence, the results brought by *OmniColor* may vary under different light conditions.

5 Evaluation

Finally, three participants claim that they found the projected image of Google Glass annoying or have a problem to focus on the projected image. They have needed to close the left eye in order to clearly recognize the image.

6 Conclusion and Outlook

This master thesis shows how colorblind people or people with a color vision deficiency can take benefit of the new technical devices in combination with state of the art application development. Beside certain improvements of the application that had been found out during the evaluation phase of *OmniColor*, it turns out that the Google Glass also have problems and limitations that reduce the user experience of the applications.

Although Google Glass have these limitations, the intermedia attention of the device was enormous. On one hand, a variety of businesses saw new possibilities in the device such as hospitals or manufacturer, but on the other hand privacy concerns have given the device a bad image and led to an aversion towards the population. In fact, before smartglasses are accepted by the population, laws and rules have to be created to ensure privacy and improve the image of such devices.

Sadly, the Google Glass explorer edition project ended on January 19th and with it, the possibility to buy the device. Google confirm that the development of a eyewear-mounted computer doesn't end with the Google Glass Explorer edition project. Instead, future versions of the device should overcome the known limitations of Google Glass and provide new a user experience for the user. Therefore, the Google Glass explorer project could be seen as a beta program that gave Google the possibility to hear what people say about the device.⁴³

Finally it can be said that the smartglasses offer exciting new possibilities. The perception of colorblind people or people with a color vision deficiency

⁴³<http://www.eweek.com/mobile/google-ending-its-google-glass-explorer-edition.html> (last visited May. 30, 2016).

6 Conclusion and Outlook

can be improved by either real-time approaches or non real-time approaches. With *OminColor*, a Google Glass application prototype that uses a non real-time approach had been evaluated to significantly improve the results of the standard Ishihara color plate test. The underlying process is called Daltonization, a color shifting algorithm which is known to be performant and only perform marginally perceptible changes on the input image (people without a color vision deficiency can also recognize the number on the plates after they had been processed). This circumvents the problems with real time approaches that are primarily caused by the device, such as head development and processing power. Further work may include other approaches (e.g. pattern based approach etc.), the usage of parallelism to increase the performance of the application, tests on other Android based smartglasses (e.g. Epson Moverio BT-300) and so on.

List of Figures

2.1	Chroma	6
2.2	DanKam	11
2.3	EnChroma glasses	13
3.1	Color spectrum of non-colorblind people compared with the three main colorblindness types	17
3.2	Simulation of different color blindness types	19
3.3	Introductory Plate	21
3.4	Transformation plate	21
3.5	Vanishing Figure	21
3.6	Qualitatively Diagnostic	21
3.7	Anomaloscope	23
3.8	Online implementation of the D-15 color arrangement test . .	24
3.9	Result of the color arrangement test	24
3.10	Color-Via-Pattern	30
3.11	AR provided by Google Glass	33
3.12	Reality-Virtuality continuum defined by Milgram	34
3.13	The Sword of Damocles	35
3.14	augmented reality for outdoor navigation	38
3.15	Battlefield augmented reality system	39
3.16	Video see-through and optical see-through display	41
3.17	Google Glass Explorer Edition 2	45
3.18	Epson Moverio BT-200	46
3.19	Recon Jet Black	47
4.1	Card regions of Glass	56

List of Figures

4.2	Recommended colors from Google for Glass development . . .	57
4.3	Roboto light 32pt	58
4.4	Roboto light 40pt	58
4.5	Roboto light 48pt	58
4.6	Roboto light 64pt	58
4.7	OmniColor Glassware Flowdesign	62
5.1	Original image	77
5.2	Daltonized image for deuteranopes	77
5.3	Daltonized image for protanopes	77
5.4	Daltonized image for tritanopes	77

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