Chroma: A Wearable Augmented-Reality Solution for Color Blindness

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ABSTRACT
Color blindness is a highly prevalent vision impairment that inhibits people's ability to understand colors. Although classified as a mild disability, color blindness has important effects on the daily activity of people, preventing them from performing their tasks in the most natural and effective ways. In order to address this issue we developed Chroma, a wearable augmented-reality system based on Google Glass that allows users to see a filtered image of the current scene in real-time. Chroma automatically adapts the scene-view based on the type of color blindness, and features dedicated algorithms for color saliency. Based on interviews with 23 people with color blindness we implemented four modes to help colorblind individuals distinguish colors they usually can't see. Although Glass still has important limitations, initial tests of Chroma in the lab show that colorblind individuals using Chroma can improve their color recognition in a variety of real-world activities. The deployment of Chroma on a wearable augmented-reality device makes it an effective digital aid with the potential to augment everyday activities, effectively providing access to different color dimensions for colorblind people.

Author Keywords
Augmented-reality; Glass; Wearables; Color blindness

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI)

INTRODUCTION
Color blindness is a vision deficiency that inhibits the perception of colors. Colorblind people typically perceive a narrower color spectrum compared to those with normal color vision. Color blindness was first described by Dalton in 1798 [9] and despite its pathogenesis is well-known there is still no current treatment. Although it is classified as a "mild-disability" it affects a considerable portion of the worldwide population (8 percent of males and almost 0.5 percent of females) [49]. The more common types of colorblindness are deuteranomaly (56% of all colorblind individuals) and protanomaly (15%) the "less severe" versions of protanopia (14%) and deuteranopia (13%). Tritanomaly and tritanopia along with other specific deficiencies are more rare. Figure 1 shows the color spectrums as seen by people with six different types of colorblindness with respect to standard vision. A common misconception about colorblindness is that colorblind people are unable to see certain colors or some colors appear grey for them. Colorblind people are actually unable to *distinguish* certain colors. As evident in the figure, colorblind people can see a variety of colors, but depending on the type of colorblindness, some colors are off. For example, a person with deuteranopia sees red as a shade of green and people with deuteranomaly often misclassify brown as red.

Color blindness affects people on a daily basis since many daily activities require the ability to distinguish colors. For example, while cooking, colorblind people have difficulties distinguishing cooked meat from raw meat. They often use other factors to guide their assessments, such as cooking time and amount of charring. However, burnt meat does not always mean that the meat is cooked. Many colorblind individuals have problems with other activities, such as identifying colors in art and fashion (flowers, photography, etc.), reading color legends (maps, medical charts, etc.). Also, many tasks require the ability to distinguish colors in real-time. Preparing food or drink, driving, and first-aid operations are example activities that require the ability to see color changes in real-time.

Correcting for colorblindness is, however, not just a matter of day-to-day convenience. This vision deficiency affects the professional lives of a variety of knowledge workers. In studies of general practitioners and medical students with color vision deficiencies, participants described

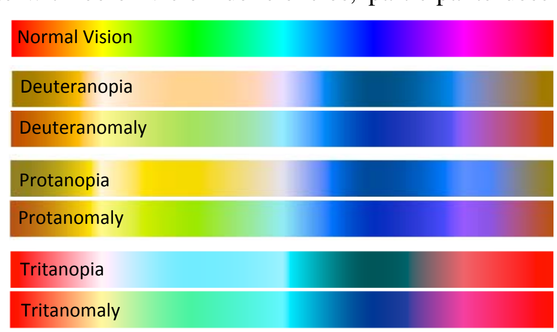

Figure 1: Top: color spectrum that non-colorblind people can see (Standard Vision). Below: the three main colorblindness types paired with their "less severe" versions.

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their common difficulties in practice [39, 40, 34, 33]. They complained of difficulty recognizing widespread body color changes (such as jaundice, and cheery red), skin rashes and erythema, charts, slides, prints, and codes. They often reported to be unable to correctly decode test-strips for blood and urine, ophthalmoscopy, oral and throat lesions, titration endpoints, tissue identification in surgery, and blood or bile in urine, feces, sputum or vomit. This elucidates a significant potential for medical errors. In fact, Campbell and colleagues found that general practitioners with colorblindness were less able to detect the color signs of illness in color photographs, compared to physicians with normal color vision [6]. One physician interviewed reported, *"I once diagnosed a hematemesis [blood in vomit] as bile [fluid produced by the liver]. The patient was lucky to survive"* [39].

Color blindness is often underestimated in schools (starting in kindergarten), and may lead to uneven education. Even though every class probably has at least one colorblind student, teachers are often unaware of this *invisible disability* [42]. In fact, a study comparing school achievement demonstrated that colorblind children performed significantly lower than those without colorblindness [38]. Although a number of modifications can accommodate those individuals, students often feel embarrassed and do not report discomfort, so possible solutions to help colorblind students are usually not implemented. This is particularly problematic in science classes where color discrimination is often used.

Abnormal color vision can also restrict the profession in which an individual might be able to work. Standards for employment and colorblindness in fields where risk for human injury is high originated in Sweden in 1875, after a colorblind train conductor missed a signal [15]. Since then, restrictions have existed for military pilots [27], commercial airline pilots and air traffic controllers [46, 13]. Additionally, rail conductors, signal controllers and anyone using color-coded displays, are banned from any signal-critical rail operations if they are colorblind. A colorblind individual wanting maritime employment will be restricted as well and limited to operating during daylight hours only [45]. Finally, commercial truck and bus drivers need to pass a specific screening: the Farnsworth Lantern test [8, 30].

Because color serves as an important indicator for a number of activities that are ubiquitous in our daily lives, those with colorblindness are at a disadvantage compared to those with normal vision. Although no treatment is currently available, the advent of wearable augmented-reality technology allows us to develop new solutions for colorblind people. In this paper, we present Chroma, a real-time wearable solution deployed on Google Glass [17] that transforms the colors captured by the Glass scene camera and presents the scene back to the user in a way that supports colorblind people in their everyday activity. By using the Glass heads-on display, Chroma supplements vision and allows users to exploit the additional display to see an augmented version of the real-world scene in front of them. Chroma is designed to help a colorblind person answer questions like *"Is there any redness here?"* or *"Is this green?"* or *"Is this shirt blue or purple?"* We believe that focusing on augmenting real-world vision with supplementary information is key to enabling colorblind individuals to answer those questions. In this paper we describe how our approach is rooted in the problems that colorblind people currently experience, and how the deployment of augmented reality on a wearable format will help colorblind people *see* the colors they were not able to recognize before.

RELATED WORK

Over the last few years a range of approaches, algorithms, applications and commercial products have been designed and developed to help people with color blindness. This is usually achieved either physically, by wearing special lenses, or through hand-held technology with dedicated software. EnChroma [11] developed optical sunglasses designed to improve color vision. By looking through these glasses, colorblind people see colors more vibrantly, resulting in a stronger and more saturated image. Although EnChroma improves color vision, it does not solve most of the practical issues that are experienced by colorblind people. For example, individuals who fail the Ishihara Color Vision Test identifying color blindness [19], often still fail the test even with the aid of EnChroma. This is because EnChroma, like any pair of optical glasses, alters vision globally (anything in the visual scheme will be altered without discrimination), and it can only marginally increase global contrast. Moreover, this solution is bound to specific disabilities (deutans and protans) and requires adaptation of the eye (30 min) to be effective. We want to keep the glasses form-factor, but create a solution for all types of color blindness that works immediately, adds extreme contrasts, and augments vision selectively.

Many colorblind people exploit other tools to help them decode information. One example, SeeKey [37], consists of two small semi-transparent light filters: red and green. Looking through them changes the way users perceive the color of the object they are focusing on. Alternating between the two filters enables a colorblind individual to *guess* the color, by gauging the difference between the two perceived colors. Using SeeKey alone will assist red-green color deficient people to achieve an 86% improvement on the Ishihara test [31].

In addition to physical glass-like solutions and tools, there are many available apps for smartphones that can help colorblind people. Many of these (e.g. HueVue [2]) are asynchronous and not real-time, requiring the user to take a picture and tap a point on the picture where they are interested in determining the color. The app will then identify the color of that point using a textual overlay. Despite their usefulness in reporting color, these apps are often impractical and cumbersome to use during day-to-day activities. Other apps, like DanKam [22] and in particular its HueWindow mode, present more useful real-time features. DanKam allows a user to change the hue values of the camera image, accentuating colors usually hard to see for colorblind people. However, due to its hue-based approach, colors can change dramatically. Smartphones also present a sub-optimal form-factor: grabbing a device in the middle of an activity (e.g. cooking) is often troublesome.

The advent of Google Glass and the potential for wearable augmented reality to help visually impaired people [41] makes it possible to exploit this technology for color blindness. The idea of augmenting reality through a wearable platform such as a pair of glasses is not new. In the 1980's wearable computer pioneer Steve Mann [24] developed the EyeTap digital eyeglass. Mann considers these glasses more mediated reality than augmented reality, due to the fact that the light entering the eye is completely replaced with a projected image [23]. The use of Google Glass, however, enables the user to see the physical reality while having simultaneous access to an augmented reality display containing additional information when needed. Augmented reality through Glass technology enables users to continue to make eye contact with those around them, while at the same time access information relevant to the current activity. Two approaches using Google Glass to assist color blindness–Color Picker [5], and Color Identifier [18]–have recently been proposed. Despite their potential, both apps work similarly to the HueVue app, only giving real-time *textual* feedback about the color at the center point of the scene. Because of the indirect way this interface is designed, and the additional cognitive task needed to map textual information to the real world object, it is not clear if this approach will really help individuals in their day-to-day activities. With Chroma, we aim to design an efficient aid for colorblind people that helps in the management of color deficiencies, and gives a more direct experience that allows them to make color connections easier and faster.

Many other new initiatives recently started to investigate Glass in the context of a variety of health-related dimensions [16, 36, 29, 28, 1], but we feel that color blindness is particularly interesting given the natural affordances of Glass and its direct mapping to vision. Since Glass itself is designed to be utilized with the human eye, this makes it a natural platform to experiment with augmented reality for color blindness. Chroma aims at filtering real-world images as detected by Glass by means of a variety of image processing algorithms and *re-coloring* the captured image. The ultimate goal is to find effective ways to manipulate images recorded by the Glass camera to support specific vision deficiencies.

Re-coloring real-world images through filters and displaying them back to the user allows them to see the world in a different way. Already in 1994, Mann and Picard developed an algorithm to completely re-color an image based on different exposures with the goal of showing a more dynamic range of features [25]. For Chroma, we are addressing the specific case to re-color an image to make it it more *readable* and recover information *lost* due to color blindness. A range of algorithms in this realm already exist and are classified as *Daltonization* algorithms. They range from increasing the contrast between all colors, to converting the invisible colors to brighter, darker, and/or a completely different coloration [47]. LMS Daltonization algorithms, in particular, follow a naturalistic paradigm of simulating how a colorblind person would view the scene by using their L, M and S cones in the retina and then shifting colors based on that simulation [10]. A variety of approaches have been proposed to improve the discriminability of colors and increase accessibility [48, 35], and by applying smart recoloring algorithms in controlled situations [20, 35], as well as in unstable lighting conditions [14]. Similarly to Chroma, recent work also looked at algorithms and solutions for specific real-world scenarios [44].

The focus of our work is not in distilling new Daltonization or re-coloring algorithms, but on integrating and adapting existing algorithms as part of our Chroma Google Glass application in such a way to enable users to see the colors they are not able to see due to their color vision deficiency. Similarly to work by Jefferson & Harvey [21], and Ohkubo & Kobayashi [32], Chroma adapts standard vision colors so that they can be seen by colorblind people. In the next section we highlight how the integration of those algorithms and the design of Chroma is the result of a careful investigation of the current issues of colorblind individuals as well as the strategies that they designed to overcome their color deficiency.

UNDERSTANDING COLOR BLINDNESS

Designing and developing for a specific target population such as colorblind people requires an in-depth understanding of their daily problems as well as of the strategies that they have been developing in order to overcome obstacles. The main motivation of our work came from the personal experience and frustrations of the first author of this paper, who is himself colorblind. Although this internal view of the colorblind world is important to understand the problem space, equally important is to cross-correlate it with a more ecologically valid view that comes with confrontation with other colorblind individuals. We believe that combining personal insights with a wider set of experiences with colorblindness brings both breadth and depth to our investigation of a wearable augmented reality solution for colorblindness.

We recruited a variety of colorblind participants and performed semi-structured interviews. While our semi-structured interview protocol was open to dive into any particular insight resulting from the discussion with our participants, we were particularly keen in trying to derive strategies that our participants used in their daily life, to inform the design of specific features as part of Chroma. Given that colorblindness is a genetic condition, colorblind individuals are particularly experienced in finding strategies. However, for the same reason, it was particularly difficult to uncover those strategies since they have been part of the individual's normal life for years and they are de-facto parts of their routine.

Participants

We recruited colorblind individuals interested in being part of our study through posters spread throughout the campus of our university, emails from select campus professors to their students and postings on social network groups local to the school. Recruiting information was approved by the university human protection program. Flyers described our research on colorblindness and Google Glass and included a printed red-green Ishihara test. No specific effort was made to reach pre-defined demographic, ethnic or social groups.

Over a four week period, 23 participants were recruited and interviewed. Most interviews lasted 20 to 30 minutes. We used an online colorblindness test [12] to determine participants' colorblindness types. Participants were distributed across different levels of deutans or protans (1 medium

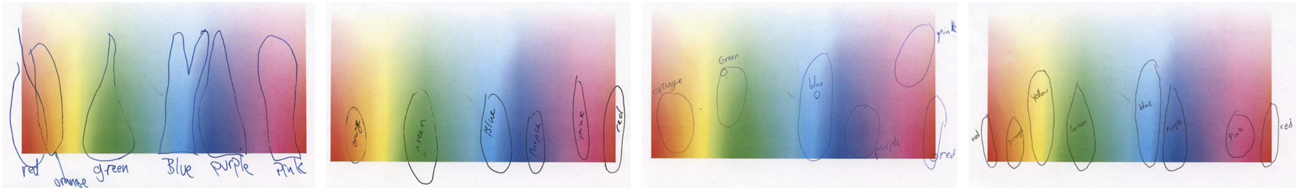

Figure 2: Color spectrum test results showing participants' own sketching of color perception. Examples are for strong deutans (the two on the left) and strong protans (the two on the right). These examples illustrate the individual differences and how the colors at the intersection of primary colors (e.g. orange, light green, dark blue, light pink) are often not uniquely identified.

protan, 7 strong protans, 1 mild deutan, 1 medium deutan and 13 strong deutans). Due to the nature of colorblindness (only 5% of colorblind individuals is female), all participants were male. Most of them (12 out of 23) were between the ages of 20 and 24 years, averaging 23.4 yrs. (max: 47, min: 18). Sixteen of our participants (74%) were students in computer science (4), electrical engineering (3) biochemistry/biology (3), design (2), and management, structural engineering, mathematics/economics, psychology, international studies (each 1). The remaining seven participants (26%) were active in design (3), IT (2), physics (1) and software development (1).

During the interview, participants were asked about their first experience with their condition and what colors they usually struggle with. Most of them were not aware of their type of colorblindness, and it was with our test that they first learned the classification of their condition.

We wanted to better understand how the different types of colorblindness affect the visible color spectrum and we therefore asked all of our participants to draw the boundaries of the different colors on a standard color spectrum. Analysis of the reported colors highlighted the many individual differences and also a common tendency to mistakenly classify colors at the boundaries of primary colors (see Fig. 2).

Obstacles and Strategies

We asked participants to tell us about their daily routine and to share with us situations where they noticed their colorblindness and whether or not the condition had an effect on dealing with those specific situations. If it did, we further explored their strategies in dealing with the specific issues.

Insights from the interviews were summarized. Data was analyzed based on qualitative data analysis techniques [3] and elements of grounded theory [43] to extract emerging common strategies to overcome daily obstacles. We detail those strategies next, grouping them by activity.

Playing Games – Given the participant demographics, the most commonly occurring obstacle was games in which color played a large role. These games included: board games, card games, console video games, computer games, and smartphone games. Regardless of the type of game, participants agreed that the level of enjoyment from playing the game was reduced due to the added difficulty of identifying colors.

Many of the participants played competitive games in which teams are identified by certain colors. They noted it was often difficult to distinguish between members of opposing teams even if the team colors were highly contrasting to the non-colorblind eye (e.g. red/green). Some participants discovered a limited number of digital games including a 'colorblind mode.' Most participants observed that it was helpful to use the mode, but others did not know such a mode existed.

In the case of physical games like puzzles, matching colored pieces is usually involved. Participants noted that these games required more effort for them to play with respect to their non-colorblind companions, since they need more time to identify the colors. To deal with this obstacle, participants found other ways to identify pieces, such as the shape. However, in many of the games the shape and the color were not linked.

Choosing Clothes – Another common obstacle for our participants was choosing clothes to buy and wear. Given the importance of clothing in terms of 'public scrutiny', our participants noted how being unable to match colors or choose the right outfit for the right occasion often lead to unwanted scrutiny and criticism.

In order to avoid those instances, most participants asked someone to check the clothes that they picked to ensure that they were actually choosing the color that they believed they were. One participant, for example, commented: *"I always bring my girlfriend when it is time to go clothes shopping."* Another common strategy among our participants was to avoid colorful clothing in general and to stick with dark and earth-tone colors that go together easily, resulting in a much narrower–and less interesting–selection.

Cooking – Many participants stated they had trouble telling the doneness of meat while cooking. They were not able to distinguish the brown, cooked portions of meat from the red, raw portions. Due to their inability to tell doneness, many participants only cooked meat when someone was available to check doneness for them. Others avoided cooking entirely. Some commented on dealing with this obstacle by *"cook[ing] with a timer and test[ing] the doneness by touch."*

Driving/Parking – As expected, a large number of participants stated they had difficulty differentiating the colors of driving signal lights and painted street curbs. In the case of signal lights, participants noted that while they might have difficulties differentiating between colors, they could still tell when a light was on versus when it was off. Lights on/off in combination with the knowledge of light position was enough information for them to identify which signal was active. This is a nice example of how redundant information (matching color and position) is actually an effective strategy.

Painted street curbs were more problematic. Many participants stated that the risk of getting a fine for parking in a no-parking zone (painted red curb) often caused them to avoid the parking space. One participant stated: *"if there is even the slightest doubt in the color of the curb, I would fully avoid the parking space altogether."* Participants who often attempted to park in a painted space, would exit their cars and spend a considerable amount of time focusing on the curb paint trying to identifying the color. All participants, however, noted that even if they did identify a color, it was never with full confidence, leaving them in uncomfortable situations.

Summary and Design Choices

Through the interviews with our participants, we found that the common theme in all of the obstacles described was a sense of uncertainty. Whether picking out a shirt to wear out or while checking the doneness of a piece of meat, the participants' responses indicated that they wanted a form of reassurance in whatever decision they were making. It was important for us to ground the design of Chroma into users' needs and from our interviews it clearly emerged that some sort of visual feedback would help colorblind people in the process of better understanding the world around them and decrease the level of uncertainty, limiting frustrations. This led to the main design choice of highlighting certain colors of the recorded scene in real-time and presenting them back to users through Chroma on the Google Glass display. Given the different requirements in different life situations, we decided that we would allow users to select a color they had trouble discerning and highlight that selected color on screen with a color unaffected by colorblindness. To account for the different but recurrent situations described by our participants, we opted for an application that would give users the flexibility to *see the world* in different ways. This led to the several modes described in the following section.

CHROMA

The formative work described above allowed us to uncover specific situations were colorblind people struggle to identify colors during their daily activities. These situations, as well as those described in the introduction are recurrent situations that would benefit with real-time feedback. Additionally, given that these are time critical, tools for colorblind people must have interfaces that will not increase their cognitive load excessively.

Current physical and camera-based tools to support colorblind people in real-time during their daily activities are limited in scope and functionality or are cumbersome and not practical to use. None of the current approaches are flexible enough to allow colorblind people to pass the Ishihara Color Vision Test (see Fig. 3), and none allow a user to easily answer questions like *"Is there any redness in this meat?"*

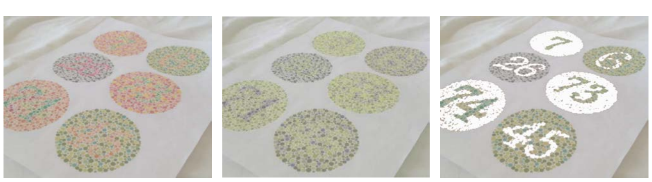

Figure 3: Testing with Ishihara plates without the support of Chroma for normal vision (left) and for a colorblind individual with deuteranopia (center), and with Chroma (right).

We developed Chroma, a wearable real-time augmented-reality application based on Google Glass that promises to address real-life issues of colorblind people. Chroma was informed and highly influenced by our formative work. The main idea behind Chroma is to create a flexible and automatic way for colorblind individuals to compensate for their lack of color detection in real-time. It serves as a digital aid delivering information to colorblind users in a practical and convenient fashion. Furthermore, Chroma acknowledges colorblind people can see colors but have trouble *distinguishing* certain colors, and therefore strives to assist colorblind people so that they can distinguish colors that they naturally have trouble with. We first allow users to choose a specific color of interest (depending on their disability). Then we make this color particularly salient for them in Chroma's augmented-reality view of the scene.

We chose to implement Chroma on Google Glass (Fig. 4) due to its natural affordances. Glass allows for easy and intuitive interaction between the user and the interface since the display is already positioned at eye level. Glass also complements Chroma well since vision is the main medium through which it acts. This physical affordance also eliminates the need for users to reach into their pocket for a smartphone, turn it on, navigate to the application and initialize it. Not only is this process considerably longer, it also creates an unnatural division of the user's attention between the scene and the mobile device. With Glass, using Chroma becomes an augmented reality experience requiring minimal user's effort.

Functionality and Implementation

Our system consists of Google Glass Explorer Edition and Chroma, our application that utilizes the camera, display and processor of Glass to render an augmented reality for the user.

User Interaction with Chroma and Glass – Chroma can be started by invoking the native Google Glass Application List or using the standard Glass voice command *"Ok Glass, Start Chroma."* Upon starting Chroma, a video stream from Glass' camera is displayed to the user in the "Home View." In order to interact with Chroma, we exploit native interactions through swipes and taps on Glass' touchpad.

The user can interact with Chroma in the Home View in several ways. A Swipe-Foward (back-to-front) invokes zoom-in, while a Swipe-Backward zooms-out. Double-Tap toggles visibility of a label indicating the current mode, while Single-Tap brings up the "Settings View." The Settings View

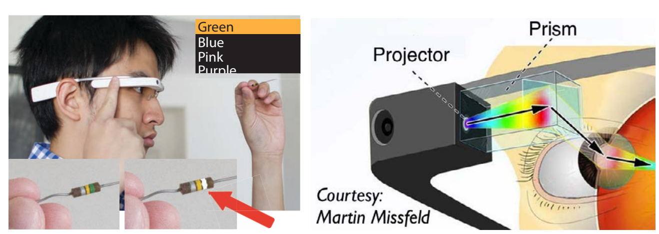

Figure 4: Left: colorblind user wearing Glass; in the detail Chroma's menu and the results of the Green Highlighting on a resistor. Right: Glass's semi-transparent prism acting as display, and micro-projector casting the image on the prism. The projected image is reflected on the user's retina.

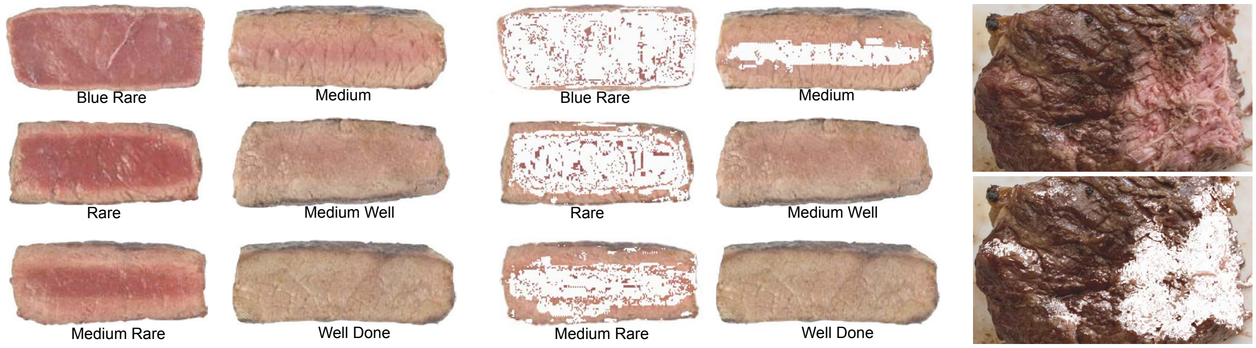

Figure 5: Chroma applied to gauge meat rawness. The left image is unfiltered and shows different levels of meat rawness. The middle image is filtered using Chroma's red and pink highlighting. The rightmost images show actual meat that we grilled, before and after Chroma's red and pink highlighting. Without the highlighting, a colorblind person may not notice it is not fully cooked.

displays a list of of Chroma's modes, including the selection of the specific color to be changed, and allows users to select one of them. As explained below, each mode implements a different solution to filter the videos recorded by the camera and alter them in real-time to assist colorblind users. While in the Settings View, Swipe-Forward allows users to navigate up the mode list and Swipe-Backward to go down the list; Single-Tap selects the highlighted mode and returns to the Home View activating the selected mode.

System Architecture – Chroma is designed as an Android application that uses a pre-release version of Glass Development Kit (GDK). In addition, we utilize OpenCV's Android Library to simplify the interfacing between the data captured by the camera and the data displayed on the screen. We extended OpenCV's `CvCameraViewListener2` to utilize it's ability to modify each video frame. For each frame loaded from the camera, we use `cvtColor`, an OpenCV's Image Processing function that converts the colorspace from RGBA32 to HSV. We decided to use HSV because it separates luminance (image intensity) from chrominance (color information), allowing more accurate detailing of actual color shades and less background noise. Then, we apply our own algorithms on the HSV frame and send it back to `cvtColor` to convert back to RGBA32 and render on the Glass heads-up display. As OpenCV interfaces are written to run asynchronously, the image processing for each frame does not block the following frame and thus after initial loading we are able to run our application in near real-time. In addition, we exploit the OpenCV `CVCameraViewListener2` both to apply the filters implemented by the different Chroma modes and selected by the user, as well as to operate our implementation of digital zoom that allows users to zoom into specific parts of the camera view to get a better and more detailed view. Figure 6 illustrates Chroma's main architecture.

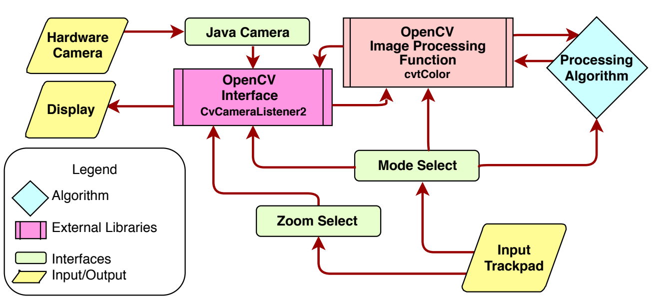

Figure 6: System Architecture: Chroma's software interaction with Google Glass hardware and input interfaces.

Color Blindness Modes

Chroma is based on four basic modes: (1) highlighting mode, (2) contrast mode, (3) Daltonization and (4) outlining. Once the application is launched, a real time video stream is displayed on the small screen, showing the view from the Glass camera. The user can select a mode as previously described and Glass will display an altered view based on the desired filter and render the altered view in real time.

Highlighting Mode – The Highlighting Mode allows users to select one or few color of interests and Chroma highlights every pixel within the range of those colors. The goal is to help colorblind people to find a color in the real world that they have trouble seeing or confirm a color that they are unsure about. For example, a colorblind person can select both red and pink as colors of interest when grilling a steak, and Chroma will highlight the red and pink areas of the meat indicating what parts of the meat are still uncooked. Figure 5 clearly illustrates this example. By default, highlighting is achieved by using the color white, since it is the easiest color to see on the Glass screen and it is easily contrastable with all other colors. In case users can not easily see white, they may change to another color for each of the colors of interest.

Contrast Mode – The Contrast Mode is designed to help colorblind people compare and contrast two different colors. This mode allows them to select two colors, and filters the scene so that the first color appears, for example, red and the second appears blue, while everything else is darkened (colors are configurable). Figure 7 illustrates this approach. The main rationale behind this design directly arises from our formative study: given a task to identify a color, colorblind people are often confused between two colors, but usually this confusion only relates to those two colors. Most commonly, colorblind individuals confuse blue and purple, green

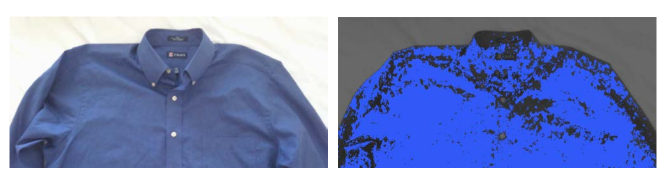

Figure 7: Left: an unfiltered blue shirt. Right: the same shirt filtered using Chroma's purple vs. blue mode.

Figure 8: Chroma's Daltonization. Top: for a person with deuteranopia, this field of roses (left) appears to be a field of grass and lilypads (right). Bottom: daltonized scene, parametrized for a person with deuteranopia but shown for normal vision (left), and colored scene as perceived by a person with deuteranopia; roses are now clearly defined (right).

and brown, red and brown, and red and green. Colorblind people do not confuse red and blue since they are on distant parts of the color spectrum. Following this rationale, Chroma maps the first color picked to red and the second to blue. The example of Fig. 7 shows a 'purple vs blue' contrast; purple is mapped to red, and blue is mapped to blue while the rest is darkened and users can focus on comparing and contrasting the two colors.

As previously mentioned, colorblind people are often confused between blue and purple, green and brown, red and brown, and red and green. Chroma provides these color pairs directly as part of the Contrast Mode menu, so the user does not have to manually select those two-color combinations. In case users are confused with a pair of colors not available in the menu, they can manually pick two colors of their choice.

Daltonization – Given the loss of information that often occurs due to the altered perception of colors, colorblind people might not be able to correctly decode what they see. Figure 8 (top) outlines this common problem, showing how a person with deuteranopia might not be able to see a field full of roses but instead sees a flat image of grass and lilypads.

Such loss of information complicates the colorblind person's ability to enjoy or comprehend scenes. Although Chroma can highlight all areas that fall in specified color regions, it is still valuable for userS to be able to view the scene in its entirety as well as differentiate betweens shades of a specific color. Chroma's Daltonization algorithm accomplishes such recovery by shifting all colors in a scene to a color spectrum more accessible for the colorblind person. Figure 8 shows the results of our Daltonization algorithm, illustrating both how the image would be seen through normal vision and by deutans.

Outlining – Very often a colorblind person does not realize that the color they are currently perceiving is different from what the color actually is. Thus, the user would not consider using any of the highlighting modes described above unless they are actively in a situation where they are aware that their color blindness affects their color perception. In order to discover those situations, Chroma allows users to select the outlining mode. During normal activity or while wandering around, users select the outlining mode, which outlines all areas strongly affected by the person's color blindness. The outlining mode can be configured for different types of color blindness. Figure 9 shows the effect of the outlining mode.

Figure 9: Daltonized image with outlined areas.

Color Classification Algorithms

The four modes described above are based on a set of simple algorithms that have been combined and integrated in Chroma. We now describe how we achieve those results.

Highlighting and Contrast – In order to highlight the selected color, Chroma's color classification algorithm takes the textual color selection (e.g. 'blue') and *compares* it with every pixel in the image. Given the HSV values of a pixel, we test whether those HSV values are within the thresholds of any color. For all colors we experimentally calculated the H, S, and V thresholds that define the boundaries for the selected color. If the H, S, and V values of the pixel fall within the threshold of a particular color, then Chroma classifies the pixel as this color and if it is the one selected by the user (e.g. 'blue') it then highlights it. Although this seems simple, there is no single correct formula for color classification because different people have different names for colors. For example, given a bluish-purplish object, one might say that it's blue, and another might say that it's purple (and none of them is necessarily colorblind). In order to manage this problem, Chroma's color classification algorithm leaves a gap between two colors that are close to each other (e.g., blue and purple). In addition to the *human* classification problem, this is done also because even in ideal lighting, current camera technology often does not capture the true color of the scene. Thus, the captured HSV values might deviate from the true HSV values. In a room with non-natural light the deviation can be extreme (see Discussion section for further details). Given this premise, it is important to leave a gap between two colors to reduce the probability of misclassifications. This gap will result in pixels being classified as 'no color', creating unknown regions. However, the real world never looks like a solid color and every object is depicted using gradients of colors, especially due to lighting and shadows, so different parts have different colors. Therefore, in general, most parts of a real world entity will fall within a "known" region in the color spectrum; hence the entity can still be classified.

Daltonization – The Daltonization algorithm used for the corresponding Chroma mode is illustrated by the matrices (1)-(5) below and is defined as follows: for each color, Chroma converts the color from the 0-255 range of the RGB color space to

LMS color space (conversion matrix is the product of RGB-to-CIE 1931 and CIE 1931-to-LMS matricies [26]) (1). It simulates color blindness `cb` by applying a color vision deficiency matrix that has been experimentally calculated for each color blindness type based on their "confusion lines" (lines in color space that the colorblind person can not distinguish between all colors on that line [4]) (2), and then converted back to RGB color space using the inverse of the RGB to LMS conversion matrix (3). Space precludes including the matrices for all color blindness and types, but we list the resulting values for a person with Deuteranopia.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 17.8824 & 43.5161 & 4.11935 \\ 3.45565 & 27.1554 & 3.86714 \\ 0.02996 & 0.184309 & 1.46709 \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} L_{cb} \\ M_{cb} \\ S_{cb} \end{bmatrix} = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.494207 & 0.0 & 1.24827 \\ 0.0 & 0.0 & 1.0 \end{bmatrix} \times \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} R_{cb} \\ G_{cb} \\ B_{cb} \end{bmatrix} = \begin{bmatrix} 0.0809445 & -0.130505 & 0.1167211 \\ -0.0102485 & 0.0540193 & -0.113615 \\ -0.0000365 & -0.0041216 & 0.6935114 \end{bmatrix} \times \begin{bmatrix} L_{cb} \\ M_{cb} \\ S_{cb} \end{bmatrix} \quad (3)$$

When the simulated color blindness has been derived, we obtain Chroma's compensation values by calculating how erroneous the colorblind person perceives the original color. We calculate the shift `s` necessary to make the color more visible (4), and then add the compensation values to the original RGB color values (5), resulting in a matrix of the Daltonized color `d`. The following equations summarize this process.

$$\begin{bmatrix} R_e \\ G_e \\ B_e \end{bmatrix} = \begin{bmatrix} R \\ G \\ B \end{bmatrix} - \begin{bmatrix} R_{cb} \\ G_{cb} \\ B_{cb} \end{bmatrix} \quad \begin{bmatrix} R_s \\ G_s \\ B_s \end{bmatrix} = \begin{bmatrix} 0.0 & 0.0 & 0.0 \\ 0.7 & 1.0 & 0.0 \\ 0.7 & 0.0 & 1.0 \end{bmatrix} \times \begin{bmatrix} R_e \\ G_e \\ B_e \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} R_d \\ G_d \\ B_d \end{bmatrix} = \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} R_s \\ G_s \\ B_s \end{bmatrix} \quad (5)$$

Our algorithm is similar to other re-coloring algorithms that attempt to preserve color and information. In particular, Chun-Rong Huang's method [7] attempts to re-color the image by clustering colors into regions known as key colors, calculate the color-vision deficiency (CVD) color space empirically, and re-map the colors into CVD space based on the key colors. For each key color, this method re-maps it in consideration with CVD space and other key colors and shifts all colors associated with that key color accordingly. This means that less colors needs to be processed, but if implemented with real-time processing, this algorithm must re-calculate the key colors for each frame and then reformulate how the colors will be re-mapped, which may create significant latency. To reduce computational time, in Chroma each color is mapped to its corresponding Daltonized color in a hash-map as a pre-process before Chroma performs image processing. As Chroma processes each frame, for each pixel it simply looks up the corresponding Daltonized color, records it onto a new image, and finally displays the new image to the user. Although it is hard to judge subjective preferences in terms of re-coloring, our algorithm is more efficient and it demonstrated to be effective for real-time processing.

Outlining – In order to enable outlining, Chroma creates a mask of the original image, marking all pixels where its colorblind simulation has significant deviation from the original. Significant deviation means that the Euclidean distance between the 0-255 range RGB value of the colorblind-simulated pixel versus the original pixel is more than a specified threshold integer (currently 30, user-configurable). Once this has been determined, the outlining mode draws contour outlining onto the image, based on the mask's marked areas.

EVALUATION

Development of Chroma was informed and driven by our interviews and formative work. After implementing Chroma and deploying it on Google Glass we wanted to evaluate its efficacy and suitability to solve the outlined problems, as well as its possible deployment as part of daily activities of colorblind individuals. We therefore designed a laboratory test that would simulate some of the obstacles we discussed earlier and would assess Chroma in those situations.

We recontacted selected participants from the earlier interview based on their interests in our research, as well as on their professions. Subjects had the following colorblindness and professional backgrounds: deutan/electrical engineering, protan/electrical engineering, deutan/arts, protan/structural engineering, deutan/biochemistry, deutan/physics. We wanted to get a good feeling for how Chroma addressed the obstacles that were common among the majority of all interviewed participants as well as in select fields of work. We therefore designed three *general* tests to perform with all the users, as well as three *specialized* tests that would be given only to people active in particular fields.

Since we did not want to skew results in terms of color perception by showing the 'real' colors with Chroma beforehand, each of the six subjects participated in the tests twice, first without and second with Chroma. Test distribution was randomized. The low number of subjects does not ensure generalizability to our results, but this was never our goal. With this first evaluation we wanted to gain an initial feeling about the improvement that Chroma would enable. With two sets of results from each test, we were able to check improvement in performance at the participant level.

Description of Tasks

– *Ishihara Test (General)* – We used the same colorblindness test as during the interviews [12] to detect the presence and type of color vision deficiency. This is an online version of the Ishihara standard test that once completed, classifies participant's intensity and type of colorblindness. The goal of this task was to see if Chroma helps to reduce or alter a participant's colorblindness severity.

– *Blackboard (General)* – This test consisted of a blackboard with two graphs: a connected line drawn in green with one point drawn in orange and a bar graph with two bars colored green and two colored orange. The idea is that instructors sometimes use different colored chalk to highlight important material in lectures, which may be difficult to see for colorblind people. Participants were asked if there was an element that was a different color than the rest.

- *Clothing (General)* – We asked participants what colors they generally like to wear and what colors they usually avoid wearing. We showed participants different colored clothes and asked them what color they thought these were and asked if they would wear it. The goal was to verify troubles distinguishing different colored shirts and check if Chroma could help pick out the colors they like to wear.
- *Pictures (General)* – This test consisted in showing a collection of photographs ranging from pictures of street curbs, meat of varying doneness, cars, and flowers. For each photo, we asked participants to identify colors by name or circle certain colors in the photo. The goal was to document visual scene changes with and without Chroma.
- *Art (Specialized)* – This test consisted of a pack of unlabeled crayons and a coloring-book. Participants were asked to color a scene and label each color they chose to use. The goal was to identify problems for artists or designers and to gauge the utility of Chroma in this context.
- *pH strips (Specialized)* – For this test participants measured the pH of different liquids by comparing pH strips to different colors. The goal was to gauge problems for colorblind scientists working with chemical tests and see how useful Chroma could be in differentiating shades of a color.
- *Resistors (Specialized)* – This test consisted of different resistors, each with different colored bands. Participants were asked to name the colors of each band and the specific resistance if known. The goal was to identify how useful Chroma could be in identifying a small object's color.

Results

All participants but one had their online Ishihara test results reduced from a level of strong to mild. One participant went from Strong Deutan to Normal Vision when using Chroma. Five of the six participants improved considerably on the general Pictures test. During the Blackboard test, all participants failed to distinguish the orange chalk marking from the green without Chroma. However, with Chroma, all participants were able to distinguish the markings that were orange using the Contrast mode, but were not able to identify the color of those markings. Since they used the Contrast mode, Chroma helped them see the differences, but did not help in identifying the true color of the chalk. Five of the six participants improved their scores on the general Clothing test.

Four participants took the specialized Resistor test. Two of them were able to improve their scores, while one participant got all correct with and without Chroma, and one participant decreased his score. Two participants took the specialized Art test, both improving scores to 100% correct. One participant took the specialized pH Strip test showing no improvement.

Overall, participants were able to identify more colors correctly during the study with Chroma than without Chroma. While the general tests showed considerable improvements (Blackboard test from 0% to 100% success rate, Pictures test from 44% to 82%), specialized tests resulted in only slight or limited improvements (Resistors 73% to 85%, Art 75% to 100%). Additionally, although the level of colorblindness was decreased for each participant during the online color vision test, only four participants stated that they found Chroma useful in performing the tasks in the experiment and would find Chroma useful in everyday life. Two participants expressed concerns on Chroma's utility due to the fact that it lags and takes time to switch between modes. One participant did not find the application helpful since Chroma led him to worse results than normal during the specialized tests.

In general, participants found Chroma most useful when verifying their color guesses. One participant stated that *"the single color mode is most useful because I usually have an idea of what color an object is, so I can just pick the color mode and check."* Three out of the six participants shared this view. Two participants preferred the contrast mode, because it does not require much interaction with Glass to see different colors. Similarly, two participants commented that they appreciated the Daltonization mode because it helped them identify most colors without needing to switch coloring modes. While taking the online color vision test, participants were amazed to be able to see shapes and color with Chroma but not with their naked eyes, and therefore trusted Chroma's coloring algorithm especially in those situations when they could see nothing on the screen without using Glass. One of the participants commented *"With my own eyes, I can't see anything"* when looking at a pink circle on the computer screen, *"But with Chroma, I can clearly see a circle using Daltonization mode."* All participants were pleased to see the severity of their colorblindness drop at the end of the experiment.

Participants seemed to trust Chroma less when they had a good idea of what the color was or if Chroma's highlighting was scattered instead of solid. When trying to verify that a shirt was brown, one participant switched to brown mode only to find that Chroma did not highlight the shirt as brown. In general participants found Chroma least useful when trying to identify colors of clothing. This might be explained by the consistent failure of Chroma to highlight brown colors, as well as the wrong highlighting of blue as mostly purple in the blue vs. purple contrast mode. This is probably due to a problem with the Glass camera's perception of colors (see Discussion, below). Results confused participants, especially the ones who could recognize the brown color when *not* using Chroma. In those occasions, participants ended up disregarding Chroma's results and told us that the shirt was brown with less confidence. One participant stated that the red and brown coloring modes needed more improvement. He thought pink and green coloring modes were very useful due to the fact that they highlighted objects solidly. However, red and brown had scattered highlights, which made Chroma seem 'unsure'.

DISCUSSION

Chroma's overall results are encouraging and show that a wearable augmented-reality tool performing real-time color correction can in fact help address some of the current obstacles that colorblind people face in their daily activities. However, the Google Glass platform might still be too experimental to be used in real-world activity. Nevertheless we feel that our research and experiments showed interesting insights into the current issues of colorblind individuals and highlighted potential ways to improve the current approach.

For instance, participants preferred to use Chroma to verify their guesses. This indicates that despite having to overcome color barriers for most of their lives, the participants' strategies are sub-optimal and they need ways to confirm experience-driven guesses. When color blindness affected our participants so that they could not make any guess, they trusted Chroma. This illustrates how this technology could be a useful tool in those situations.

The form factor and the deployment of Chroma as a wearable device was perceived positively. In fact, our observations confirmed how users liked a *passive* tool that could just do the color highlighting for them. Our participants commented on how Chroma went in the right direction, but still required too much interaction. Going forward we feel that having more automatization, context-aware features, and voice commands might further enhance Chroma and similar applications for Glass, during real-world everyday activities.

Chroma's approach in communicating colors is new with respect to existing colorblind tools. Highlighting and overlaying contrasting colors as part of an augmented display was a successful strategy. However, users commented on how scattered overlays, a normal consequence of non-uniform color spectrum in real-world, communicated some sort of unreliability. In future work we will improve this aspect and visualize overlays using uniform shades based on interpolation.

The four modes implemented by Chroma have been tested in realistic scenarios, but in a laboratory setting. This resulted in a hybrid artificial environment where only partial evaluation was possible. Although we are already deploying Chroma for longer periods with our participants and observing how it impacts their daily lives, the reported experiment still informs us on the use of some of the functionality. For instance, we observed the prevalent use of the Contrast mode, but also how this should have been better integrated with the Highlighting mode to allow both the differentiation of different colors, and the identification of specific colors (such as the orange chalks) after the main differentiation was achieved.

Finally we noticed how Chroma performed better in the *general* tests with respect to the *specialized* ones. Although much speculation is possible here, we feel that colorblind individuals are probably very well trained in their own field of expertise and are therefore more proficient in finding successful workarounds for color barriers in those settings. Chroma's color verification holds, but we feel that there is space to explore and find new ways to better support knowledge workers.

Limitations

Chroma and its deployment as part of our experiment also uncovered current limitations of Google Glass that at times impacted the success of our application. Glass itself is still a prototype with a few hardware limitations which still do not allow it to be used in a continuous way. Processing power, battery life and camera limitations are major hurdles towards an effective deployment and usage as part of everyday life.

Due to the relatively old components included in Glass the processor is 3.2x slower than Nexus 5, Google's current reference device. In our particular case we notice how this resulted in a lag when running some of the modes, especially Daltonization. We considered offloading computation to a more powerful device through the Bluetooth connection on Glass, but the lack of drivers for interfacing with Bluetooth for our application did not make this practical to complete in our prototype. Moreover, the inherent latency of Bluetooth (roughly 150ms) did not fit the real-time interactive video requirements that our system demanded. Bluetooth 4.0 Low Energy claims that it can have a latency as low as 3ms, but at the time of implementation, this was not supported on Glass.

The battery is also a limitation of Google Glass, as it only holds 570 mAh. With Chroma running the camera, display and processor continuously, we were able to use Glass for a maximum of 1 hour from a fully charged battery. In comparison the Galaxy Nexus (Google's reference phone from 2011) contains a standard battery of 1850 mAh. Such a small battery life is a huge limiting factor if applications like Chroma are to be utilized for daily use.

Finally, the current camera technology is also sub-optimal, especially because the captured image colors deviate from the true colors. This is particularly problematic for Chroma. Google Glass does not currently support calibrating the visual display or the camera so Chroma is limited to the factory specifications of the device. Even with our 'gap' approach misclassification still occurred due to these reasons and, as we described, this might confuse users. Additionally, we observed how color deviation is worsened when the scene is under nonnatural light. Current white balance algorithms can not correct white balance variance as well as humans, thus causing the captured colors to deviate from the true colors of the scene. As a consequence Chroma performs differently under different lighting situations.

We are in the process of evaluating Chroma in a real-world scenario where colorblind users wear Glass throughout the day and have the possibility of using Chroma whenever they need. Although the described issues with Google Glass do impact this more naturalistic approach, we are confident that our *in the wild* study will allow us to uncover real and novel usage patterns that will inform further developments and improvements of Chroma.

CONCLUSION

By studying color blindness activity and strategies to overcome daily obstacles, we developed Chroma, a wearable real-time augmented reality support for colorblind individuals. Chroma's form factor and implementation demonstrated considerable potential in addressing the problems that colorblind people face in their daily lives.

There are many activities that colorblind people have difficulty accomplishing, and we expect Chroma to help them address these deficiencies. Such activities include, but are not limited to, cooking, choosing clothes or flowers, reading signs and maps, creating works of art, and manipulating photos. With wearable technologies such as Google Glass improving at an impressive rate, we believe that applications such as Chroma will be shortly available as a support for people with a variety of disabilities.

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