# ChromaGlasses: Computational Glasses for Compensating Colour Blindness

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**Figure 1. ChromaGlasses overview: (Left Top) Standard Ishihara test marker as seen through non-active glasses and cropped region. People suffering from red-green colour vision deficiency tend to see "21" instead of the correct "74". (Left Bottom) The same test marker when seen through active ChromaGlasses. A pixel-precise overlay causes a shift revealing the correct "74". However, depending on the severity, a less drastic shift might be sufficient. (Middle and Right) ChromaGlasses prototype for creating a precise correction overlay utilizing current optical-see through head-mounted displays extended by custom cameras demonstrating possible miniaturization.**

## ABSTRACT
Prescription glasses are used by many people as a simple, and even fashionable way, to correct refractive problems of the eye. However, there are other visual impairments that cannot be treated with an optical lens in conventional glasses. In this work we present ChromaGlasses, Computational Glasses using optical head-mounted displays for compensating colour vision deficiency. Unlike prior work that required users to look at a screen in their visual periphery rather than at the environment directly, ChromaGlasses allow users to directly see the environment using a novel head-mounted displays design that analyzes the environment in real-time and changes the appearance of the environment with pixel precision to compensate the impairment of the user. In this work, we present first prototypes for ChromaGlasses and report on the results from several studies showing that ChromaGlasses are an effective method for managing colour blindness.



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## INTRODUCTION
Depending on the ethnicity between 0.5-10% of the population or several hundred million people in the world have some sort of colour blindness or *Colour Vision Deficiency* (CVD)[9]. In contrast to the wide availability of corrective glasses refracting light to effectively compensate far/near-sightedness, there is no solution available which selectively converts colours in the user's field to compensate for CVD.

Recently, optical see-through head-mounted displays (OSTHMDs)—head-worn glasses with an integrated semi-transparent display in the user's view such as Microsoft's Hololens or Epson's Moverio BT-300—are entering the consumer market. While current OSTHMDs are still bulky and obtrusive, future appearance will move closer to conventional prescription glasses [24]. This paper thus explores the potential of OSTHMDs to support people suffering from CVD.

There are physical filter-based glasses that only work for mildly colour blind[1] but unlike the approach presented in this work these glasses are tinted (filter), behave similar to sunglasses and are optimized for specific wavelengths. They are not ideal for indoor scenarios nor do they address the fact that colour blindness is specific and requires individual settings nor, most importantly, do they allow for an environment-selective compensation—they colour-filter the entire view.

There is also research on recolouring images displayed on screens to support people with CVD [17, 30, 32] but the presented techniques cannot assist users away from the screen. Some existing works have employed similar recolouring algorithms, but use a camera to capture the environment and a video see-through head-mounted device as the output [38, 34]. While this supports visually impaired users to perceive their environment, it requires them to look at a screen rather than at the environment directly. This is impractical in most cases.

Our approach does not require users to look at a screen and with this decoupling them from their environment. Instead, Computational Glasses like ordinary glasses, allow users to directly see the environment with their own eyes as they are based on OSTHMDs. Research on OSTHMDs has mainly focused on superimposing digital information [24] and not on compensating visual impairments with pixel-precision by sensing and modulating the environment via a semi-transparent display, which is challenging [20, 28].

This work will present four novel contributions: 1) The concept of *Computational Glasses* as a class of vision correcting devices augmenting the concept of prescription glasses with OSTHMDs. 2) *ChromaGlasses*, a specific implementation of Computational Glasses aimed for compensating the effect of CVD. In our prototypical implementation we address the problem of how to sense the environment as seen by the users, identify critical environment colours, and modulate them via a semi-transparent display and with pixel-precision, assisting colour blind users to perceive and interact with their environment (see Figure 1). 3) We present the results from three studies using different implementation of ChromaGlasses providing first feedback on their feasibility and mental workload. Finally, 4) We give guidelines for researchers on Computational Glasses and in particular when addressing CVD as well as we address some limitations of the presented research giving an outlook for possible improvements when designing future systems.

## BACKGROUND

Assistive technologies that target CVD have been explored in many computing disciplines including human-computer interaction, computer graphics, and even electrical engineering. However, most of the existing works target optimizing human-computer interfaces or graphic renderings for the specific needs of colour blind users when using their desktop computer. Our work however, looks into Computational Glasses for supporting colour blind users when away from their desktop computers.

### Interfaces for the Colour Blind

CVD is a vision impairment most commonly caused by a genetic anomaly of the cones in the human eye[9]. Contrary to rods that are mainly responsible for perceiving brightness, cones are responsible for seeing colours. The genetic anomaly associated with colour blindness leads to a malfunction or absence of certain cones. This creates a decreased sensitivity in red-green hue discrimination. In rare cases, the anomaly can also lead to a decreased sensitivity in blue-yellow hues or even a total colour blindness. Research into addressing colour blindness using computer displays has a long tradition. Early works investigated to use computer displays and new mathematical colour models to simulate the view of colour blind users but also to create models that allow for selecting user interface colours that are easier to distinguish for colour blind users [25]. Usually, these approaches use identified colour transformations to recolour the image and simulate the appearance of the image to colour blind users. Existing research reports on different forms of these transformations but they often rely on transformations in the LMS colour space which models the human colour perception [35, 23]. Some research also proposed a custom adaption to adjust for personal preference [17] taking into account the fact that CVD can have different forms and severity. Existing research also reports on specific recolouring algorithms, for example aimed at speed and temporal coherence as required for recolouring videos [22], or recolouring algorithms that aim to have a more natural appearance [19]. The few approaches not applying recolouring make use of geometric patterns [30] or use a binocular Luster effect (different images for both eyes) which creates a subtle highlight effect around the modified image areas [7]. Common to all these approaches is that they aim to change the colour appearance for information shown on displays but do not consider support for modulation with the physical world.

Research also employed mobile phones for supporting people affected by CVD [31]. Here the phone's camera feed is recoloured and displayed to the user to help distinguish otherwise similar colours, with the inherent issue of decoupling the view. Carcedo2016 et al. proposed to utilize tactile feedback using wrist bands with RGB sensors which potentially works for larger objects in close proximity [6].

### Head-mounted displays for the visually impaired

With the introduction of head-mounted displays in the research labs, researchers started to realize the potential for adapting these devices for managing visual impairments. While not targeting colour blindness, Peli et al. were among the first who thoroughly analyzed the application of optical-see through head-mounted displays to different visual impairments [27, 28] and the potential was later supported by other works [36]. Itoh and Klinker explored also the possibility of vision augmentation and proposed to compensate near-/far-sighted vision by displaying compensation images on an OSTHMD [15]. Their research on *Augmented Vision* also highlighted one major technical challenge; moderating the environment with

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pixel-precision requires an on-axis camera that is virtually placed at the position of the users eye [27, 28, 15].

To overcome this problem and to ease development, most other researchers opted for Virtual Reality displays to compensate for visual impairments by turning them into video-see through head-mounted displays [1, 38, 37]. Here, the user is fully immersed and an integrated camera captures the environment and the captured imagery is manipulated for the user by applying image processing. Examples are the simulation of visual impairments [1], or vision augmentations for providing additional cues similar to the ones proposes by Peli et al. [38, 37]. While these video see-through approaches support visually impaired users and are easier to program and calibrate, they have two main disadvantages: 1) the form factor very much differs from normal prescription glasses and 2) they require the user to look at a screen rather than at the environment directly. This is impractical in most cases as it decouples the user from their environment.

Tanuwidjaja et al.have used Google Glass for treating visual impairments [34]. Google Glass devices look rather similar to normal prescription glasses and comprise a display that sits off-axis at the visual periphery of the users' view. This placement does not allow for a direct moderation of the environment and forces users to constantly switch their focus between the video feed displayed on the Google Glass and their real environment, as it is not possible to look at both at the same time. Despite these drawbacks Tanuwidjaja et al. showed with *Chroma* that Google Glass can be applied for managing CVD and is probably the most closely related work to our approach.

### Summary

Overall, most existing approaches focus on supporting people affected by CVD when working on screens. However, they cannot provide a continuous support and are consequently only of limited help for people with CVD. Vision augmentation research using head-mounted displays opens a new pathway, but most current approaches either use fully enclosed Virtual Reality headsets where the user sees the world via the camera feed or Google Glass based approaches, which cannot provide a direct overlay but provide a recoloured camera view in the visual periphery. Instead the proposed ChromaGlasses are a first implementation of our concept of Computational Glasses aiming at a direct moderation of the physical environment to compensate the effect of CVD.

## CHROMAGLASSES

Research on OSTHMDs originates in the field of Augmented Reality (AR) [33]. Here, OSTHMDs can be used to augment the physical environment with digital information such as navigation information [8], digital annotations [21] or medical data [2]. However, there are other use cases for OSTHMDs outside the domain of traditional AR research. In this work, we propose the concept of Computational Glasses. Unlike existing vision-augmentations, Computational Glasses are similar to traditional prescription glasses as one can physically see-through (transparency) but go beyond traditional glasses in housing an integrated transparent display providing a precisely registered overlay which can be used for compensating the effect of many visual impairments. These characteristics set Computational Glasses for vision augmentation apart from existing solutions that are either not transparent (e.g. [1]) or cannot provide a precisely registered overlay [34, 28]. The main reason for the latter is the dependency on off-axis cameras capturing the environment from a different angle than the human eye [28, 20]. This makes a pixel precise mapping from the camera to the user eyes very challenging or computational very expensive.

ChromaGlasses are a first prototypical implementation of Computational Glasses for compensating the effect of CVD. They need to be able to 1) sense the environment as seen by the user, 2) identify critical features in the environment, in particular colours that cannot be distinguished by the colour blind user, and 3) precisely moderate the critical features in the semi-transparent OSTHMDs to compensate for the visual impairment, in our cases CVD.

As we will show, the main technical challenges are in particular the sensing of the environment as seen by the user, as well as a precise moderation of identified features in the user's view. In the following, we will introduce the ChromaGlasses hardware and their calibration and provide details about the software implementation for sensing and moderating critical colours in the environment.

### Hardware

For building ChromaGlasses, we started with standard OSTHMDs. We were looking in particular for smaller head-mounted displays that are easier to modify. So instead of Microsoft Hololens or Meta Glasses, we opted for Epson's Moverio Series. Here we started with the Epson Moverio BT-100 for the first prototypes but later changed for an Epson Moverio BT-300 as it is smaller but also has an OLED-based display covering a larger colour space.

The main challenge is to create a hardware setup combining the display of the OSTHMD with a camera in a way that allows later to create a direct mapping from a camera pixel to a display pixel as required to moderate the environment with pixel-precision. Many head-mounted display such as the Microsoft Hololens or the Epson Moverio BT-300 integrate at least one camera used in traditional AR applications for hand or device tracking. However, these cameras are always off-axis cameras. This means that they see the environment from a different perspective as the eye of the user.

Instead, we opted for the idea by Langlotz et al. presented in the context of radiometric compensation for OSTHMDs [20]. A camera is virtually placed at the position of the eye using a beamsplitter (see Figure 2). For our prototypes we use 50/50 half-silvered mirrors that are reflecting half of the incoming environment light towards the cameras (in our case colour calibrated PointGrey Blackfly with Sony Pregius IMX249 sensor). Depending on the wearer of the OSTHMD and despite virtually placing the camera very close to each eye, there remains a small error. To reduce this error and create a pixel precise mapping between the cameras, the user's eyes, and the display we apply a calibration to the overall system. This

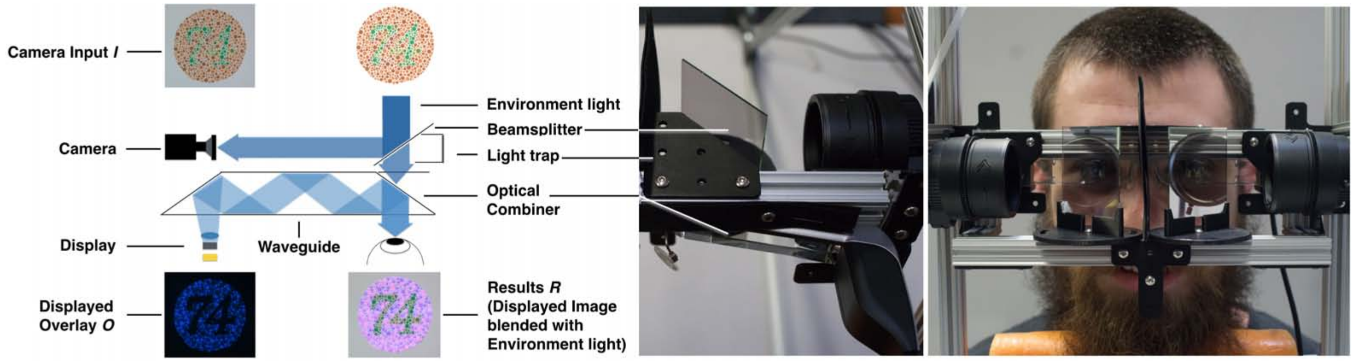


**Figure 2. Overview of the implementation and prototype. (Left) Illustration of the key components for ChromaGlass depicted for the left eye only. (Middle) Actual built prototype with key components for the right eyes. (Right) Full prototype as used for the study mounted in a frame with chin rest.**

calibration is only done once per user and can be done in less than two minutes.

Firstly, we perform an eye-display calibration similar to SPAAM [10] requiring the user for each eye to line up eight known points in the display with the real world. The real world points are visual patterns (markers) displayed on a screen that are also relatively easy to detect in the cameras' images (via the beamsplitter). So when aligning these points we are actually creating point correspondences between the display and the user's eye allowing us to compute an eye-display relationship [10]. Secondly, we also use the detected point correspondences between the display and the camera to compute a homography that is compensating for the small placement error between the display and the camera allowing us to create a pixel-precise mapping between them. While this calibration requires manual input, it is relatively easy to do and there are approaches that can automate this further in the future but would require eye tracking [14, 29].

At this stage, we have a hardware platform for our ChromaGlasses that consists of standard OSTHMDs (Epson BT-100 or BT-300) and senses the environment as seen by the user with a camera while also maintaining a pixel-precise mapping from the camera to the display as seen from the users perspective. This allows us for every pixel in the camera image to map it to the corresponding display pixel as seen by the user. As mentioned earlier we actually built two prototypes. One initial hardware prototype using the Epson BT-100 that was used in the first study and was mono (only for one eye) and a refined prototype using the Epson BT-300 that was stereo (for both eyes) (see Figure 2). Unless otherwise stated all shown results are produced using the ChromaGlasses built from the Epson BT-300. We also built a miniaturized version based on the Epson BT-300 but using smaller cameras and beamsplitters (see Figure 1). While this miniaturized prototype houses all required components, we did not use it to produce any results in this paper as the used components are hard to adjust for a precise enough adjustment. Thus is only serves as proof of concept for further miniaturization.

PointGrey Blackfly cameras have a linear response curve, so we did not apply further colour linearization but corrected for vignetting in the optical system (cameras and display).

## Software

Given that the described ChromaGlasses prototypes used similar or even exactly the same hardware (e.g. cameras), we implemented one common software platform that can be used to control all prototypes. The main tasks are to 1) identify the colours in the physical environment that are critical for CVD and 2) to precisely modulate the part of the environment seen from the perspective of the user via the OSTHMD.

### *Identifying critical colours*

As stated earlier, there are different forms of CVD. We focus mainly on describing a solution for managing a weaknesses in red-green hue discrimination as this is the most common form of CVD, also easing recruitment for study participants in the later stages. However, other forms of colour blindness can also be compensated with our proposed solution with only minor changes to the software.

In the first stage, we simulate the current view as perceived by a colour-blind user utilizing our calibrated camera virtually placed at the user's eye position (see Hardware). We based this simulation on the vast number of previous works on simulating colour blindness [35, 23]. We use the recent frames from the camera feed of the cameras $I$ and multiply each pixel by an adjustment matrix to simulate a CVD version of the image ($I_{CVD}$) (see Figure 3. After an informal evaluation with colour-blind participants, we based our implementation in particular on the adjustment matrices proposed by Viénot et al. [35]. According to our informal test they resulted in the most convincing simulation. However, as initially stated there are several other proposed equations for simulating CVD (e.g. [23]). To apply the matrices of Viénot et al. [35], we had to initially convert the input image from an RGB colour space to LMS colour space. LMS is frequently used in research on CVD and models the human colour perception. After conversion, we applied the proposed adjustment matrices depending on the form of colour blindness (e.g. Protanpoia or Deuteranopia). Thus our system needs to know the form of colour blindness as input to deliver the best simulation results.

In the next stage, we subtract the computed simulated view ($I_{CVD}$) from the original image to create an error mask describing the error between the original image and the image as seen

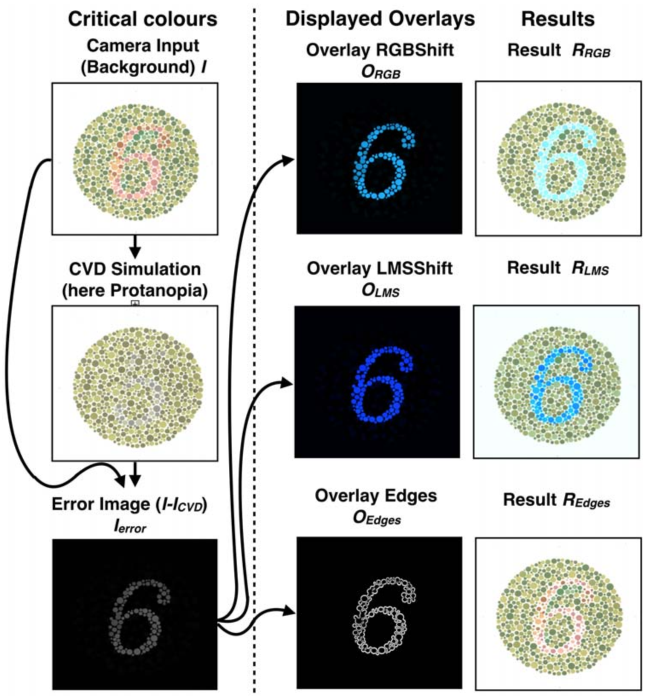


**Figure 3. Overview of our correction algorithm with major in-between steps. The computed final overlays *O* are displayed in the ChromaGlasses where they optically mix with the background producing the results *R* that are perceived by the user.**

by colour blind users. The resulting error mask is stored in a grey scale image ($I_{error}$).

Figure 3 shows the main stages of the overall pipeline and an example of the simulation and the corresponding error mask.

All computation models were implemented in our framework using Qt 5.4 and OpenGL 3.3 and GLSL shaders were used for all image operations to allow for real-time performance that is limited by the update rate of the cameras. OpenCV 3.0 was used for computing the lookup-table and the homography for calibrating the displays and cameras.

### *Mediating critical environment colours*

There is a large body of work on methods for managing CVD (e.g. on TVs or computer screens) [16, 17, 19, 30]. However, given that ChromaGlasses represent a new class of correction devices there is a lack of knowledge on the correction techniques and their feasibility in see-through glasses. We consequently investigated the feasibility of different correction techniques inspired by the literature on managing colour blindness. One main criteria for choosing suitable techniques is the impossibility of OSTHMDs to subtract colours (e.g. making the display darker). This excludes techniques that change the colours of the environment (e.g. [19, 7].

One of the most common approaches for visualizing critical colours is termed Daltonization [3]. Dependent on their form of CVDs, individuals with a colour vision deficiency can not distinguish certain colours placed on a line in the CIE 1931 colour space. These lines are called confusion lines [3]. The key idea of most Daltonization algorithms is to shift colours away from the confusion lines. The algorithm shifts the colours towards areas that can be distinguished by people with colour vision deficiency (e.g. shift towards the blue for Protanopia). We implemented in total five different techniques for compensating for color blindness: RGBShift, RGBShift Adjusted, LMSShift, LMSShift Adjusted and Edges.

**RGBShift:** Our first implemented correction technique is applying a recolouring in RGB space [12] that approximates the effect of Daltonization. For the identified critical colours given by our computed error map $I_{error}$, we apply a shift in the RGB colour space that uses pre-computed correction values based on the source colour. However, unlike the work by Tanuwidjaja et al. we do not apply the shift directly on the video feed [34] as we want to directly overlay the colour shift over the physical environment using our ChromaGlasses. Within ChromaGlasses we display the shift as an overlay $O_{RGB}$ where, thanks to the pixel-precise mapping, it optically combines with the physical background to form the visible result $R_{RGB}$. Apart from the pre-computed shifts that are based on the form of colour deficiency and the error caused by the colours in the environment, we also integrated the option to select a custom shift in RGB space (**RGBShift Adjusted**) that can be interactively controlled by the user.

**LMSShift:** This approach is similar to RGBShift, however, instead of Daltonization in RGB colour space using pre-computed shifts, the Daltonization is applied in LMS colour space as proposed by Jefferson et al. and Brettel et al. [17, 4]. The main idea is that the shift away from the confusion lines corresponds to a rotation in LMS colour space (with the rotation being dependent on the form of CVD). Again, we do not apply the shift directly on the video feed $I$ but display the required shift $O_{LMS}$ in our ChromaGlasses where they mix with the physical background to $R_{LMS}$ when seen through the optical combiner. While being conceptually similar to a shift in RGB space it gives a slightly different result. Also for LMSShift, we implemented a version where the displayed colour shift can be interactively controlled through by the user (**LMSShift Adjusted**).

**Edges:** This correction method highlights the outlines of contours with critical colours similarly to the outlining method presented by Tanuwidjaja et al. [34]. In contrast to the previous techniques that change the actual colours, this technique highlights the edges between critical colours. For this purpose, we use the error mask ($I_{error}$) as input and apply Gaussian blur to it. On the blurred error mask we run an edge detector (Sobel edge detector) to find edges in the error mask. These edges mark the transitions between critical colours in the environment. In contrast to the method of Tanuwidjaja et al., we adjusted this method to the specifics of the OSTHMDs and display white edges rather than black (OSTHMDs cannot display black colours; similarly to projectors they cannot make the environment darker [20]). When displaying the edge overlays $O_{Edges}$ in ChromaGlasses they precisely blend with the physical environment ($R_{Edges}$).

Unfortunately, OSTHMDs always blend colours with a background in a fixed ratio (depending on the used optical com-

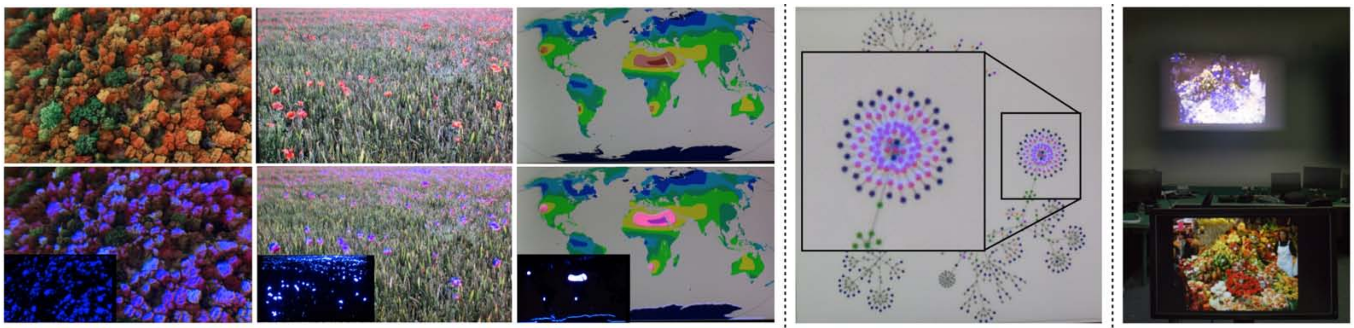

**Figure 4. Results using selected images also used in Study 3. (Left) Uncorrected and corrected images as seen through ChromaGlasses. The small inlay shows the actual overlay against black background (all using LMSShift). (Middle) Magnification of an already cropped image area. The typical pixel error for a well-calibrated system is typically within 1 pixel. (Right) Setup showing the off-axis Google Glass based approach as used in Study 3.**

biners and the displays and their specification) and cannot fully replace a colour. For example, when highlighting the outlines of contours with critical colours, the white of the overlaid edges mixes with the background and will fade and look less uniform. To compensate for this effect, we correct for the characteristics of the system (e.g. colour response of the display, vignetting, transparency level of the optical combiner) while also compensating for the current background colour. This correction is implemented in a shader and is based on the approach by Langlotz et al. [20] who similarly compensated the radiometric error caused by the optical blending with the background.

Overall, our ChromaGlasses present a first implementation of Computational Glasses for colour blind by incorporating optical-see through head-mounted displays. Figure 1 shows some results for LMSShift when looking through ChromaGlasses towards a standard Ishihara test as used for the identification of colour blindness. As one can see we shift colours from the red spectrum into the purple by precisely overlaying it with blue when seeing through our ChromaGlasses. Figure 4 shows some realistic uses cases also highlighting the accuracy that can be achieved with our ChromaGlasses. All pictures are made with an off-the-shelf digital camera and cropped to only show the area covered by the ChromaGlasses with an aperture set to 3.5 roughly resembling an aperture in the range of the human eye [26]. In the following, we report on the studies investigating the feasibility and workload of ChromaGlasses.

## STUDY 1: FEASIBILITY USING USER-PERSPECTIVE CAMERA

It is difficult or even impossible to exactly see what other people are seeing when using OSTHMDs. Physiological differences (e.g. different eyes, different head geometry) result in a different eye display calibration. In our first study, we were interested to evaluate the feasibility of our ChromaGlasses. However, we wanted to control the study as much as possible to exclude external factors such as the eye-display calibration. For this purpose, we decided to evaluate our first ChromaGlasses prototype using a user-perspective camera as a proxy for the human eye. This study as well as the following studies have received ethical approval and followed the given requirements.

**Design:** We designed a within-subject study to investigate the feasibility and compare the different implemented methods for correcting CVD using four different Ishihara plates —a standard visual test for detecting CVD [13] requiring users to correctly identify the shown numbers. The dependent variables were the *success rate* and the *confidence score*. The success rate describes how many numbers on the plates were correctly identified (resulting in a success rate of 0.0 if no answer was correct or 1.0 if all answers where correct). The confidence score is a subjective measure that describes the perceived confidence when answering the question (using a Likert-scale from 1 to 5). The confidence score was adjusted for correct and incorrect answers. For this purpose, we converted the confidence values to a positive confidence value if their answer was correct and to a negative confidence rate if the answer was incorrect (see supplementary material for equations). This confidence rate allows us to penalize wrong answers with a high confidence and reward correct answers with high confidence.

The independent variable was the correction method with six conditions: None, RGBShift, RGBShift Adjusted, LMSShift, LMSShift Adjusted and Edges.

**Apparatus:** We positioned a camera at the position of the user's eye and calibrated the overall system for this camera. The user sees through ChromaGlasses by seeing the camera image on a computer screen. The advantage of this setup is that we can calibrate the setup beforehand controlling the calibration quality of each user. In our case we used a Point Grey Blackfly camera which is factory colour calibrated for a linear response. We calibrated the overall system as outlined earlier.

**Procedure:** After signing the consent form, participants filled out the demographic questionnaire. The demographic data collected information on age, gender, ethnicity, and vision impairments (colour and refractive), as well as familiarity with similar systems and technologies. Each participant was checked by us for CVD using the standard Ishihara test [13]. For this initial CVD assessment, we used the standard Ishihara test plate set with 38 test plates which is relatively easy to conduct and for which we received an introduction by colleagues from ophthalmology. This allowed us to capture the form and severity of CVD.

For the actual study, the participants observed four Ishihara test plates which were not used in the initial assessment. As described earlier, in this feasibility study the participants were not wearing the ChromaGlasses, instead they were seeing through them towards the Ishihara test plates using a user-perspective camera placed at the position of the human eye. Apart from the camera feed displayed on a monitor in front of the participants, the participants had no direct view on the test plates. For each Ishihara plate, we applied all different correction methods.

These correction methods were applied in a semi-randomized order. We always started with no correction and then applied RGBShift, LMSShift and Edges in a randomized order. Finally, we used RGBShiftAdjusted and LMSShiftAdjusted and receive feedback if the results can be further improved using custom shifts. For each plate and correction technique, we asked the participants what number they see and their confidence on a 5-point Likert scale. For conditions RGBShiftAdjusted and LMSShiftAdjusted, participants were asked to set the adjustment parameters to increase their confidence. The adjustment parameters were the amount to add to each to channel for RGBShift and rotation angle for LMSShift. The participants were able to interactively change the parameters using a keyboard. The settings were stored on the computer for later analysis. Overall, this study took approximately 30 minutes to complete. During the experiment we took notes, and participants were encouraged to vocalize their thoughts regarding their experience.

**Participants:** We recruited only people with CVD. We mainly recruited from staff and students. Due to the overall occurrence pattern between 3-8% of the male population (depending on ethnicity) we recruited by talking to roughly 2000 students and sending out emails to the general staff. Given the occurrence pattern of CVD we expected a mainly male cohort of participants but did not excluded woman in the recruiting.

Overall, we had 19 participants with a average age of 24.0 ($\sigma = 10.04$), all were male and had forms of red-green colour blindness.

**Hypotheses:** For the feasibility study, we were mainly interested in the aspects how much the CVD of the participants can be compensated and how much more confidence can be created using the correction methods. To investigate these aspects, we postulated two hypotheses:

- H1:Using the ChromaGlasses correction methods, participants would improve their ability to pass a colour blind test (would not be detected as colour blind while seeing the corrected view).
- H2:Using the ChromaGlasses correction methods, participants would feel more confident when recognizing the correct content on the plates.

**Results and Discussion:** For each plate and correction method, we computed the success rate describing the ratio of right or wrong answers. We tested the success rates for normal distribution using the Shapiro-Wilk test, showing that it is most likely that the data is not normally distributed. Thus, we performed a Friedman test that showed significant differences in the success rate ($\chi^2(5) = 79.154, p - value < 0.001$). Based on this, we performed a post-hoc analysis using Wilcoxon signed-rank test (Holm correction). The results show that all ChromaGlasses correction methods have a significantly higher success rate compared to the uncorrected condition ("None") (Figure 5, Left, p<0.005, details in supplementary material). LMSShiftAdj performed best (mean 0.97). Furthermore, results showed significant differences between all conditions, except RGBShift-LMSShift, RGBShift-Edges, LMSShift-Edges and RGBShiftAdj-LMSShiftAdj.

In addition, we asked the participants to rate their confidence and computed the confidence score as described earlier. The results of the Friedman test showed that there are significant differences between the answers ($\chi^2(5) = 75.332$, p-value <0.001). The post-hoc analysis using Wilcoxon signed-rank test (Holm correction) showed that there are significant differences between all correction methods, except RGBShift-LMSShift and that all correction methods performed significantly better than the reference method using no correction ("None") (Figure 5, Right, p<0.005, details in supplementary material). Again, LMSShiftAdj performed best (mean 4.43).

We also looked for correlations between the adjustment parameters for the RGBShiftAdj and LMSShiftAdj. For this purpose, we performed a Pearson correlation test between each of the parameters for each plate over all participants (details in supplementary material). The correlation tests did not show any consistent patterns showing us that for our participants the parameters were more set to a personal taste but can in any case further improve the results for success rate and confidence.

With the feasibility study, we were able to confirm both hypotheses (H1) that participants would improve their ability to pass a colour blind test using any of our correction methods and (H2) that participants would feel more confident when recognizing the correct content of the Ishihara plates. We also showed that while the default colour shifts and edges achieve a significant improvement, the success rates and confidence scores can be further improve with custom correction matrices set by the participants. We could not detect differences between the default colour shifts (RGBShift, LMSShift) and edges (Edges) with respect to the success rates. However, people were significantly more confident using the default colour shifts (RGBShift, LMSShift) compared to the highlighting edges (Edges). These results align with the verbal feedback from study participants.

## STUDY 2: FEASIBILITY WEARING CHROMAGLASSES

The main objective for the second study was to replicate the first feasibility study with a setup where the participants actually look through the ChromaGlasses and where the ChromaGlasses are calibrated for each participant. For this purpose, we used the same task as in the feasibility study asking the participants to identify numbers on Ishihara plates.

**Design:** As in the initial feasibility study, we designed a within-subject study to investigate the effectiveness by ask-

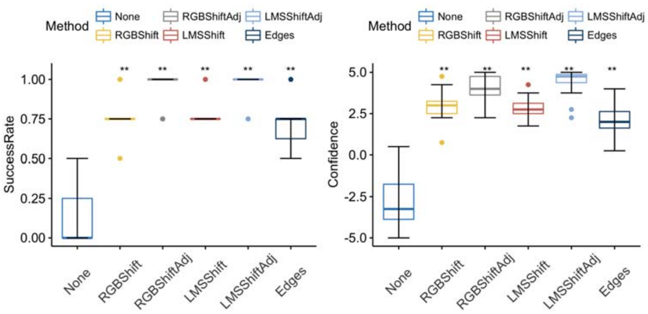


**Figure 5. (Left) Boxplots for the success rate and (Right) confidence rate for each method in Study 1. Significances are indicated against the reference group without correction ("None").**

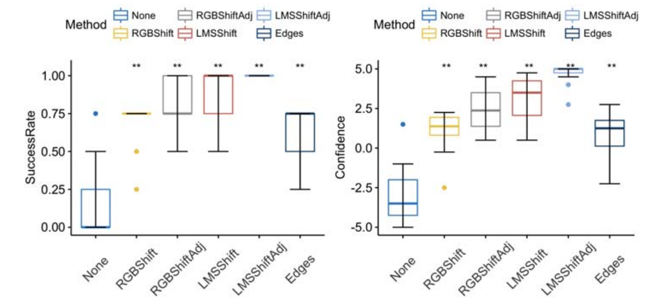


**Figure 6. Boxplots for the success rate and confidence rate for each method for the evaluation of Study 2. Significances are indicated against the reference group without correction ("None").**

ing participants to identify numbers on Ishihara plates using different correction methods. We used the same dependent variables as in the first feasibility study: success rate and confidence score and the same independent variable: the correction method.

**Apparatus:** Instead of using a camera to show the results of the different correction methods to the participants, in this study we asked the participants to use the ChromaGlasses directly. To control the tests, we setup a rig that fixed the ChromaGlasses and provided a head rest (Figure 2, Right) to fix the distance between the test plates and the participants, and to maintain the quality of the eye display calibration during the study. The Ishihara plates were then shown on a colour calibrated LCD display to provide a consistent and fast exchange of the shown content.

**Procedure:** We maintained the same procedure as in the feasibility study consisting of signing a consent form, filling the demographics questionnaire and checking each participant for CVD using a set of Ishihara plates. For the actual study, we again showed a set of Ishihara plates (different to those in the first study and those in the initial test for CVD) using the different correction methods in randomized order and asked them what number they see and about their confidence.

**Participants:** For this study, we recruited 19 colour blind participants. All participants, but one were male and aged between 18 and 51 (average: $23.21, \sigma = 9.23$) and all but one had forms of red-green colour blindness with one participant showing total color blindness (very rare) who was treated separately. Participants were recruited using the same mechanisms as in the feasibility study and were compensated by a $20 voucher.

**Results and Discussion:** We performed a Friedman test for the success rate that showed significant differences in the success rate ($\chi^2(5) = 73.446$, p-value < 0.001). The post-hoc analysis using Wilcoxon signed rank test (Holm correction) showed that there are significant differences in the success rate between the uncorrected option (None) and all correction methods (Figure 6, Left, p<0.005, details in supplementary material) and that all correction methods performed better than the uncorrected option. The methods allowing for a custom shift again performed best. All correction methods showed significant differences to all other methods, except for RGBShift-Edges and LMSShift-RGBShiftAdj.

We also performed a Friedman test for the confidence score that showed significant differences ($\chi^2(5) = 78.926$, p-value < 0.001). The post-hoc analysis using Wilcoxon signed rank test (Holm correction) showed that there are significant differences in the confidence score between the uncorrected option (None) and all correction methods (Figure 6, Right, p<0.005, details in supplementary material). All correction methods showed significant differences to all other correction methods, except for RGBShift-Edges and LMSShift-RGBShiftAdj.

With the replication study where participants look through the ChromaGlasses directly, we were able to reproduce similar results as in the initial feasibility study. This increases the internal validity of our results by removing the confounding factor of the eye-display calibration as this second study was less controlled when compared to the initial feasibility study with participants actually looking through the ChromaGlasses requiring a unique calibration for all participants. We confirmed again both hypotheses that H1) participants wearing the ChromaGlasses would significantly improve their ability to pass a colour blind test using any of our correction methods compared to using no correction and that H2) participants wearing the ChromaGlasses with the correction methods enabled would feel more confident when recognizing the correct content of the Ishihara plates. More specifically, we showed that the edge-based technique (Edges) perform significantly worse in terms of success rates and confidence compared to LMS colour shift-based approaches (LMSShift,LMSShiftAdj) which was hinted already in the confidence test of the first study. In contrast to the initial feasibility study, we detected difference in the default colour shifts (LMSShift,RGBShift). But we confirmed again that success rates and confidence scores can be significantly improved using custom shifts over the default shifts.

We also received feedback from one participants showing total colour blindness (treated separately). Not surprisingly, the default shifts (intended for red-green vision deficiency) did not help, but custom shifts allowed also for this participant to improve the scores to nearly 100% success rate with high confidence.

## STUDY 3: USABILITY AND MENTAL WORKLOAD

As discussed in our related work section, there are earlier works that proposed to use Google Glass for addressing CVD [34]. Instead of seeing-through the glasses, they are based on the concept of displaying a moderated camera image in the peripheral display of the Google Glass. In the following we report on a study comparing our approach (ChromaGlasses) against a Google Glass based approach (reassembling the work by Tanuwidjaja et al. [34]). Based on our previous studies and the results from Tanuwidjaja et al. [34], we considered both solutions as viable solutions. Consequently, we were primarily interested in the workload and the efficiency for both solutions.

**Design:** As the previous studies, we used a within-subject design. As the main goal of this study was to investigate the efficiency and workload of the ChromaGlasses compared to a Google Glass-based approach, the dependent variables in this study were the results of the NasaTLX and a subset of SUS questions (that were suitable for our systems). The independent variable was the display device with the conditions ChromaGlasses and Google Glass.

**Apparatus:** Since our main objective for this study was to investigate the difference between the two devices, we added a Google Glass-based solution to the study setup from the second study. We prepared a set of six different task with two test images each. The tasks are: 1) Identifying red fruits on a fruit-stand, 2) identifying red areas in a landscape, 3) identify the red graph within a complex graph, 4) identify red areas in maps, approximate number of 5) red flowers or 6) red fruits on a tree. All task were tested beforehand with people affected by CVD and were considered challenging tasks (see some examples images in Figure 4). For fair comparison both approaches used the same default shift colour shift (LMSShift) and we always shifted the same colour (red) which was explained to all participants. During pilot testing we identified one issues with the Google Glass. The camera and display are so small that even larger details in the captured environment are completely lost and objects have to be held very close to the eye (30cm) to reveal details. To still be able to run the study, we gave the Google Glass-based approach an advantage: Instead of showing the test images captured with the integrated camera, we loaded the actual test images in full resolution on the device.

**Participants:** For this study, we recruited from the same cohort of participants as in the second study as we still had their eye-display calibration stored reducing the time for calibration ChromaGlasses.

**Hypotheses:** We hypothesized that our solution ChromaGlasses will:

- H1: show similar mental workload
- H2: show similar efficiency

when compared to the Google Glass-based approach reported in the literature. These hypotheses are based on the assumptions that we despite our early prototypes and larger form factor we can compete with the current state-of-the-art solution using an off-the-shelf device.

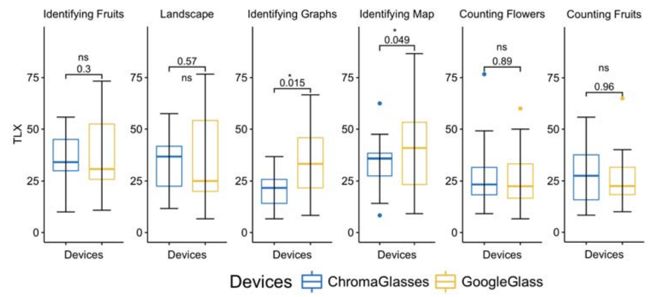


**Figure 7. Mental workload as measured via Raw TLX for ChromaGlasses and Google Glass**

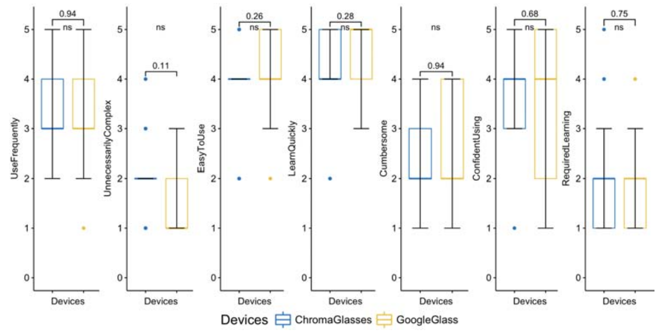


**Figure 8. Usabillity as measured via selection of SUS questions for ChromaGlasses and Google Glass**

**Procedure:** After giving consent each participant calibrated our ChromaGlasses to match their specific eyes. Similarly, the participants adjusted the display on the Google Glass to fit their eye. For each user, we randomly selected an labeled image from each image category (fruit-stand, landscape, graphs, maps, flowers and fruit trees) that is seen through ChromaGlasses, with the remaining image for each category seen while wearing the Google Glass. For each shown image, we asked the participants to identify the red labeled objects (fruit-stand, landscape, graphs, maps) or to decide between 4 options of how many red objects were shown (flowers and fruit trees). After each task we asked the participants to fill out a Raw NASA Task Load Index (non-weighted NASA TLX). We also had a final questionnaire containing questions on efficiency (a subset of the SUS). We decided to remove three questions that were not fitting our scenario such as "need support of a technical person to be able to use this system", "various functions in this system were well integrated", as well as "too much inconsistency in this system".

**Results and Discussion:** As shown in Figure 7, we found significant differences for the raw TLX overall score between the ChromaGlasses and Google Glass for the tasks on graphs (Wilcoxon paired: $p=0.015$) and maps (Wilcoxon paired: $p=0.049$). For both tasks the score was lower for the ChromaGlass (Graphs: mean=21.76, Maps: mean=33.87) which indicates that the workload is smaller compared to the Google Glass (Graphs: mean=34.26, Maps: mean=40.2). When testing for differences in the questions on efficiency (subset of

SUS) we could not find any significant difference between both devices (Figure 8, details in supplementary material).

With this study, we showed that we have to reject our initial hypothesis H1. In fact our approach showed a significantly lower mental workload for two out of the six task while showing no effect for remaining four tasks. When looking at the tasks, we identified that when higher amounts of details are required to solve a task, the workload was significantly smaller when using our ChromaGlasses. This is despite the fact that we gave Google Glass an advantage and details were clearly visible. We argue that the increased workload for the Google Glass comes from the need of matching the information seen on the display in the periphery with the real work which becomes harder for small details. This was anecdotally supported by user comments. For the efficiency measured using a subset of the SUS questionnaire, we were able to confirm our second hypothesis H2 that ChromaGlasses are similarly efficient to the current state-of-the art solution using Google Glass.

## DISCUSSION AND FUTURE WORK

In this work, we proposed the ideas of Computational Glasses as vision aids utilizing optical-see through head-mounted displays. With ChromaGlasses, we introduce first prototypes for Computational Glasses aimed at compensating the effect of CVD. ChromaGlasses employ a novel head-mounted display design using an on-axis camera virtually placed at the location of the user's eye allowing a pixel-precise mapping from camera into the user's view. By detecting critical colours in the user's view and shifting these colours on a per pixel-base using the integrated display, we can support users in mitigating the effect of CVD. We received feedback on the feasibility from two user studies with two different prototypical implementations of ChromaGlasses showing that our approach increases the success rate and confidence when running standard tests for CVD to the level that they cannot be detected as colour blind. Additionally, we show that setting custom parameters can further improve the results for success rate and confidence. We also conducted a third study comparing our approach against a Google Glass-based implementation providing a recoloured image in the users periphery. This study found hat ChromaGlasses has a lower workload for some tasks involving smaller details even when give an advantage to the Google Glass-based implementation.

*Limitations.* The current evaluation was within a controlled environment to maintain consistency between the participants but the prototype works outside some of these constraints. Lighting for example is less of a problem given the relatively bright Epson glasses used which was tested in different environments. Unlike the setup used in the evaluation, the head position can be relaxed as long as the eye display relation is kept which can be assured with tight head-mounts (e.g. such as with Hololens) or can instantly be re-calibrated by using eye tracking (such as in [14]). Once calibrated the distance to physical objects can be further relaxed as the calibration is not for specific distances or focus planes. However, we still face the problem of *accommodation-convergence mismatch* as consumer-grade OSTHMDs have a fixed focal plane which causes the problem of accommodation-convergence (an unnatural focus adaption with conflicting cues) [18]. Surprisingly, for our work this was less of a problem as initially expected. Users tend to focus on the high contrast physical environment causing the overlay to be out of focus. As the overlay in the ChromaGlasses itself is relatively low in contrast this difference is hardly noticeable but using varifocal displays would still improve the results. The current hardware is also still relatively large making it currently difficult to investigate everyday usage. However, the issue is more the low scientific reward for continued *hardware miniaturization* rather than the lack of potential for miniaturization. We already showed a smaller prototype (see Figure 1), but further miniaturization is possible by fully integrating the cameras and beamsplitter into the housing. One of the biggest issues is the relatively high latency which is still around 300ms; a consequence of how the images are transferred to the Epson BT300 OSTHMD via USB which can be avoided by using other hardware with more direct access.

*Future work.* The majority of compensation techniques are driven by existing research and are based on recolouring images in a way that works for the majority of people suffering of CVD resulting in strong colour shifts. However, for permanent vision augmentation such as with ChromaGlasses, strong colour shifts might be obtrusive to the wearer in particular as users do not necessarily need such a strong shift (see Figure 1). Unfortunately, existing approaches for more *natural re-colouring* [19] or potentially less obtrusive highlighting [7] would not work in OSTHMDs as they require to darken the environment via the display which cannot be done with current OSTHMDs. Colour shifts could also lead to semantic issues when shifting towards colours already present in the environment [30]. We propose to apply the idea of *context-awareness* as also required for other applications requiring continuous augmentations [11]. More precisely, we proposed *context-aware recolouring* for vision augmentations where the system can adapt by shifting towards colours not present in the environment to avoid semantic conflicts. This could be combined with user-controlled colour shifts [17, 34]. However, we would advocate to also consider eye-tracking for interactive selection and highlighting not requiring hand gestures [5].

Overall, we think that this work shows the potential of vision augmentations using Computational Glasses, opening a pathway for future research not only on CVD but also on other vision impairments. The presented research has also strong implications for supporting non-impaired users as in Augmented Reality or the concept of Augmented Human where real-time image analysis would allow for overlaying additional information or providing a x-ray view [39].


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