Seeing Colours: Addressing Colour Vision Deficiency with Vision Augmentations using Computational Glasses

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Colour vision deficiency is a common visual impairment that cannot be compensated for using optical lenses in traditional glasses, and currently remains untreatable. In our work, we report on research on Computational Glasses for compensating colour vision deficiency. While existing research only showed corrected images within the periphery or as an indirect aid, Computational Glasses build on modified standard optical see-through head-mounted displays and directly modulate the user's vision, consequently adapting their perception of colours. In this work we present: an exhaustive literature review of colour vision deficiency compensation and subsequent findings; several prototypes with varying advantages - from well controlled bench prototypes to less controlled but higher application portable prototypes; and a series of studies evaluating our approach starting with proving its efficacy, comparing to the state-of-the-art, and extending beyond static lab prototypes looking at real world applicability. Finally, we evaluated directions for future compensation methods for computational glasses.

CCS Concepts: • **Human-centered computing → Accessibility technologies**; *Ubiquitous and mobile devices.*

Additional Key Words and Phrases: Computational Glasses; Augmented Reality; Colour Blindness; Colour Vision Deficiency; Augmented Human; Near-Eye Displays; Head-Mounted Displays; Augmented Vision

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1 INTRODUCTION

Whilst modern prescription glasses provide a socially accepted and effective solution to refractive errors such as myopia and presbyopia, there remains a wealth of unaided visual impairment affecting members of our society such as peripheral and central vision loss, or night blindness [99]. One of these problems is *Colour Vision Deficiency* (CVD), which is more commonly known as colour blindness. CVD is a condition in which those afflicted perceive colours in a manner that is considered abnormal. This condition affects an estimated several hundred million people worldwide [19] and is most commonly seen in the form of a genetic condition under which red or green wavelengths are perceived as being closer to the other than they are under normal vision. However, there are also other more uncommon causes and effects.

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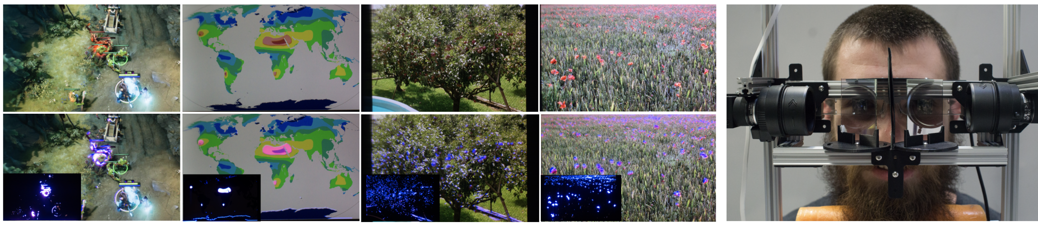


Fig. 1. Examples demonstrating the results from using Computational Glasses to create a spectral wave-length shift for CVD. Top: Pictures presented in front of a user wearing our prototype. Bottom: The pictures when viewed using a compensation technique, insets demonstrate what is displayed on the glasses. Note that these are exaggerated compensations for paper clarity. Right: The large, stable stereoscopic prototype used for controlled user studies. All images were captured through this system and are not simulated. We also demonstrate the development of smaller portable versions.

Techniques to address CVD through computational means have been explored for over 20 years [13, 83, 130] and usually focus on optimising user interfaces (e.g., web pages or navigation interfaces). Most user interface techniques shift the representation of the confused colours by changing either their hue or brightness thus improving the user's ability to distinguish between them. Given the focus on computer screens and its applications for exploring the web and digital content, only a few works considered applications in everyday activities, such as deploying the system onto a mobile phone [4, 111] or a *video see-through head-mounted display* (VSTHMD) [140, 141]. Whilst they can improve a user's ability to discern colours, the mobile phone applications require the user to be aware of the presence of confusing colours, making spontaneous or continuous use difficult. At the same time while VSTHMDs could potentially be worn continuously, the systems suffer from extreme drawbacks such as camera positioning blocking the user's view, latency, and limited colour response of the cameras, making them impractical.

A more ideal assistive technology would closely resemble the currently accepted glasses having a small form-factor, and being lightweight, see-through, and non-intrusive. These requirements match those demanded from, and seen in the development trends of, near-eye *optical see-through head-mounted displays* (OSTHMDs). Works have utilised off-axis *head mounted displays* (HMDs) in the form of Google Glasses [124], however until our recent work, where we presented ChromaGlasses [69], the first instance of Computational Glasses, no system compensated the wearer's perspective of the world by using OSTHMDs. We build upon this work here. Computational Glasses present a unique advantage compared to prior approaches in that the user's view of the world is directly modified and does not require a conscious shift from scene exploration to confirm colours. This would allow the system to become even less obtrusive and be more naturally integrated into the user's daily life.

We present our prior work verifying the feasibility of Computational Glasses for CVD mitigation in a series of increasingly realistic studies, ranging from an initial technical validation of a monocular prototype, to a more realistic stereoscopic system. Our tests showed our concept was feasible and indicated that a colour shift might provide good discernability when tested on the standard Ishihara test for colour blindness. A comparison with state-of-the-art CVD compensation on Google Glasses showed that our system performed better for small details without increasing a participant's workload. Example output from our Computational Glasses for CVD can be seen in Figure 1.

We have conducted two subsequent studies. Firstly, we conducted an explorative study looking for feedback on our concept in which we asked participants to wear a portable prototype and tell us about their experience of observing a poster whilst wearing a prototype of our system. This evaluation underscores the need for personalized and situation aware corrections and presents a variety of remaining challenges and potential application avenues.

Finally, as there have been many ways proposed for correcting CVD and to identify other viable techniques, we selected several techniques that could be deployed on Computational Glasses from the literature. We conducted a short study on these techniques using a more diverse dataset of images that included tasks users could face outside the laboratory setting. Our results indicate that whilst many of the techniques worked on extreme case synthetic material the obtrusion and applicability to more general scenarios was limited.

Overall, we make three contributions in this work:

- We provide an exhaustive review of the related work in CVD as it pertains to computational compensation techniques and highlight gaps in the literature in regards to comparisons between presented techniques and sufficient data sets to perform comprehensive tests with high generalisablity.
- We revisit our exploration of Computational Glasses for CVD compensation. We developed a series of prototypes, transitioning from highly constrained lab prototypes to less constrained portable ones. We present these prototypes and discuss the lessons learned.
- We conducted a series of studies with participants affected by CVD starting with controlled lab studies to test the efficacy of our glasses, and evaluate internally using various techniques to aid CVD, as well as externally against prior AR work as to the usability of our devices. Finally, we conducted an explorative study looking to garner feedback from participants in a less constrained environment and explore other feasible compensation techniques for Computational Glasses.

2 BACKGROUND ON COLOUR VISION DEFICIENCY

CVD has been studied for several centuries, initially being described by ophthalmologists and various scientific fields before being simulated and depicted on computers. Since then, various techniques have been explored to address CVD mainly within the field of human-computer interfaces. While most existing techniques for CVD target user interfaces on general displays, we are mainly interested in computational techniques that support those affected by CVD when interacting with their physical surroundings. More particularly, using head-mounted displays to directly augment the user's senses. In the following we provide an extensive review on literature in the field. We start by providing some background on CVD. Then, as the first of our main contributions, we provide an exhaustive review on computational techniques that address CVD. Finally, we briefly addressing the general idea of vision augmentations.

In 1798 Dalton reported on the observed differences in his own colour perception compared to that of others, and found that this was not unique to himself, before speculating as to the nature of this anomalous colour vision [23]. Although his explanations were not complete, subsequent research revealed how our eyes process incoming light and the causes of CVD. It is now known that the human eye has a number of photo receptors on the retina that are sensitive to different wavelengths of incoming light (*cones*) and light intensity (*rods*). Normal colour vision, also known as *trichromacy*, is the result of different response functions from cones to incoming light waves, in particular red, green, and blue. These cones are also termed *Long*, *Medium*, and *Short*, respectively, due to the wavelengths that produce the strongest response in each type. Anomalous cone responses result in various forms of CVD. The mildest form is *anomalous trichromacy* where the eye retains all cone types however the colour response of at least one of them is reduced. Depending on the affected type of cones this condition is referred to as *protanomaly, deuteranomaly, or tritanomaly.* In more extreme forms, the response from one cone type may be missing entirely, resulting in colour vision

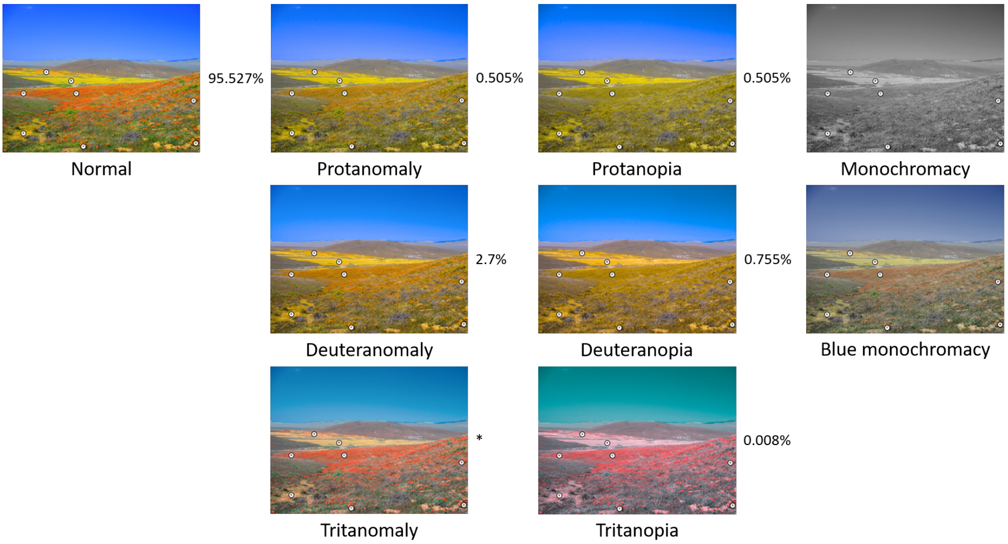


Fig. 2. Types of CVD and estimated world percentages. Values estimated based on The Perception of Colour [62]. * Percentages for tritanomaly, and forms of monochromacy are not available due to their scarcity.

consisting of variations of only two colours, also known as *dichromacy. Protanopia, deuteranopia, and tritanopia* are all forms of this. Note that whilst dichromacy is considered abnormal in humans due to a lack of cones, it is a common state among some animals, for example dogs and cats [54]. The commonly used term of "red-green blind" or "red-green weakness" is an overarching term used for: protanopia; protanomaly; deuteranopia; and deuteranopia. This is due to all people within these groups exhibiting similar colour differentiation problems[1]. The rarest forms of CVD lacks the response from two, or even all three, cone types resulting in lack of colour vision, or *monochromacy*. See Figure 2 for example simulations of the colour confusions seen by those with CVD and their estimated occurrences within the population.

Studies have shown that CVD affects an estimated 4% of the population worldwide [114]. The distribution of those affected varies by gender, with much stronger prevalence among the male population. Some 7.4% of men are estimated to be afflicted, compared to only 0.5% of the female population in northern Europe [112]. The bias towards males is due to deuteranopia and protanopia being caused by a recessive X linked gene making its occurrence in women exceedingly unlikely [24]. Whilst deuteranopia and protanopia (and the associated nomalies) are X-linked, tritanopia and monochromacy are not, so do not show the same gender bias, being relatively uncommon across the board. Furthermore, prevalence varies with ethnicity, with Singapore reporting rates closer to 5% of boys and .2% of girls [18] and some works reporting values between 8% and 14% of men [114].

CVD affects the lives of those afflicted in various ways, many of which can be considered mostly inconsequential, however can have a severe effect on home/general life and occupational opportunities, with many professions requiring applicants to have normal colour vision. Previous literature has reported on CVD's impact on one's career choice, such as doctor specialties [16] and the military not accepting applicants affected by CVD. Various daily activities such as determining

[1]https://www.color-blindness.com/

fruit ripeness or cooking [116], and even the abilities of children to learn [16] are also effected. Some evidence also exists for increased trouble driving [129].

As part of our studies into compensation for CVD on Computational Glasses we completed an exhaustive related literature search to identify how CVD has been studied and compensated for previously in the field.

Colour Spaces:
Before covering the CVD compensations presented in literature, we would like to review some key colour spaces commonly used in CVD research as they are a mixture of colour spaces used when controlling imaging devices or in computer-vision tasks, and colour spaces that are modelled around human perception.

RGB: The *RGB* colour space is a colour space made up of three chromaticities; red, green, and blue. Any colour can be defined in *RGB* as an addition of varying amounts of these three chromaticities and this colour space is commonly used for defining colours in computer graphics and pixel colours in images.

HSL/HSV/HSI: HSL, HSV, and HSI are all similar colour spaces, and alternatives to RGB. All three spaces share common axis of hue H and saturation S. The $V/I/L$ component however is computed differently for each space and describes how light a colour is.

LMS: The *LMS* colour space is designed to represent the responses of the long, medium, and short cones in the human eye to different spectra or wavelengths of light. This colour space is commonly seen in CVD research as CVD is a result of abnormal cone response to spectra.

Luv/uv: The *Luv* colour space encodes lightness in the L axis whilst using the two other axes to encode chromaticity. A significant aspect to *Luv* space is that it tries to encode colours in a perceptually uniform way. The *uv* chromaticity diagrams of this colour space are commonly used to show the potential visible spectrum of chroma to humans and show what colours are included in colour gamuts.

Lab: Another perceptually uniform space similar to *Luv*, *Lab* encodes colour on two chromaticity axes a and b, and a lightness asix L. a describes red-green ratios and b describes blue-yellow ratios.

In the following we discuss in detail how CVD has been approached in the computing literature. To our best knowledge, there is no prior work summarising the different attempts and techniques, but they are critical to understand our research and certain design decision. We believe this is also a main contribution of this work.

2.1 Identification of critical colours and areas

To compensate or correct for CVD, we first need to identify user interface elements or features in our environment that are critical for people affected by CVD. Usually, algorithms for this identification work in image space (e.g., image of the user interface or a camera image of the environment). The most common technique is to first simulate the scene as seen by those affected by CVD before extracting those critical features by comparing it to the original view. Although some techniques skip the simulation and directly identify critical areas [98, 102, 119].

Simulation of Colour Blindness/Creating a CVD Gamut:
Our initial understanding of how people affected by CVD see the world was developed using unilaterally colour blind participants who were affected by CVD only in one eye. Early work used the results of a CVD test to shift all points on some lines in UV space into a singular value to show confusion areas [83]. This concept was termed *confusion lines*. Since initial approaches we have seen different approaches for simulating CVD with the main difference being the colour space (or spatial representation of the colour space) in which the colour transformation is computed. For example identified confusion areas and confusion lines are still commonly used [125]. Later computer simulations were designed using the *LMS* colour space and the fundamentals of the

human eye [13], which was then expanded to generic versions that allowed for easy legibility checks for dichromats [130]. *LMS* space was further utilised to create a simulation by transforming *RGB* values to cone responses as per dichromatic viewer then transforming back using normal cone responses [133, 134, 137]. Similar simulations using the stage theory of vision [46] and opponent-colour nulling [63], as well as two stage cone replacement have been created [78, 107]. Riemann space has been used to create a dichromatic simulation technique [85, 86, 95]. When looking into the literature, one can see that the simulations by Brettel et al. [13] and Vienot et al. [130] are some of the most commonly used simulations for CVD which can be explained by being among the oldest and most easy to implement simulations. However, they come with the limitations of only being given for dichromats. More recently the work by Machado et al. [78] has also provided transformations to simulate CVD whilst also providing precomputed matrices for varying degrees of CVD.

As generic simulations cannot correctly represent subjective variations of CVD, some research allows for personalized modifications of the prior simulations [71]. Other personalized models have been created from just noticeable colour differences. This allows to create a personalized transform [113] or even more sophisticated personalised models that consider a confusion range for different colours [30, 32, 33]. As this process is quite time consuming and depends on the number of collected observations some efforts focused on improving its speed and accuracy [31, 76]. It is important to note that the environment conditions, such as background brightness and illumination, can affect the simulation accuracy [30]. Overall, we can conclude that despite the amount of research in simulating CVD there are still open issues. Mainly because early approaches try to only considered certain forms or severities of CVD. Personalised simulations of colour confusions provide an interesting prospect to overcome those limitations, as they can be tailored to the exact needs of someone with CVD, as well as being used for situations where normal trichromats misperceive colours due to lighting. This extends the application of CVD research. However, in many applications such as our scenario, it would require development of some form adapativity to adjust between known calibrations, or to estimate simulations based on scene parameters in real time which is why many current works are still using non-personalised CVD simulations.

The result of the simulation is usually an image showing how the user interface or environment is perceived by certain forms of CVD with more advanced algorithms also allowing for better representation of variations within the individuals. It is important to understand that despite having different forms of CVD there is still a large variation within individuals having the same form of CVD.

Extracting Critical Areas:
After simulating CVD, we need to identify critical areas. Either to highlight them as problematic (e.g., to the designer) or to automatically change them (as shown later). Commonly these critical areas are identified by comparing the simulation to the original representation. However, different metrics have been used for this comparison. A common technique is to determine colour differences in different colour spaces, e.g., *LMS* [56, 63], *RGB* [3, 26, 92], *Lab* [108, 109]. Thresholding of the differences has also been introduced [59, 61]. Several weighting systems based on colour differences have also been used [44, 65, 117].

Rather than considering differences with normal vision, several techniques look at neighbouring areas that could be difficult to discern. Colour segmentation to break an image into colour segments and find segments that are likely to cause confusion [98] and various levels of clustering [22] have been used to identify problems. Gradient maps [115] and similarity maps in *Lab* space [125] have also been used. Generally, segmentation methods increase the computational complexity of extracting problem areas without a strong benefit, although have situational use such as that of Chua et al. [22], or separating neighbouring confusions.

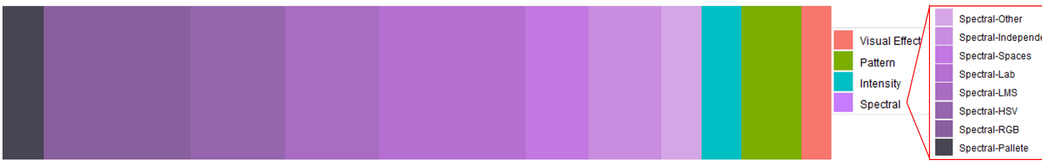


Fig. 3. Visualisation of the prevalence of different CVD compensation techniques. We can see that techniques applying a spectral shift far outnumber other approaches and we thus further broke them down into subcategories.

To reduce computational demand on mobile devices, some techniques consider simple classifiers, instead of computing a simulation and comparing it. Such simple classifiers are a red filter [102] or testing if highest channel value in the original view in RGB corresponds to the CVD type [119]. Although less computationally expensive, these techniques are usually more inaccurate.

After simulating CVD vision and extracting problematic features, one has usually identified critical areas and the corresponding image pixels. The main differences is that naïve algorithms only have a rough approximation of CVD also being able to only approximate some forms of CVD while more advanced algorithms are more accurate in the simulation of CVD even accounting for individual differences which consequently also improves the identification of critical areas.

2.2 Compensation of critical colours and areas

While a designer might only need to be able to identify critical areas, in our work we are aiming to visually adapt those areas to compensate for CVD. There exists a large number of compensation techniques for this and we can identity four main directions. The vast majority of works aim to compensate for CVD by shifting the spectral wavelength of identified critical image areas. Another direction is to compensate by changing the amplitude or intensity of identified image areas to increase the distinguishability of colours within. Rather than shifting the colours of image areas, some approaches introduce an artificial pattern to visually separate otherwise similar areas. Finally, a few works exploit the characteristics of human visual perception and create visually salient effects such as binocular rivalry to emphasize otherwise similar image areas. Figure 3 shows the distribution of these directions.

Spectral Wavelength Adjustment-Colour shifts:
The most common approach for compensation techniques is to adjust the colours such that those wrongly perceived as similar by CVD viewers are adjusted to be colours that are perceived as different. Figure 3 shows the distribution of techniques created and the prevalence of colour shifts.

Some of the early works on CVD assistance focused on improving the legibility of figures that featured confusing colours. By replacing the colour palette used for the figure creation, these techniques ensure the colours within the colour palette remain distinguishable by observers with and without CVD. First detailed by Meyers et al. [83] and then explored by Vienot et al. [130], various palettes have since been proposed for different tasks [57, 58, 126].

Among the techniques that target general applications we can differentiate between different colour spaces used to adjust the confused colours.

The most regular space to create techniques is *RGB*. Due to its relative simplicity and that final colour outputs in computer graphics are encoded in this space many researchers choose to remain in this space. The effects of CVD can be loosely approximated to problems identifying red - protanopia, protanomaly -, green - deuteranopia, deuteranomaly -, and blue - tritanopia, tritanomaly. Because of this easy but inaccurate adjustments can be made in *RGB*. In the *RGB* space, a common approach has been to use a mutating matrix to shift chromaticity values between *RGB* channels [3]. This matrix is adjusted iteratively and only applied where the difference for dichromatic viewers is above a certain threshold. Versions of this approach have been used in various works [26, 61, 80, 122, 124]. Other channel reassignments have also been created [96], including creating temporally consistent versions [60] and expanding colour ranges using histogram equalization [72]. Simpler techniques used a filter on the *R* channel to adjust red values for CVD [102], highlighted selected colours [124], or changed pairs of colours that users identified as difficult to differentiate [124]. Whilst simple channel adjustment in *RGB* is not the most precise technique, we do see a number of works implementing and expanding on this concept [3]. It is readily implemented and computationally efficient, making it easy to use in a number of scenarios. An alternative technique working in *RGB* uses a network that connects colours with generated confusions for dichromats and iteratively changes them until no connections within the colour network remains [27]. Bin-based algorithms that work on difference between bins for dichromats and trichromats [55], as well as clustering techniques using k-means clustering [84, 119] have also been created.

The *HSV*, *HSI*, and *HSL* colour spaces have been explored in some early techniques. This provides a means to directly manipulate the hue of colours, the range of which is reduced for those affected by CVD. In the *HSV* colour space, adjustments of all axes have been considered. *H* values have been adjusted based on ratio of colours [20, 106] or by stretching and compressing them [11], or rotating affected areas [91]. Other works also allow for *S* [133] or *V* [67] variance. Whilst in *HSL* space, techniques adjust red and green pixels by either H, S, L or S, L based on their predominance [45], or adjust H, L [4]. Similarly, adjusting *S* in *HSI* has also been used [17]. Generally, adjustments in these spaces are rare and the choice between *HSV*, *HSI*, and *HSL* has minimal impact. Recently, techniques have tended to use more perceptually based spaces such as *LMS*, *Lab*.

LMS is regularly used as a space for adjustments due to its relationship to CVD. Whilst works in *RGB* and *HSV* use simple spaces without direct regard to CVD, *LMS* can directly, and accurately, represent the effects of CVD. Early works for anomalous trichromats transforms from *RGB* to *LMS* based on normal trichromacy and anomalous trichromacy to find *RGB* values that produce equivalent responses for anomalous viewers [93, 133–136]. An adjustable transformation matrix that is modified by a slider [56] or computational means [1] has also been created. A shear transform has also been utilised [70] as well as a shift-rotate-left algorithm looking to maximise visibility whilst minimizing difference [63]. It is notable here that both the *LMS* matrix transform [56], and shear transform [70] look to provide user driven adaptability to techniques. These works note the need for users to be able to control and adjust the techniques to their current needs.

Various efforts have been made to work in the perceptually uniform *Lab* space. The perceptual uniformity of *Lab* enables the effect of CVD on the discernibly of colours to be measured as distances. This space more accurately reflects the effect of changes that *RGB* or *HSV*, and enables the quantifying of colour differences to trichromats vs their dichromatic counter parts. This does however presupposes that *Lab* holds relative uniformity of those affected by CVD. The first work to use *Lab* looked to trade-off between readability and naturalness [43] by rotating colours around the *L* axis (on the *ab* plane). Subsequent work used a mass spring system to optimise colour adjustments, basing masses on the distance between trichromatic and dichromatic perception of a colour [65]. This was then used to create a shift based on maximal contrast enhancement that works in a quick and temporally-coherent way [77]. Temporal consistency was also considered in subsequent works [41]. It is important to highlight the notion of introducing temporal coherence. Some techniques rely on aspects of the input image to determine the compensations, as well as techniques proposed to be adjusted automatically, or by users. Doing so in a manner that does not consider the user's current scene understanding can lead to further confusion and ultimately cause compensations to have a negative impact on the user. This is particularly important to consider within our proposed scenario as user have a constantly changing view of the world that must be compensated. Minimization optimisation [120], and octree clustering with subsequent optimisation [59] have also been explored. Further clustering techniques in *Lab* include Gaussian clustering [42]. Image segmentation has also been utilised with shifts in *Lab* used to move any colour pairs that lie on confusion lines [21, 98]. For stereoscopic setups an optimisation which looks to increase distinguishability for dichromats whilst avoiding binocular rivalry has been developed [39, 40, 113]. These algorithms look to utilise stereoscopy to enhance distinguishability for dichromats whilst making minimal changes for trichromats. Compensations that aim to facilitate to improve viewing experiences for those affected by CVD without degrading them for those unaffected present an interesting future research direction. Allowing for various forms of CVD and improved colour quality are still of interest. Constrained optimisation for CVD has been demonstrated looking to preserve colour contrast and areas of similar colour whilst increasing distinguishability [131] or preserving aspects of activity, temperature, and weight [28] utilising the perceptually uniformity of *Lab*.

Transforms between higher and lower spaces have also been used as an approach to compensate for CVD. Similarity matrices to transform between the higher trichromat space and a reduced dichromat space [7, 25] have been used as well as Riemann spaces [85–87, 95].

Some algorithms work independent of space dependent characteristics. Machine learning has also received some attention with initial efforts looking at genetic algorithms to adjust colours in HTML pages and palettes [46, 47, 126]. Self-organising maps were used to create a mapping to adjust colours in an image [74, 94]. More recently, some techniques adjusted images with a neural [12] or generative adversarial network [138].

A different approach was taken by some researchers who showed a grey-scale version of colour differences for trichromat and dichromat vision, or trichromatic colour contrasts to inform viewers of the location of differences [90, 109]. The only works specifically designed for monochromats preserves distances between colours in greyscale for monochromats and trichromats [104, 105].

Intensity Based Adjustment-Lightness shifts:
Similar to adjusting wavelengths to ones distinguishable for CVD, some researchers have looked at adjusting the lightness of CVD critical areas. Whilst some works in spectral shifts have looked to maintain the effect or meaning of colours, the semantic meaning of colours are still affected by all spectral shifts. This is particularly problematic when trying to use the names of colours when discussing colours with those who have viewed content in the original form. As such techniques have looked to alleviate the effects of CVD without changing the colours. Works in *HSV* have looked to preserve dynamic/static and vivid/sombre aspects of an image by adjusting S and V [2] whilst in *Lab*, the L component has been modified in various ways [81, 82, 121]. This is generally one of the less explored areas of CVD compensation. Few works look to exploit intensity adjustments separate from colour adjustments unless they are incorporated as part of a pattern. This may be due to adjusted colours still being considered as confusing. However, it has the potential to allow for differentiation between colours incorrectly perceived as similar if only applied to one.

Patterns:
Rather than adjusting the spectral wavelength or amplitude of colours, some researchers have investigated how different overlays can help users affected by CVD differentiate otherwise confusing image areas. These techniques ensure the original colour, and its associated name and meaning are retained whilst still aiding those affected by CVD. However, these techniques can introduce occlusions or false textures. Highlighting the edges between potentially confusing areas for dichromats can help users distinguish between similarly appearing colours [124]. Other techniques explored overlaying hatching (angled, coloured lines) based on chromaticity [44], hue [110], colour terms [37], or *RGB* values [29], as well as simply overlaying text of common colour names [29] over the image. Whilst opposing patterns make it easy to distinguish between similarly perceived

colours, actual understanding of the patterns themselves requires interpretation. Furthermore, patterns can only be used if there is sufficient area to make it apparent. This is of particular concern when considering the use of text to identify colours. Areas need to be large enough to overlay the name, and the resolution must be high enough for text to be legible. These two aspects make text based overlays very impractical for many scenarios.

Visual Effects:
As a final style of adjustment that maintains the original colours. Some researchers have investigated applying visual effects that take advantages of the human visual system to adjust for CVD. The general idea of all these effects is to create a visually salient separation between otherwise similar colours but doing so without changing the colours much. Three such effects have been investigated: the Craik-O'Brien effect, binocular rivalry, and flicker.

The Craik-O'Brien effect uses slight ramps in brightness up and down on either side of the border between similar colours to create the overall visual perception of a different brightness for each colour. The idea is again to aid differentiation [8, 117].

Binocular rivalry is a perceptual effect that occurs when the images presented to each eye differ significantly enough that the brain will not be able to fuse them together, and if they are not too significantly different the brain will not reject one but continue to try to fuse them leading to a perceived salient effect often described as a halo [22]. Finally, some research proposed to use flicker by applying a rapid temporal colour shift to another colour and back which allows for better distinguishability [10, 36].

In summary, we can see different strategies for adjusting critical colours with adjusting the spectral wavelength (colour) being the most commonly used one. However, because of the semantics of the colour itself, that might be lost when changing the colour (either via a colour shift or intensity shift), researchers have explored approaches such as patterns or utilising perceptual effects. As these come with their own challenges, the approach taken needs to be carefully considered when designing and applying techniques.

2.3 Identified Research Gaps

Analysis of the related work on methods for compensating critical colours revealed several challenges and research gaps that affect us in pursuing our research goals on building Computational Glasses for CVD. These gaps are also of relevance to general researchers working on computational solutions for CVD. More specifically, there is a lack of datasets that provide a widely accepted baseline for testing, formal user studies with CVD participants, and comparisons between techniques presented in literature.

Datasets:
When looking at the datasets used in literature there is a lack of a consistent and accepted dataset that can be used as a baseline. The only dataset commonly used are the pseudo-isochromatic plates (Ishihara plates) that provide an easily evaluable technique for testing efficacy however they are a niche use case designed to be extreme. This makes them abstract with limited direct application to the world being designed to be readily understandable. Whilst this provides an easy way to measure a technique's viability, the applicability of the results based on them to wider scenarios is limited. Works that evaluated the efficacy of their technique not only on tests used to determine if someone is affected by CVD usually utilize only a small dataset of less than 10 other images. Furthermore, most works do not provide any details on these images identifying them only as "natural images". We do note that some works used a large number of images (1000-65000) selected from the internet, however, these are commonly used for building a dataset, e.g., to improve image search results for those affected by CVD. An example of commonly used images (and similar variations) is shown in Figure 4.

Fig. 4. Overview on used datasets and evaluations in CVD research. Left: Examples of commonly used natural images to showcase effectiveness of compensation algorithms (from [55, 65, 105]) Right: Showcase of works that reported only visual results (red), results with participants (green), and statistical results of user studies (blue). The corresponding connection shows that two techniques were compared in a publication. The numbers correspond to the papers in the references. We can see that much of the prior work only reported visual results that are not supported by user studies. Only a few studies involved actual users and even less ran comparative studies.

Not having a consistently used and verified dataset for testing CVD techniques that is representative of real world scenarios, as well as easy baseline tests for efficacy causes problems with testing and comparing techniques in a manner that can be generalised. Throughout this work, we looked to mitigate this problem by using the common Ishihara plates for baseline efficacy tests and by introducing a set of real-world images with related questions to represent real-world scenarios. We verified that people affected by CVD could not readily answer the questions, however the image set is relatively small and not formally verified. As such we do not redress this issue but hope to provide a basis and direction for future work.

User Studies:

From the reviewed works only slightly more than half (57 out of 101/ 56.4%) had any evaluations with users, and among these only 29 had more than 10 participants. Studies with more than 50 (3) or 100 (1) participants were almost non-existent clearly highlighting the question of the generalisability of the findings to a larger population.

Among the user studies conducted we identified three common tasks. (1) Colour disambiguation that requires users to either judge what is shown in similar colours (e.g., Ishihara patterns) [66], or whether areas in an image have the same or different colour [113]. (2) Colour matching that requires participants to decide which colour patch matches a reference colour, or determine matches between a graph and a legend [27]. (3) Identification of colours where participants are asked to name a colour and compare it against a ground truth, e.g., obtained from participants with normal vision [22]. For subjective evaluations the most common judgement criteria are naturalness, quality, colour preservation, and confidence when choosing colours. It is important to note that whilst we do not doubt the effectiveness of the presented techniques, only 12 of the conducted user studies reported statistical evaluations whilst of the remaining works only 4 report on user feedback and the rest just report measured metrics. As most of the techniques are only compared against the baseline of no modification, these tend to show improved results on the measured metric. A major limitation of the conducted studies is that they were conducted in laboratory settings. While this allows researchers to control confounding factors and reduce the bias in comparisons against the baseline, they do not indicate how well the system would perform in real world scenarios. For example, how often would users utilize the system deployed on a mobile phone vs. a head-mounted display? Even if participants can imagine themselves using the system in an interview, will this really be the case? In what situations do users actually require continuous assistance, and do the systems perform well for that task?

The generally low number of user studies, limited tasks, and low numbers of participants produces problems with determining the generalisability of the research and the general effectiveness of developed techniques. In our work we look to utilise comparatively high numbers of participants (10-19 per study), however still only utilise a limited set of tasks due to the aforementioned lack of available dataset. Furthermore, due to the pioneering nature of our research we were also unable to extend our studies outside of the lab.

Comparisons:
The third limitation we identified in the literature is a lack of works that compare the newly developed techniques with existing ones. Out of the 101 works we identified, 62 had no comparisons with previous techniques. From those that had comparisons, the most common was with the technique of Huang et al. [43] (7), Kuhn et al. [65] (6), Machado [78] (4), Rasche [104] (3) and Doliotis et al. [26](3). Among the other comparisons 6 techniques were compared against twice, and 17 were compared against once. At the same time, when considering publications that included user studies, we find that only the techniques of Kuhn et al. [65], Huang et al. [43], Shen et al. [113], and Machado et al. [78] were compared against in two works, and 5 other techniques were compared against only once. Furthermore, whenever algorithms were compared with each other in user studies participants observed differences in "quality", "accessibility", or temporal consistency and found only minor differences in the effectiveness of the algorithms on CVD mitigation. This highlights that although there is a large number of techniques that could be potentially used, there is a lack of knowledge on how they compare to each other, especially when studied with participants.

Figure 4 Right shows the comparisons between techniques. It is apparent that there is a lack of comparisons between techniques to show advantages, disadvantages, and improvements. This is exacerbated by the lack of user studies showing the user impacts in these comparisons.

Whilst we look to work around these limitations in this work and provide initial steps to solving, our primary focus remains to introduce and explore the concept of Computational Glasses for CVD.

2.4 Display Technologies for CVD

People with CVD are not only affected within their everyday environment but also when working with their computer. Consequently the largest numbers of works presenting computational techniques for compensating the effect of CVD have been presented in the context of standard displays with the general aim to improve the user interface [20, 22, 28, 45, 46, 56, 89, 98, 108, 109, 113, 126, 130, 131]. However, with the rise of mobile and wearable devices with also see more works utilising those to support their users when interacting with their physical environment. Examples include mobile phones [4, 29, 37, 70, 108, 111], *Head-Mounted Displays* (HMDs) [66, 67, 80, 91, 92, 101], and custom displays [75]. Examples of the various display technologies, including our work, can be seen in Figure 5.

Computer Screen Aids:
The majority of work done on digital aid for CVD has targeted computer screens and users. Works look at palette modification targeting general user interfaces [126, 130], website adjustment [20, 28, 45, 46, 108, 109] or stereoscopic systems [22, 113]. Specific applications such as direct volume rendering have also been considered [6], alongside frameworks for content adjustment [89, 131], and screen overlays [56, 98].

Mobile Aids and wearable aids:
Despite the prevalence of adapting on-screen user interface elements, researchers identified the

potential of mobile devices and novel display technologies to support people affected by CVD when interacting with their everyday environment. A simple example is the use of projectors to augment and visually adapt the environment of those affected by CVD even though this would require either mobile projectors or multi projector environments [1]. As this is less practical, researchers have looked at using mobile phones to provide a mobile aid for CVD by utilising the embedded cameras to capture the environment to display adjustments and information for CVD. Some applications simply transformed colours in the camera image [4, 37, 70], whilst others allowed for colours in the image to be selected and provided a name, or highlighted colours [5, 29, 108, 111]. Custom devices that achieve a similar dedicated interface to that of the mobile phone have also been created [75, 96].

As mobile devices require users to actively capture an image of the scene, more ubiquitous and wearable interfaces have been considered and here in particular HMDs and smart glasses. One of the first such devices was a monocular HMD that used a CCD to capture an off-axis view of the user's world and presented it to a display in front of one of the wearer's eyes [91, 92]. Subsequently several researchers used VSTHMD to replace the wearer's view of the physical world with a camera-modulated one [17, 66, 67, 80].

Whilst VSTHMDs allow for full control over what the user sees, it has always been problematic that the wearer is completely decoupled from the real world and only sees the camera image. Consequently, research has started to propose using OSTHMDs as some researchers have used augmented reality [101, 124]. However, initial works presented the idea [101] or prototypes running on Google Glass that are incapable of actually displaying a precise overlay [124]. In fact, our own earlier work was the first to present a fully working prototype called ChromaGlasses that utilised Computational Glasses to precisely compensate CVD for the wearer. This work is an extension of our earlier work, not only summarising our earlier results but also extending it with new prototypes and additional studies that among other things provide feedback from more realistic scenarios. It should also be noted that since our earlier work also some other techniques emerged that aimed to change the core principle of traditional OSTHMDs. OSTHMDs are only able to add light on a per pixel level (additive), however these techniques are also able to filter light (subtractive modulation). These can also be used in the context of CVD compensation even though they were not evaluated and were optical bench prototypes [50, 122, 123]. By attaching an LCD panel in front of the OSTHMD [122, 123] one can adaptively diminish the brightness of the scene allowing better control over what color the user sees due to the mixing of the background and the modification displayed on the OSTHMD. However, utilizing an LCD panel that reduces the brightness overall also affects the colors of areas that do not require compensation. With our concept we look to only adjust the wearers view as necessary, avoiding unnecessary degradation of the wearers vision. Alternatively, one can utilize a phase-only spatial light modulator to adjust the phase of the light on a per-pixel basis [50] thus adjusting what color the user sees without the need for an OSTHMD. However, this reduces the color range that can be shown to the user, depends on the brightness of the background, and requires a very complicated optical setup. Furthermore, as stated, all of these prototypes were constrained to bench prototypes with none of them being demonstrated in a form-factor allowing for wearability or even direct viewing by a user. Overall, while wearable technologies such as HMDs are still in its infancy and have technical limitations that are currently addressed within the research community [51, 64] they already demonstrated their potential for compensating CVD. As they could potentially take on a form factor similar to normal glasses they could also represent a socially acceptable form of addressing visual impairments.

2.5 Human Augmentations and Vision Aids beyond CVD

Besides assistive aids for compensating CVD there are other applications of visions aids including those who aimed at enhancing human capabilities. Some of the simplest forms of this is the use of

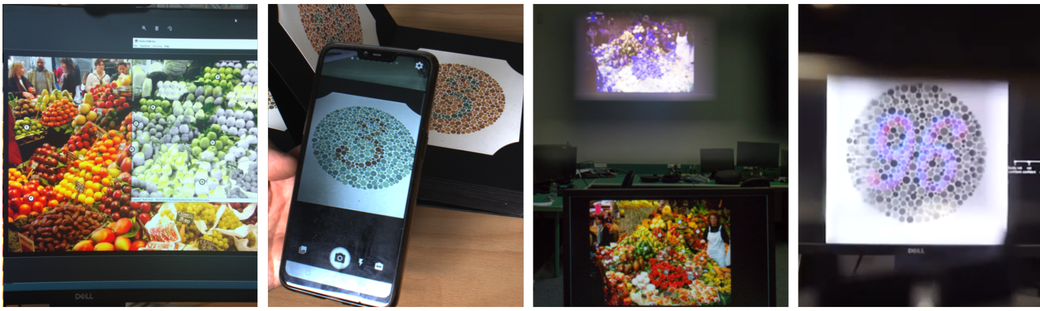


Fig. 5. Examples of addressing CVD on different devices. From Left: Compensation on monitors, mobile devices, an indirect approach on a Google Glass, direct compensation using Computational Glasses (our approach).

mobile devices to support vision. Nowadays there is a myriad of visual assistive apps, ranging from simple zoom functionality, to search assistive applications like SuperVision Search [2] and colour correction applications like NowYouSee [3]. The main limitation of mobile devices is that they cannot be easily accessed for unhindered and spontaneous use, i.e., the user needs to take out the mobile phone to take images of the scene before they can be processed. As such, they are very different to traditional glasses that are almost always "on". One way of overcoming this limitation is the use of projectors that directly overlay appearance enhancements onto the scene [1, 139] but this requires specifically prepared environments with integrated projectors. Instead, the most versatile device for presenting visual aids are likely HMDs.

HMDs have the potential to be similar to traditional glasses; head-worn and always on while also being self-contained not requiring external infrastructure. Therefore, applications that run on head-mounted displays could help overcome many of the previously stated limitation. Generally, when speaking about HMDs we distinguish two main approaches. Video-see through HMDs (VSTHMDs) are fully closed HMDs that have cameras that capture the environment. The live camera feed is then manipulated depending on the user's needs and displayed in the HMD. Various systems for visual augmentations have been developed such as CueSee [141] and ForSee [140] as well as prototypes from industry that have small form factor such as Relumino [4]. Because the user only sees the actual display, these approaches allow for very easy development as the vision augmentation can be summarised as a simple image manipulation using the camera feed and there are typically no calibration issues (e.g., alignment with the real world). This fundamental working principle is also one of the biggest drawbacks. Users are completely decoupled from the physical world as they only perceive it through a camera making it fundamentally different to traditional glasses and it is easy to see that this approach will see acceptability issues. For example, using VSTHMDs also decouples the users from social interaction as mutual eye contact is not possible when wearing these devices affecting important social cues.

Consequently, we and other research groups believe in the potential of OSTHMDs, the focus of this work, as they overcome not only the issues with mobile devices (always on) but also do not decouple the users from the physical environment such as VSTHMDs. In fact, OSTHMDs are conceptually the closest to traditional prescription glasses as users can see through. More recently, vision augmentations using OSTHMDs, and precise modulations, have been also termed

[2]https://focus.masseyeandear.org/supervision-a-smart-app-to-help-people-with-low-vision-search-their-surroundings/
[3]https://play.google.com/store/apps/details?id=com.areyoucolorblind.nowyousee
[4]https://newatlas.com/samsung-relumino-glasses/52795/

Computational Glasses [118]. OSTHMD and Computational Glasses have recently been used for vision augmentations and vision enhancements. Works by Peli et al. looked at helping with central or peripheral vision loss using OSTHMD [99] while others enhanced vision by reducing visual haze [38]. Some works utilised a Google Glass for applications such as magnification of phone screens [103] even though Google Glass does not allow for a direct augmentation in the sense of a pixel-precise overlay as the display is not directly in front of the eye. Other works on custom AR OSTHMD or Computational Glasses that integrate additional optical elements such as computer adjustable lenses have been presented as alternatives to glasses including AutoFocals [97], FocusAR [15], Phase-modulated glasses [53].

2.6 Discussion and Motivation

Overall, we see different gaps and challenges within the related works on CVD and how it has been addressed within the computing disciplines. Probably the most relevant for our work is the absence of a continuous visual aid for CVD as we are used to from traditional glasses targeting refractive errors. Most works for CVD have been constrained to screens only and cannot be used as ubiquitous solutions to aid dichromats and anomalous trichromats. Existing mobile solutions targeted mobile phones but do not offer a continuous support as they required the user to actively reach for their device and aim for problematic areas in their field of view. Besides the additional effort, this of course requires the users to know about the presence of confusing colours which is often not given. VSTHMDs could offer a continuous support and have been demonstrated by several researchers [66, 67, 80], however as previously mentioned have practical issues. To the best of our knowledge, Tanuwidjaja et al. is the first proposing an half-transparent OSTHMD (Google Glasses) and displaying an adjusted camera feed for one eye to help users distinguish between corrected colours and colours naturally occurring in the world [124]. This idea was later also conceptually discussed by Popleteev et al. [101]. In our earlier work on ChromaGlasses, we were the first proposing and prototyping the idea of utilising OSTHMDs for compensating CVD by directly modulating the environment. This idea was later also picked up by others [122].

Throughout our work we adhere to the commonly demonstrated combination of using a CVD simulation to identify critical areas, followed by an adjustment of said areas. The are various ways to simulate CVD from generic, readily implemented, models [13, 130], to spectral response based ones [63, 133, 134], and tailored models that are calibrated per user under different lighting conditions [31–33, 76]. Due to the specific user information required for spectral response models, and the precise user calibration need for tailored ones, we utilise the generic models for the purposes of our research. When considering the compensations needed to create the adjustments we see that there are a large number of techniques, however few are designed to work on anything other than opaque screens, with exceptions looking to work on OSTHMD with LCDs or projectors. Subsequently, we look to utilise the large body of techniques and modify those already demonstrated in order to produce new compensations in our work.

In this work, we expand on our research on Computational Glasses for CVD [69]. While our prior work presented first prototypes and general efficacy of our approach to augment the vision of those with CVD, the work described here goes beyond by providing an exhaustive discussion on general compensation techniques for CVD and their applicability for Computational Glasses. We also provide feedback from additional studies and newer prototypes.

3 COMPUTATIONAL GLASSES FOR COMPENSATING CVD

In our work on compensating CVD using Computational Glasses we look to directly modulate the perception of colours of those affected by CVD. We achieve this by seamlessly aligning computer generated overlays with the world seen by the user, thus directly modulating the colours they

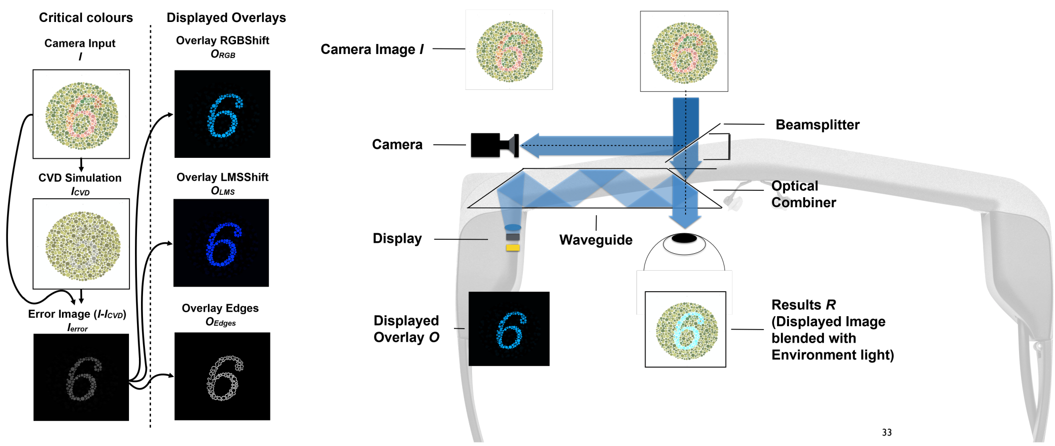


Fig. 6. Conceptual overview of Computational Glasses for compensating CVD. Left: Overview of our correction algorithm. The input camera image I in simulated as CVD I_{CVD} (here protanopia) and an error image is created I_{Error}. This is then used to create the various modulation overlays used in our studies (here O_{RGB}, O_{LMS}, O_{Edges}). Right: Overview of our hardware setup. The scene camera views the world from the same axis as the user via a beamsplitter. The Computational Glasses are then used to display an overlay that aligns with the user's view and compensates it.

perceive. This would improve the separation of otherwise similarly perceived colours. To this end we require a precise understanding of the user's view of the world to determine where modulations are required and need to be displayed. Although there is a large number of potential commercial displays for AR, such as VST and OSTHMDs, these do not satisfy the requirements for our work. While VSTHMDs allow pixel-precise control of the displayed colours, they block the wearer's view of the world, limiting it to the capabilities of the cameras, such as colour response, and to be seen from the cameras' position. While OSTHMDs avoid these pitfalls, the position of the world tracking camera on the HMD does not match the user's view preventing pixel-precise control and view estimation. It is important to understand that our work does not directly benefit from millimetre-precise tracking that we have recently seen in HMDs as we do not want to add virtual objects to the scene as in traditional AR. Instead, we want to change the appearance of objects within the user's view in unknown physical environments. To emphasise this fundamental difference to standard AR HMDs, this, and similar technologies, are termed *Computational Glasses*.

The ideal Computational Glasses have a form factor and weight similar to normal glasses but incorporate a computer and battery (either built-in or as a tethered unit) that utilise computational power and computational optics or displays to produce new or improved forms of permanent vision aids. A major difference of Computational Glasses to traditional OSTHMDs as used for AR is that Computational Glasses do not place 3D content into the world, but directly compensate the user's view of the world by changing its appearance. Although there is a stark difference in the application of Computation Glasses and OSTHMDs, they share many similarities, such as the optical elements and displays that send computer generated imagery into the user's eye. As such we start our research on building Computational Glasses for CVD from commercial OSTHMDs that are modified for our purposes.

An alternative to Computational Glasses for assisting CVD are filtered lenses such as those provided by Enchroma[5]. On a high level these glasses are similar to sunglasses, indiscriminately filtering light, rather than adjusting where needed as is achievable with Computational Glasses. Furthermore, they are unable to be tailored for specific individual requires. On a practical level several research papers have shown the efficacy of these glasses to be limited with them showing: no improvement in diagnosis tests [34]; improvement for protans but new errors for deuterans [9]; reduce Ishihara plate errors for deutans only, and Farnsworth test errors for protans only [128]. Although there are some positive results, we believe Computational Glasses can provide an alternative and potentially better solution catering to all forms of CVD.

In the following, we summarise the main conceptual idea of Computational Glasses for compensating CVD as presented in our initial work [69] while expanding on it by providing details or the needed calibration and introducing new prototypes.

Overall, the biggest challenge for our research is the pixel-precise modulation of the environment. Doing this has three main challenges. Firstly, being able to capture the environment as seen by the user. Secondly, being able to process the captured environment as seen by the user to identify areas of interest. Finally, being able to modulate these areas via the semi-transparent head-mounted display. For our work we took inspiration from earlier work in the field of traditional AR that tried to improve colour rendering in semi-transparent displays by considering the background colour on a per pixel basis [68]. The key is to virtually place a camera at the position of the user's eye. This can be achieved by adding a beamsplitter to off-the-shelf OSTHMDs for each eye. These beamsplitters redirect a portion of the light traveling towards the user's eye to a camera (the scene camera).

While the cameras can only be moved close to the ideal position and human eyes differ, we also apply a software calibration similar to the Single Point Active Alignment Method (SPAAM) [127] to account for potential minor misalignment. We cannot take the traditional SPAAM used for eye-display calibration but have to extend it by incorporating the added scene camera. The details of the calibration differ between the prototypes and are laid out later. However, for all prototypes the resulting eye-display-camera calibration creates transformations allowing a mapping from camera to display via the eye consequently allowing a precise modulation from the user's point of view. Thus for each pixel within the scene camera imagery (representing a part of the physical environment), we can compute the corresponding pixel within the semi-transparent display of the OSTHMD, so that they both align with each other from the perspective of the user's eye.

Once calibrated, the overall processing pipeline can be summarised by the following. We grab the input from the scene camera. In this image we sense the critical areas that are characterised by having colours that are critical for people affected by CVD (e.g., could be confusing or lacking contrast). We achieve this by running a real-time CVD simulation on the input image from the scene camera. This CVD simulation requires the specific type of CVD as input and the resulting image represents a simulation of how the image is perceived by that person. This technique for simulation is outlined in detail by Brettel et al. [13] and commonly used when compensating CVD in user interfaces. The difference between the original Trichromatic view (the input image) and simulated Dichromatic view (the CVD simulation) results in a error mask I_{error} that identifies all pixels within the image that are critical in the sense that they are perceived differently for someone having that specific form of CVD. In the next step we compensate the pixels given by the error mask by computing an overlay that changes the colour of the pixels identified in the error mask. There are different compensation techniques that affect the modulation which we will lay out later but most of them change the appearance of the pixel by shifting them towards blue. Finally,

[5]https://enchroma.com/

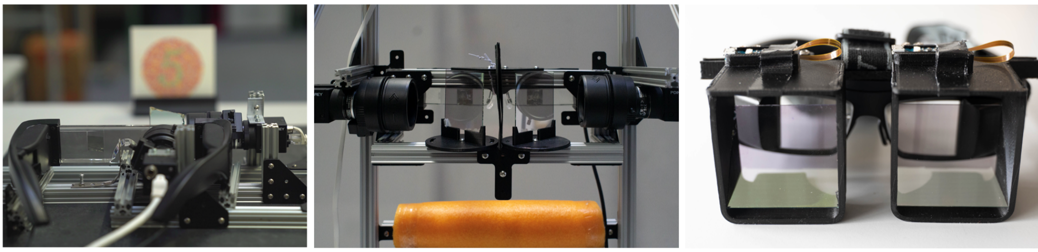


Fig. 7. The prototypes developed for our research and used in our studies. Left: The bench prototype used in the initial efficacy study. Centre: The stereo prototype used in the efficacy study on user calibrated Computational Glasses and in the study comparing Computational Glasses against an indirect compensation (Google Glass). Right: A version of our portable prototype which was modified for use in an exploratory study.

the initial calibration gives us the per-pixel transformation that allows to compute the position at which the overlay needs to be presented to the user via the Computational Glasses so that it aligns with the background. This general overview can also be seen in Figure 6. It is worth to mention that our pipeline considers the parameters of the optics (e.g., transparency of the beamsplitters) and colour response of the semi-transparent display to optimise the colour reproduction.

In the following we present our different prototypes that are developed based on the general idea presented here and will provide more specific details for the calibration of each prototype.

4 PROTOTYPES

We developed three prototypes that we used to explore the benefits of Computational Glasses for CVD compensation in our experiments. When developing these prototypes, we used commercial OSTHMDs as a base. Here, our focus was on a slim form factor and ease of modification, rather than tracking capabilities that do not play a vital role in Computational Glasses. As such, we did not utilize recent HMDs with in-built tracking capabilities, e.g., the Microsoft HoloLens, Meta 2, or MagicLeap One.

The first prototype was a monocular bench prototype, where a camera was used to capture the view through the Computational Glasses instead of a user's eye. This prototype was designed to verify that the developed algorithms could indeed assist in discerning colours for those affected by CVD by avoiding any misalignment of the overlaid modulation when users looked through the Computational Glasses.

As the first prototype was only monocular and showed the user the image captured by the camera, not the user's eyes, and to evaluate the performance of Computational Glasses when worn by users, we developed a second benchtop prototype in which users could look at the scene through binocular Computational Glasses. This presented a more realistic testing scenario than the initial prototype.

Our final prototype was a portable version that we used to learn more about what our target users may experience when utilizing Computational Glasses in daily life, as well as their impressions.

In the following we describe in detail the design and the necessary calibration steps of each of our prototypes.

4.1 Monoscopic bench prototype

The first prototype we created was a monocular bench prototype (Figure 7 Left). The bench prototype consists of an Epson Moverio BT 100 OSTHMD (960×540 pixel, 23° fov) mounted on a table with a PointGrey Blackfly camera (BFLY-PGE-14S2C, with Sony Pregius IMX249 sensor) placed at a right angle to the viewing axis of the HMD.

We refer to this camera as the *scene camera*. A second PointGrey Blackfly BFLY-PGE-14S2C camera is placed behind the Computational Glasses to capture the view a user would see. We thus refer to it as the *user-perspective camera*. We aligned the views captured by the scene and the user-perspective camera with a half silvered 50/50 mirror, directing equal amounts of light towards each camera. Due to the optics of the Computational Glasses, the amount of light reaching the user-perspective camera is less than for the scene perspective camera and we accounted for that during the calibration step described below. Images captured by the scene camera were sent to a computer to determine the content to be displayed on the Computational Glasses. The combination of the scene and the overlaid modulation was captured by the user-perspective camera and shown on a monitor.

Calibration: To correct colour ambiguities we performed two types of calibration, first a spatial alignment calibration, and second a colour correction calibration to determine the colour response of the cameras and the HMD. We followed the approach described by Langlotz et al. [68]. First, we estimated the spatial alignment between the two views as a homography (Figure 8 Left). While this did not account for any non-uniform distortions due to the optics of the Computational Glasses [49], these have only a small impact on the alignment quality. We also performed a radiometric calibration of the colours captured by the user-perspective camera to account for optical effects, e.g., screen transparency and colour response, and vignetting (Figure 8 Centre). This correction was implemented in a shader and was applied to the computed correction of images captured by the scene camera. We utilized pre-computed lookup-tables for the radiometric and spatial correction for improved runtime efficiency.

4.2 Stereoscopic prototype

As our first prototype provided only monocular correction, we designed a stereoscopic prototype (Figure 7 Centre) that provided correction for both eyes. This prototype was built on top of the Epson Moverio BT-300 OSTHMD (1280×720 pixel, 23° fov), as it provided a better colour range and a larger field of view than the BT-100. We used two scene cameras (PointGrey Blackfly BFLY-U3-23S6C) that were mounted similarly to the monoscopic prototype, one camera for each eye. As our goal for this prototype was to evaluate how users would see the modifications with their own eyes, we did not mount a user-perspective camera. Instead, the prototype was mounted on a support structure with a chinrest that users could put their head on for support. This allowed us to ensure that the user's viewpoint does not change when they looked through the Computational Glasses. As the user's viewpoint through the Computational Glasses changed depending on the eye location, we performed a user-specific calibration routine whenever they looked through the prototype.

Calibration: The most common calibration approach for spatial alignment in OSTHMDs is SPAAM [127]. In our implementation we asked users to sequentially align 8 patterns shown on the Computational Glasses with corresponding matches shown on a monitor in front of them (Figure 8 Right). We also detect the location of the patterns on the monitor in the images captured by the scene cameras. From the detected matches, we could compute a homography that aligns the view captured by the scene cameras with the user's view. We performed this process for each eye. We opted for this approach as it is easy to do and generally results in very small alignment errors in the range of 0-5 pixels [48, 88]. This is approximately 0-0.078° error for our OSTHMD in the optimal case. However, this is subject to user movement and error, and in practice errors can be greater than this. Automatic alignment techniques would require additional hardware such as eye tracking cameras and are less accurate than manual alignment [48, 88, 100].

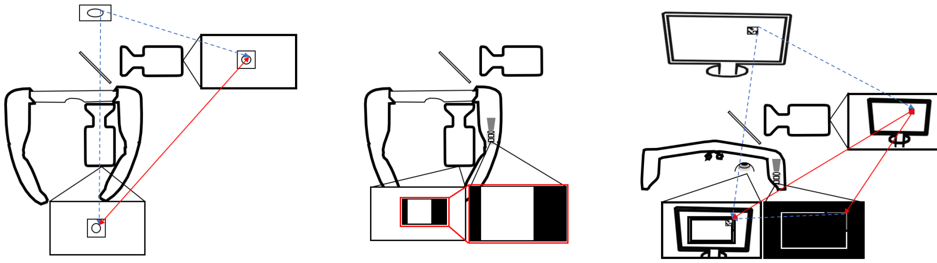


Fig. 8. Different calibration steps of our prototypes. For the camera-based bench prototype calibrations left and centre were used. For the user based stereo prototype the right calibration was used. Left: The calibration used to align the user-perspective camera with the world camera. This was achieved via feature matching in camera space. Centre: To align the virtual content in the display to the user-perspective camera structured light was used to generate a look up table. Right: To align the virtual content with the user's eye, the user aligned a marker with the virtual content. This marker was also tracked by the world camera and was used to align the world camera with the virtual content and the user's eye.

4.3 Portable Prototype

We created a portable prototype (Figure 7 Right) using a Lumus DK-52 OSTHMD (1280×720 pixel, 40° fov) as the base with custom 3D printed mounts attached in front of each eye. Each mount housed a half-silvered mirror and a Sony IU233N2-Z camera so that the camera could capture an image of the scene from the same viewpoint as the user. As shown in Figure 16 we attached our prototype to a head band to counter the increased weight pushing onto the user's nose and improve the stability. The prototype was tethered to a computer via several cables for the purposes of the study, however it could also be connected to a mobile computing device similar to commercial products by NReal and MagicLeap, or be designed to incorporate a processing unit on the device itself, similar to the Microsoft HoloLens V1 and V2.

Calibration: As the calibration we used in the stereoscopic prototype is quite time consuming, we used a simplified approach for our portable prototype. We initially placed a user-perspective camera behind the Computational Glasses and manually aligned the modulation rendered on the Computational Glasses with the pattern shown on the monitor. This step was performed for each screen separately. This provided us with an initial good estimate that was consistent for all users. Similar approaches have also been explored to simplify the SPAAM calibration [79]. When users put on the portable prototype, they were asked to adjust the overlay so that it correctly overlaid the image of four squares shown on a monitor in front of them. This routine was once again repeated for both eyes, and users were asked to confirm that the overlay remained consistent when shown for both eyes at the same time. We did not expect users to perfectly align the virtual content due to the unstable nature of the headset and limited ability to calibrate the system with a simple calibration. We understand there to be some error we could not expect to control for and consider this when using this prototype.

5 STUDY 1: EFFICACY OF COMPUTATIONAL GLASSES FOR CVD

We are the first to explore the viability of direct scene modulation for compensating CVD by overlaying graphical cues using Computational Glasses. As such it was important for us to investigate our approach in a well-controlled study, reducing confounding factors as much as possible. We therefore conducted an initial study using the monocular prototype to verify that our algorithms could indeed improve the user's ability to distinguish colours in an Ishihara test. Using this setup allowed us to exclude possible confounding factors. For example, we could ensure the quality of the eye-display calibration. Furthermore, because we could always see the visual result presented to the participants, we could assure that the system was working as intended. For this initial study we had two hypotheses that evolve around general efficacy.

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

Design: To investigate these hypotheses, we designed a within-subjects experiment with participants affected by CVD. The task required participants to judge the content of four Ishihara plates commonly used for detecting CVD. These plates show figures, e.g., numbers and animals, that are perceived differently by those with normal vision and those with a particular type of CVD. While highly artificial, Ishihara plates provide a readily available measure to test for efficacy. Without a properly verified dataset that can accurately show efficacy on more natural cases, as previously described, we opted for a standardized, widely used baseline. Due to the characteristics of the test, it is commonly used to determine if someone has Protanopia, Protanomaly, Deuteranopia, and/or Deuteranomaly. Hereby, the degree of CVD is determined by the ratio of correct answers, ranging from 0 (all wrong) to 1 (all correct). As it would be too time consuming to administer the test for all techniques, we chose a subset of four plates targeted for the participant's type of CVD (determined beforehand). During the test we measured the ratio of correct answers (0 for all wrong, 1 for all correct), as well as the participants' confidence in the answers on a 5-point semantically anchored scale. The reason for this is that it is known that people with CVD can have a different degrees of severity that in some cases allows them to perceive the shown figures, but it becomes much more challenging. To penalize wrong answers with high confidence and reward correct answers with high confidence, we computed a weighted average as

$$C = \frac{1}{4} \sum_{i=1}^{4} P_i C_i, \tag{1}$$

where C_i is the confidence for plate i and $P_i = 1$ if the answer was correct and $P_i = -1$ otherwise. As such, our experiment had one independent variable (Correction technique) with 6 levels *(None, RGBShift, RGBShift Adjust, LMS Shift, LMS Shift Adjust, Edges)* and 2 dependent variables (ratio of correct answers and weighted confidence).

Apparatus: In this experiment we utilized the monocular prototype but instead of looking directly through the monocular bench prototype, the participants saw the camera feed from a user-perspective camera placed at the position normally intended for the user's eye. The camera feed was shown on a standard 24-inch monitor. The Ishihara plates for each test were placed in such a way that they were not directly visible to the participants.

Participants: We recruited 19 participants from the student body and staff of the University of Otago through advertisements in lectures and mailing lists. All participants were male (mean age = 24, σ=10.04) and were affected by red-green blindness. We had expected this participant composition due to the higher prevalence of CVD, especially red-green blindness, in the male population.

Compensation techniques: As our work is the first to investigate CVD compensation by directly modulating the scene with Computational Glasses, we first implemented techniques explored by Tanuwidjaja et al. [124] as they also utilized an AR device, although they directly modified images captured by the camera effectively creating a HUD. We also implemented a

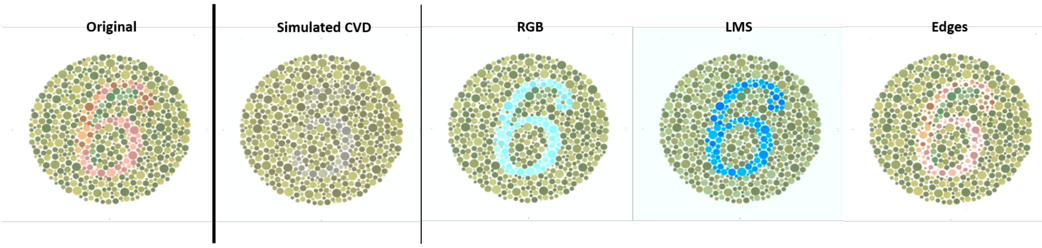


Fig. 9. Example of compensations applied to an Ishihara plate.

technique based on the work of Jefferson et al. [55] that works in the commonly used *LMS* space. This technique works by shifting points away from confusion lines using a rotation. These techniques can be seen in Figure 9. As previous work showed that depending on the severity of the user's CVD the optimal modification may vary, we also implemented a variation of each of the colour shift techniques that allowed users to adjust the degree of the compensation.

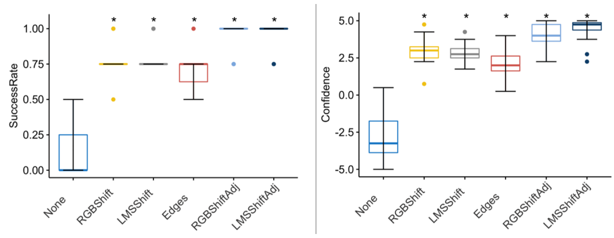
RGBShift: Colour adjustments in the *RGB* space are commonly used with screens and this technique was also demonstrated by Tanuwidjaja et al. [124]. After calculating the confusion map I_{error} we applied a linear shift in the *RGB* space to improve the differentiability. The amount of colour shift was set to values used by Tanuwidjaja et al. As in our system users perceived a displayed colour as a mix of the background and the colour shown on screen of the Computational Glasses, we computed the colour to be displayed on the screen so it matched the target colour as closely as possible based on Langlotz et al. [68].

LMSShift: As shown by our literature review, shifting colours in *LMS* space is the most common approach to address CVD. While *RGBShift* adjusts the colours directly in the *RGB* space, LMSShift first converts the original image into the *LMS* colour space and computes the adjustment within that space, before transforming the resulting image back into the *RGB* space to be displayed. If the *L*, *M*, and *S* components of the colour space are plotted on 3 axes in space, adjustments in the *LMS* colour space are computed as rotations around the axes. Similarly to *RGBShift*, we did not manipulate the original image, but rather create an overlay to optically combine with the background producing the compensation.

Edges: The final correction technique we implemented was to provide an outline of the areas with critical colours as shown by Tanuwidjaja et al. [124]. Whilst the originally proposed technique used black outlines to show edges, we utilized white outlines as the current generation of Computational Glasses cannot darken the user's view. We detected the edges to be shown with a Sobel filter on the error image to only show edges within areas of confusion. This technique represents a different approach to the *RGBShift* and *LMSShift* by outlining the contours of confusing areas whilst the other approaches look to alleviate the issue directly by adjusting the colour.

RGBShift Adjust and LMSShift Adjust: Following previous findings on user-dependent amounts of required colour shift, we created a modified version of $RGBShift$ and $LMSShift$ where participants could adjust the parameters of the compensation to better suit themselves. For *RGBShift* the adjustment was the amount of each colour channel that was used in the compensation, and for *LMSShift* it was the angle of rotation around the axes. This was achieved by giving the participants a keypad that allowed for one button to increase and one to decrease each parameter respectively. The functionality of the keypad was explained to the participants whenever they were going to use it and also displayed to them on the monitor.

Task: The task for this experiment was to identify the number on an Ishihara plate. Looking at the output from a user-perspective camera looking through our monocular prototype the participant



	None	RGBShift	RGBShiftAdj	LMSShift	LMSShiftAdj
RGBShift	0.002	-	-	-	-
RGBShiftAdj	0.002	0.003	-	-	-
LMSShift	0.002	1	0.002	-	-
LMSShiftAdj	0.002	0.002	1	0.002	-
Edges	0.002	0.286	0.003	0.283	0.002

Fig. 10. Results of the bench-top efficacy evaluation with boxplots for success rate (Left) and confidence rates (Centre). Significance is marked against the baseline condition ('None'). The full breakdown of p-values are on the right with significant values highlighted in grey.

was asked to identify if they saw anything on a plate placed in front of the prototype, and if so what. They were then asked to rate how confident they were in their answer given what they could see on the plate. This was measured on a 5-point semantically anchored scale.

Procedure: After reading and signing a consent form each participant completed a demographic questionnaire with information on age, occupation, gender, presence of CVD and type if known, and other uncorrected vision ailments. They were then screened for CVD using Ishihara plates not used in the subsequent study. This was an easy test to use for a screen and was introduced/demonstrated to us by our colleagues in Ophthalmology. It gave us an indication of the form and severity of the CVD. Based on this, the system was set to use a Protanopia or Deuteranopia simulation. The plates used in the study were excluded from this test.

We chose a semi-randomized order of the correction techniques to avoid biasing the results as participants could adjust the degree of correction for *RGBAdjust* and *LMSAdjust*, potentially memorizing the correct answer for subsequent tests. During the study, participants completed the task for each plate under all of the conditions, with the order of the conditions randomised. To collect a baseline the first completed the task without any compensation, followed by *RGBShift*, *LMSShift*, and *Edges* in random order. Finally, to understand if the results can be further improved with a personalized correction, participants were given the chance to adjust the correction strength whilst completing the task in the *RGBAdjust* and *LMSAdjust* conditions. They were allowed as much time as they wanted to experiment with the adjustments and select a personalized adjustment. The study took roughly 30 minutes and participants were compensated for their time with a voucher worth $14USD ($20NZD).

The procedure of this and all subsequent studies was approved by the University of Otago Human Ethics Committee.

Results: For each correction technique we computed the success rate as the ratio of correct answers. A Shapiro-Wilk test showed that our data was not normally distributed. A subsequent Friedman test showed significant differences in the success rate ($\chi^2(5) = 79.154$; $p < 0.001$). A post-hoc Wilcoxon signed-rank test (Holm correction) showed that all correction techniques on the Computational Glasses have significantly higher success rates than the uncorrected condition. *LMSAdjusted* performed best (mean 0.97) and significant differences can be seen between all techniques except *RGBShift - LMSShift*, *RGBShift - Edges*, *LMSShift - Edges* and *RGBShiftAdj - LMSShiftAdj*. These results are shown in Figure 10 Left.

A Friedman test showed that there was a significant difference between the weighted confidence scores ($\chi^2(5) = 75.332$, $p < 0.001$). A post-hoc Wilcoxon signed-rank test (Holm correction) showed significant differences between all techniques except *RGBShift* and *LMSShift*, with all correction techniques performing significantly better than the uncorrected baseline. Once again *LMSAdjusted* performed best (mean 4.43). It is of note that the confidence score for *Edges* was lower than that of the other techniques (mean 1.99) with a statistically significant difference (highest p value of 0.0195 for *RGBShift - Edges*. See Figure 10 Center for the results.

We considered a potential correlation between different adjustment values and the selected plates, basically we considered finding perfect parameters for the adjustment strength based on the adjustment by the participants, but we found no consistent results indicating a correlation.

Discussion: The results of our technical validation confirm the efficacy of the approach shown on our bench prototype. More specifically, we showed that we improved the participants' ability to pass colour blindness test cases (H1) and make them more confident when answering the questions (H2) independent of the correction techniques used.

We should point out that there is the possibility that learning effects affected the study's results as a consequence of presenting participants with all modulations on each image. Any positive or negative effects on the colour information presented to the participant will have subsequently influenced what they are looking for, and their confidence in what they see. Depending on the magnitude of these effects the magnitude of the improvement demonstrated by a technique will be inversely exaggerated. However, we are confident that these learning effects, while possible, are likely to be small. When observing participants, we did see them return to incorrect answers when compensations did not offer them sufficient aid after successfully correctly answering question, as we did ask them to base their answers on what they could currently see. As such we believe any learning effects would have been more prominent when considering confidence. This also means that our main hypotheses are unlikely to be affected as our main aim was the general efficacy and confidence with respect to baseline (not corrected) and not to identify the best technique.

Besides our main findings on efficacy and confidence using different correction techniques, we also see indications that personalisation of the correction further improved the participants' ability to discern the patterns, with *LMSAdjust* giving the best results in both metrics. It is important to note that the correction strength participants selected for *LMSAdjust* and *RGBAdjust* was not consistent between the different plates, suggesting that it is important to consider not only inter-personal differences, but also situational and environmental compositions. As the participants were able to adjust the values for *LMSAdjust* and *RGBAdjust*, we expected that if the techniques could work the participants would be able to learn the correct answer. This means that the participants could increase their confidence in their answers. However, these results show a significant difference between not only them and the baseline, but also the unadjusted techniques. Therefore there is evidence to support the improvements gained by customisation of compensations to an individual's needs and situation.

Overall while confirming our hypotheses, testing our concept in the monocular prototype allowed us also to control for the confounding variable of the eye-display calibration, the quality of which is hard to estimate beyond that reported by the participants. Although this ensured that all participants saw correctly modulated views of the plates, it constrained the colours presented to the participants by the camera response and the display on which the final image was presented.

6 STUDY 2: EFFICACY OF USER-CALIBRATED COMPUTATIONAL GLASSES FOR CVD

Whilst our first efficacy evaluation showed a clear improvement in participants' ability to pass a colour blindness test, it was still constrained to a bench prototype where the user's eye was replaced with a camera and the participants only saw the camera feed instead of directly looking through the prototype. As a user's perception of the overlay when looking through the Computational Glasses can substantially differ from what is captured by a user-perspective camera, we conducted a second study to further test the applicability of our correction techniques when participants were actually able to directly see through our prototype. Furthermore, instead of being a monocular prototype, we added support for actual stereo vision by utilising our approach for each eye. Given our encouraging observations in the technical validation study, we had the following hypotheses that basically aim to replicate earlier results using a more realistic prototype but still in a well-controlled environment.

- H3: Using the Stereoscopic Computational Glasses, participants would improve their ability to pass a set of colour blind test cases (would not be detected as colour blind while seeing the corrected view).
- H4: Using the Stereoscopic Computational Glasses, participants would feel more confident when recognizing the correct content on the plates.

Design: The general design for this study followed that of our first efficacy evaluation to test the effectiveness of the compensation techniques when observed directly by participants. The independent variables were again the different techniques *(None, RGBShift, RGBShift Adjust, LMS Shift, LMS Shift Adjust, Edges)*, and the dependent variables were success rate and weighted confidence score. Due to the small cohort of potential participants, we used a different set of Ishihara plates in this experiment, allowing a partial overlap of the participant pool with the first study without biasing the results. Overall, we talked directly to several thousand students to recruit the participants for this study.

Apparatus: For this study we used the stereoscopic prototype that allowed the user to directly look through the glasses and perceive the compensation. An LCD screen represented the physical world and displayed content to the participants. The Computational Glasses were mounted in a fixed rig to stabilize the prototype and maintain the relationship to the screen so that participants had a good view through the glasses onto the LCD screen. A chin rest was included in the rig to allow participants to maintain a constant head position more comfortably over an extended period.

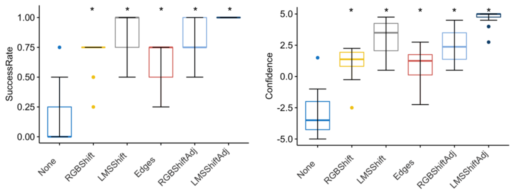
Participants: We once again recruited 19 participants (1 female; average age=23.21, σ=9.23) from the student body and staff of the University of Otago through advertisements in lectures and mailing lists. One participant showed complete colour blindness which was also medically diagnosed and is extremely rare, and thus was treated separately. The remaining participants showed forms of red-green blindness. Participants were compensated for their time with a voucher worth the equivalent of $14USD ($20NZD).

Techniques: As this was a replication of our prior study, we utilised the same techniques in this study as we detailed and implemented previously.

Task: The task for this study was largely the same as that used in the Bench-Top Efficacy Validation study. Once again the participants were presented with an Ishihara plate and were asked to identify what, if anything, they could read on the plate. They were then again asked to provide a confidence rating for their answer. However, for this study, the user was looking directly through our stereoscopic prototype, and the Ishihara plates were presented on a monitor in front of the participant.

Procedure: The procedure for this study followed that of the Bench-Top Efficacy Validation study. As the alignment of the scene camera's view with the user's view in the stereoscopic prototype is user-dependent, participants had to perform the described calibration routine before completing the task in the uncompensated condition. As in the Bench-Top Efficacy Validation study, the order of the plates was randomized for each participant, and the techniques were presented in the same semi-randomized order. The study took 45 minutes.

Results: As the success rate was again not normally distributed, we compared the results with a Friedman's Test that showed significant differences between the conditions ($\chi^2(5) = 73.446$, $p < 0.001$). A post-hoc Wilcoxon signed-rank test (Holm correction) showed significant differences between all techniques except *RGBShift - Edges* and *LMSShift - RGBShiftAdj* (Fig 11 Left). For



	None	RGBShift	RGBShiftAdj	LMSShift	LMSShiftAdj
RGBShift	0.002	-	-	-	-
RGBShiftAdj	0.002	0.001	-	-	-
LMSShift	0.002	0.591	0.004	-	-
LMSShiftAdj	0.002	0.004	0.010	0.002	-
Edges	0.002	0.020	0.002	0.011	0.002

Fig. 11. Results for the stereo efficacy evaluation with boxplots for success rate (Left) and confidence rates (Center). Significance is marked against the baseline condition ('None'). The full breakdown of p-values are on the right with significant values highlighted in grey.

the weighted confidence scores, a Friedman's test showed significant differences between the conditions ($\chi^2(5) = 78.926$, $p < 0.001$). A post-hoc Wilcoxon signed-rank test (Holm correction) showed significant differences between all techniques except the aforementioned *RGBShift - Edges*, and *LMSShift - RGBShiftAdj* (Figure 11 Center).

Discussion: The results of our study support our hypotheses H3 and H4. More importantly, these results support the internal validity of our findings as we not only replicated them with a new set of Ishihara test plates and a partially different cohort of participants, but also in an unmitigated view of the scene with participants viewing the compensation with their own eyes.

While the results supported our initial observation that all techniques improved the participant's ability to distinguish shapes shown on the plate, we also found differences from our first bench-top efficacy study. First, *Edges* performed significantly worse than the other techniques. One possible explanation is that this study utilized a stereoscopic screen. Minute errors in the alignment of the rendered content with the scene could have made the edge outline more difficult for participants to fuse to a coherent image. Another possible explanation is the abstract nature of the task with many edges being highlighted in a small space making it difficult to discern details. It is important to note that this is in line with the lower confidence participants had when using the edge compensation compared to the colour compensation techniques in the first bench-top efficacy study.

We also found that *LMSShift* significantly outperformed *RGBShift*. One possible reason for this is that *LMS* is a better representation of how humans perceive colours. Another reason could be that humans perceive colours differently from a camera, resulting in potentially insufficient adjustment. This is supported by the improved performance of the *RGBShiftAdjust* over *RGBShift*.

As with our first efficacy study, due to the replicated study design, we must point out the potential learning effects affecting our results. Participants viewed the same plates under repeated conditions. Therefore, effects caused by the compensations on the participant's ability to identify what was on a plate could have affected the results for subsequent compensations applied to that plate. However, using our experience and observations from the earlier experiment we expected those effects by minimal and not affecting our main hypotheses.

Some notable anecdotal evidence voiced by several participants was that the adjustments used were overly strong. This was unsurprising as we utilised a generic strong shift that could cater to the most severe cases of CVD. For less severe cases a reduced adjustment could suffice, as demonstrated in Figure 12 which is verified to be sufficient for a mild case. This demonstrates a need for context aware compensations that adjust to the users needs. We also garnered feedback from one participant showing total colourblindness (who we treated separately). Whilst we only had simulations to create compensations for protanopia and deuteranopia we still tested the systems ability to aid them. Unsurprisingly the default shifts we utilised were of little assistance, however utilising custom shifts they were able to achieve a nearly 100% success rate with high confidence

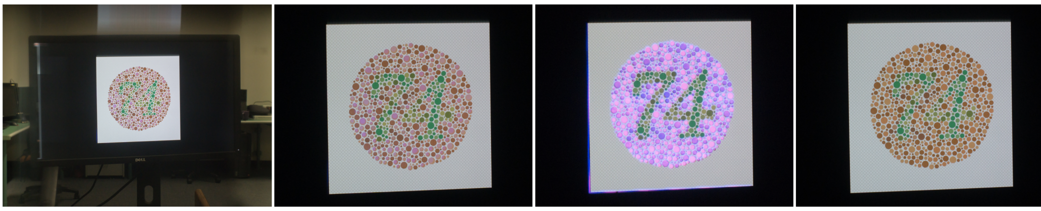


Fig. 12. From left: view of an Ishihara plate viewed through our prototype with sufficient compensation for a mild case to read a '74', maximum compensation on the same plate to clearly demonstrate the '74', the uncompensated view of the plate where a CVD viewer would read '21'.

and the qualitative feedback also indicated the benefit of our approach in particular for people with this more rare but more severe form of CVD.

As discussed with the prior study, individual eye-display calibrations are difficult to verify under the conditions presented by the stereoscopic prototype and we had to rely on participants reporting for the accuracy of their calibrations. Whilst this introduces a confounding variable, the corroboration between our initial study, where it is removed, and this study increases the internal validity of this study. Furthermore, the corroboration between the studies increases the validity of our initial study. The impact of confounding factors such as the compressed colour gamut caused by the camera and display used to present images to the participants are removed.

7 STUDY 3: COMPARISON AGAINST INDIRECT COMPENSATION FOR CVD

In our previous studies, we demonstrated the efficacy of our approach using different prototypes and by exploring different compensation techniques. As a next step, we were interested in comparing our approach against prior research in the field. To the best of our knowledge, our work is the first to directly compensate the appearance of the scene when seen through an OSTHMD as shown in Figure 13 (Top). This makes it difficult to compare our findings with other assistive devices supporting people affected by CVD. The closest to our approach is the work by Tanuwidjaja et al. [124]. In that work the authors used a Google Glass to support people with CVD. It is important to stress here that while a Google Glass is sometimes referred to as an OSTHMD, their approach is fundamentally different. Instead of directly compensating the world by seeing through the glasses, Tanuwidjaja et al. showed in the Google Glass a camera image that is compensated but this overall visual representation does not align with the real world (is off axis) as shown in Figure 13 (Bottom). It can be compared to constantly holding a phone next to one's eye and gazing at it would show a compensated version of the physical world. Given that it is the most related prior research, we decided to compare our approach with that of Tanuwidjaja et al. [124] to determine whether directly compensating the scene increased the user's mental workload or negatively affected the efficiency of the system.

Given the positive feedback on our system from our previous studies as well the positive feedback on the Google Glass as reported Tanuwidjaja et al. [124] we assumed both solutions would be viable for compensating CVD. Thus we focused this study on exploring the mental workload and effectiveness for each approach with our initial hypotheses that our approach using Computational Glasses for CVD has advantages when compared to a Google Glass based approach in terms of effectiveness and mental workload mainly because of the direct compensation. However, during pilot tests we realised that we did not consider several factors. Firstly, Google Glass might be more effective because participants have the corrected view as shown in the Google Glass as well as their normal view while our approach always shows a compensation. Secondly and probably

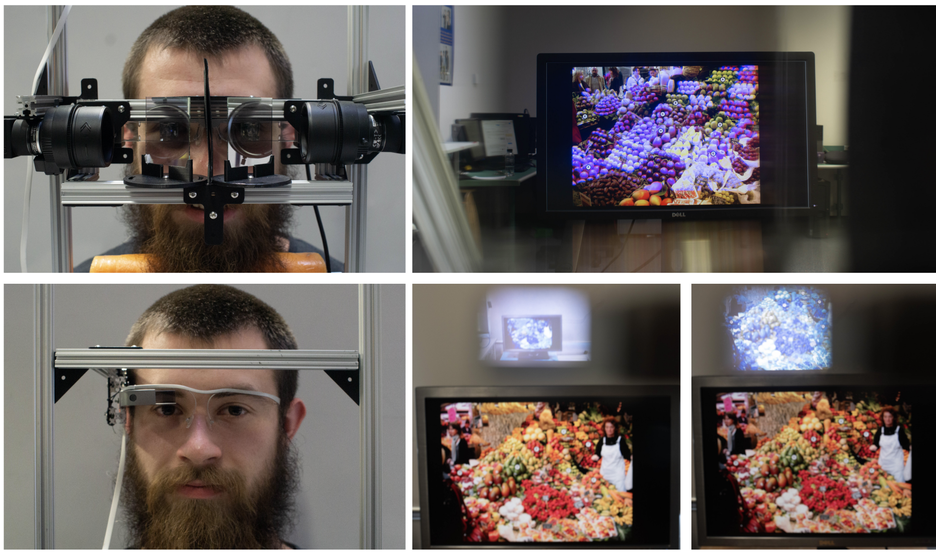


Fig. 13. We compare two compensation styles, our direct overlays (Top) vs the peripheral compensation suggested by Tanuwidjaja et al. [124] on a Google Glass (Bottom). The camera lens, image quality, and display size when shown on the Google Glass (Bottom-Center) prevented a correction of small scene elements as they were almost unnoticeable when presented to the wearer. For the comparison study we gave the Google Glass approach an advantage by showing the compensated original image (also shown in the screen) instead of the camera image (Bottom-Right) simulating a high quality zoomed in camera.

more importantly, we had to give the Google Glass approach an unfair advantage. As the camera quality is poor and the display is very small even larger details in the captured environment are completely lost and objects have to be held very close to the eye to be able to compensate for them in the Google Glass (See Figure 13 (Center)). Once we knew this we also saw this in the pattern in the original paper [124]. So instead of using the low quality camera feed of the Google Glass we decided to load the actual test images in full resolution on the device (See Figure 13(Right)). This certainly introduces a confounding factor as it gives the Google Glass an advantage of having the best possible image quality available. Consequently, we see this study more of an exploratory study with the initial hypotheses of performing on par.

- H5: Computational Glasses will show similar mental workload to state-of-the-art Google Glass.
- H6: Computational Glasses will show similar efficiency to state-of-the-art Google Glass.

Design: We designed a within-subject experiment with the goal of investigating the workload and efficiency of using Computational Glasses compared to the state-of-the-art system deployed on the Google Glass. To test the differences, we prepared six tasks that users could encounter when using the system in their daily life. Each task had two images associated with it. These had been tested with people affected by CVD beforehand to ensure they would present similarly difficult situations. The images used can be seen in Figure 14.

Our independent variable was the task and the display device (Computational Glasses and Google Glass) the correction was shown on. The dependent variables were the workload, measured using the results of the *NASA Task Load Index* (NASA-TLX) questionnaire, and the efficiency, which was measured with a questionnaire created by sub-setting the *System Usability Scale* (SUS). We excluded

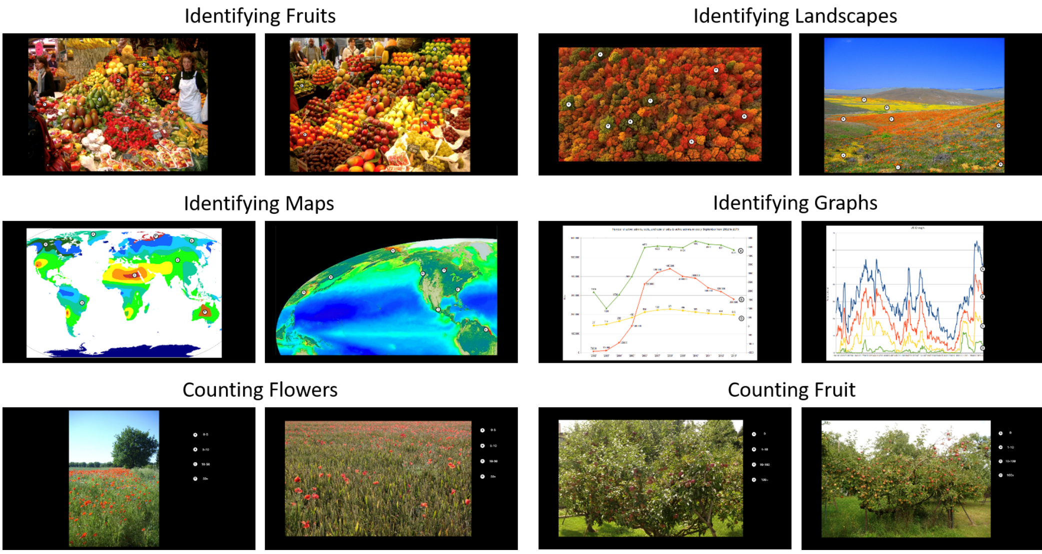


Fig. 14. Natural image material as used in Study 3. Full size images have been included in the supplementary material

from the traditional SUS the questions "need support of a technical person to be able to use this system", "various functions in this system were well integrated", and "too much inconsistency in this system" as we felt they were not applicable to our investigation.

Apparatus: In this study, we used the same setup as in Section 6. Besides our stereoscopic prototype of Computational Glasses we added a Google Glass-based solution that replicated the system of Tanuwidjaja et al. [124]. As discussed above, we modified this to overcome its limitations. As our studies had shown that $LMSShift$ resulted in best performance and our focus was on comparing user experiences with the different devices, we only presented participants with images compensated using this mode (Figure 13). For the study the Google Glass was mounted on the stabilising frame for the Computational Glasses. This ensured it remained stable for use and was in a constant position relative to the display.

Participants: All participants for this study were recruited as the 18 participants with forms of red-green blindness who participated in Study 2 (Section 6) because we already had calibrations for them, reducing the time needed for the system calibration.

Task: The tasks created for this study were: 1) identifying red fruits, 2) identifying red areas within a landscape, 3) identify red area in a complex graph, 4) identify red areas on maps, and approximate the number of 5) red flowers or 6) fruits. For tasks that required participants to identify red-coloured objects, participants were shown a number of labelled options and had to select their answers from among these. For tasks that required participants to estimate the number of objects in the image, we asked participants to select a suitable estimate among four options. At the end of each task the participant was asked to fill out a NASA-TLX and our subset of the SUS. These were completed on the monitor being used to display the images in the task.

Procedure: Before beginning the study, each participant read and signed a consent form. The participant then calibrated the Computational Glasses for their eyes. The positioning of the Google Glass was also adjusted such that the display suited each participant. We randomized the order of the devices the participants experienced the correction on. Each participant completed each of

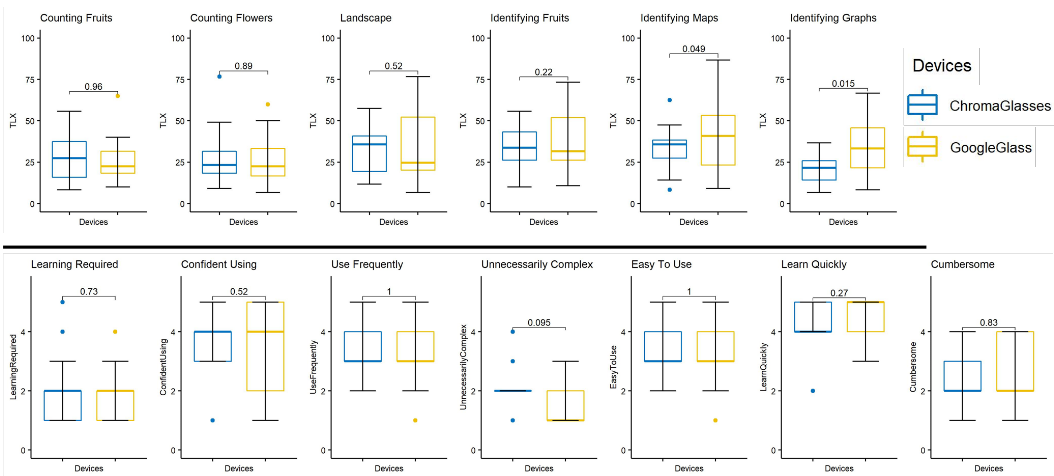


Fig. 15. We compare the subjective NASA-TLX (Top) scores for each task and questionnaire scores for the two approaches.

the six tasks in a randomized order using one of the two images associated with each task. The participant then changed to the other device and again completed each of the tasks using the alternative image. The participants were allowed as much time as desired.

Results: We compared the NASA-TLX scores of the devices for each task with a paired Wilcoxon Signed Rank test and found significant difference in the answers for graph (p=0.015) and map (p=0.049) (Figure 15 Top). In both cases, Computational Glasses (Graphs: mean=21.76, Maps: mean=33.87) received a lower score than Google Glass (Graphs: mean=34.26, Maps: mean=40.2). A paired Wilcoxon Signed Rank did not show any significant differences between the questionnaire scores of the devices for any of the tasks (Figure 15 Bottom).

Discussion: Overall this study took a different direction than initially anticipated. While planned as a comparison against an indirect compensation (Google Glass) we realised that the study required changes that are likely to have affected the overall outcome. As such we consider this comparison study to have more of an exploratory character than initially anticipated. Foremost, as we pointed out earlier we realised that because of the camera and display of the Google Glass a compensation of CVD for small scene elements is not possible unless they are held very close to the user's eye (and consequently the Google Glass camera). This is confirmed when looking at the figures and examples in the original paper [124] but was not obvious from the writing or original experiments. The fact that this effect does not arise in our approach and thus we are able to also correct scene details because the display sits in front of the user's can already be seen as one of the findings of this study.

To still be able to explore our initial hypothesis we gave the Google Glass an advantage. With respect to these hypotheses, we must reject our hypothesis H5. While Computational Glasses performed on par with Google Glass for some examples we also saw a significant reduction in mental workload for others. Given the advantages already given to Google Glass we would expect this effect to be even more pronounced in a fair comparison. When looking at those conditions where our approach performed better by showing a lower workload, we realised that those were tasks that benefited more from not needing to map from real world to the display due to the direct overlay in the user's vision using our approach. This was especially evident in the cases where participants had to pay attention to small details. We confirmed our hypothesis H6 that we would not find significant differences compared to the state-of-the-art Google Glass implementation indicating that both approaches could be similarly efficient in the presented situations. While one could argue this is surprising, we observed that the Google Glass based approach offered wearers the ability to rely on their remaining colour vision and any tricks or subtle cues they are accustomed to. This would reduce the need for reliance on the Google Glass, as well as allowing it to be ignored if desired. Together with the varying severity of CVD in the participants, when using the Google Glass based approach participants can still utilise personal cues they use to compensate for their CVD. In contrast, when using our approach participants had to rely on the compensations provided which they had only recently been introduced to. As such we would expect the Google Glass to have advantages in efficiency when unneeded, whilst the Computational Glasses to be more efficient when needed.

8 STUDY 4: EXPLORATORY EVALUATION OF COMPUTATIONAL GLASSES FOR CVD

While our previous studies showed that the participant's ability to discern confusing colours can be improved using the Computational Glasses, the tests were performed in a controlled stationary setting only partially replicating the envisioned context of use. To further explore a user's experience of using Computational Glasses in a more natural context, and to explore and identify issues not revealed by our efficacy evaluations, we conducted an exploratory qualitative study with our portable prototype.

Design: The goal of our study was to explore how participants could experience the system in everyday life, gathering information on potential scenarios they could imagine using it, and their general experiences with CVD. As we had already shown efficacy, we opted not to empirically compare the results against another visual augmentation being presented on the display. We considered a potential situation where participants could benefit from a correction via our Computational Glasses and chose a viewing task in which they had to visually explore a presented poster. We opted for a one-suits-all approach to simplify the procedure, and because we learned from prior studies that this provides good results. Thus, we only used the $LMSShift$ technique for correction and used values of (L,M,S) = (0.5,0,0).

The presented poster contained information about CVD, and several images (Figure 17) and graphs to support the text. The text also featured questions about each image that participants were asked to answer, alongside stating how confident they were answering the question on a 5-point semantically anchored scale (1, not being sure at all, and 5, being 100% confident). The images shown on the poster were designed to present difficulties for anyone affected by red-green blindness. The images were an Ishihara plate showing a 3 for those with normal vision and a 5 for those affected by deuteranopia, a pie-chart showing a modified distribution of different colour blindness types within the population and small rectangles above the chart colour coding the displayed information, and a field with red poppies in it (Figure 17). The field image was also used in our comparison studies. While observing the poster, participants were encouraged to think aloud, describing what they saw through the Computational Glasses. After observing the poster and answering all questions participants took part in a semi-structured interview about their experience, what they saw, their experience with CVD, and thoughts on the benefits of our approach. We provide the questions of the interview in the appendix.

Apparatus: For this study we used our portable prototype described in section 4.1 which was tethered to a desktop computer for the computational aspects (Figure 16 Left) with the goal of collecting general impressions of using a device like ours.

Participants: We recruited 10 participants (average age=27.0, σ=13.3) from the student body and staff of the University of Otago through advertisement by email. Nine participants were male, and one was female. All but one participant had normal or corrected to normal vision. Two of the

Fig. 16. Left: Our portable prototype based on the Lumus DK-52 modified to increase stability. Right: Participant wearing the prototype in front of the poster.

participants had taken part in at least one of the previous studies, while the remaining eight had no prior experience with the system.

Task: The task for this study consisted of two parts. Firstly, the participants were asked to explore a poster (Figure 16) situated on a wall whilst using our wearable prototype. They were asked to read the text and answer the questions therein that related to images on the poster. Afterward, for the second part of the study the participants took part in an interview with the researcher.

Procedure: After participants entered the experiment room they received an explanation of the experiment procedure, the goal of the experiment, and signed the consent form. After consenting to the study, participants filled out a demographics questionnaire, and a Covid-19 tracking document, and were tested for CVD using Ishihara plates. After that, participants were shown how to wear and adjust the glasses and received a quick introduction. Participants were then seated in front of a monitor. The monitor was placed at a distance from the participant similar to the distance they would view the poster from when completing the first part of the task. Participants performed the geometric calibration routine described in Section 4.1. Once calibrated, participants were free to walk around with our wearable prototype and complete the first part of the task. After doing so participants were seated and took part in the second part of the task. The entire procedure took about 30-40 minutes, and participants received a voucher worth 13 USD (20NZD) to compensate for their time. Everyone taking part in the experiment wore masks and the equipment was disinfected after each participant in accordance with current Covid-19 requirements and guidelines.

Results: Results gathered from the study pertain to their reactions and feedback whilst viewing the poster, their reflections on their compensated vision afterwards, their thoughts on the prototypical device in its current state, as well as general reflections on being able to correct for CVD and how it affects their lives.

Feedback when viewing the poster: There was a high variation in the answers given for the poster. All participants correctly identified the Ishihara plate, most noting the aid of the blue overlay increases ease and therefore confidence. The modified areas of the chart were noted to only show slight variations in blue when compensated, which coupled with the small legend size, made correct identification difficult, making it still challenging for participants to answer the question correctly or with high confidence. For the poppy field scene participants either noted the individual flowers or realised that something was being highlighted but for the latter they did not immediately identify individual poppies.

Fig. 17. The images used on the poster used in our explorative study. Participants were asked to read the plate, identify what the image contained, and correctly identify the segments of the pie chart.

Reflections on their compensated vision: Several participants noted the system's great assistance for the plate, but mentioned the confusion that is generated when compensated results in colours already present (e.g., graph). This once more highlights the practical limitations of recolouring compensations such as when not utilising Ishihara plates but utilising realistic scenarios. Shifting colours towards colours already present not only affect the cues those suffering from CVD have come to rely upon but also introduce new confusions when observing a diverse color palette. While this limitation has been noted before, e.g., [36, 65], it remains an unsolved problem. Participants suggested that context-specific compensations could address some of the issues and that different compensations could be less obtrusive or more suited to specific situations. Utilizing patterns or textures was suggested. Alternatively, one participant noted that simple, quick, identification of confusing colours could be sufficient.

Thoughts on the prototypical device: Most participants commented on some of the limitations we know to be current limitations of our prototype but not the general concept. Latency between head movements and the display were mentioned, creating visually incoherent or unstable overlays whenever participants moved their head too quick. While the latency made the system currently ill-suited for non-stop utilization, some participants mentioned it could already help in specific static scenarios. It was also noted that whilst the compensation could be seen on the poppies, in particular when further away from the poster the low resolution of the cameras (further reduced during eye-camera-display adjustment) made individual flowers hard to interpret as high frequency structures got lost ("blobs of blue"). Some participants mentioned that there is a perceptual variance between the overlay display for both eyes. We attribute this variance to the eye position within the eye-box, and to variances in the brightness of the cameras which can easily change perceived brightness. When queried as to who could most benefit from the envisioned approach, most participants noted the effects on career choices (e.g., architecture, medicine, military) and hobbies (e.g., sailing). Three participants raised problems for children and potential bullying, with one recalling such events due to wearing an incorrectly coloured shirt, and another referencing teasing (although not so far as to be considered bullying). Participants thought the glasses could help children distinguish colours or identify when they needed help (a sentiment also echoed by participants for their own use). One participant detailed asking friends for help when using colours at school and almost all highlighted here the issues in their childhood and early youth. While encouraging, it is important to highlight the need to verify these observations with the target audience. The answers could have been affected by biases when recalling ones past situations or imagining another person's needs. Another bias could have been introduced from the participants feeling the need to give some answer to the question posed by the interviewer.

General feedback on their experience of CVD: We asked our participants if they would consider correcting their CVD through surgery, or glasses similar to our prototype. Although most participants felt that CVD did not significantly affect their daily lives, most would consider correction.

All bar one would consider glasses, either for daily or occasional use. They did note however that form-factor was very important and would have to resemble current glasses. Specific benefit was questioned, and participants noted that they would want to evaluate resulting corrections. Only two participants would definitely consider surgery, a further two would consider it if it was safe and cheap. One participant had looked into using traditional lenses to compensate for CVD in the form of EnChroma[6]. They preferred our system as according to the participant, the colour shift in EnChroma was of little apparent practical effect. Computational Glasses enabled clearer understanding of confusions. Another participant noted they had explored the same option but cost and time requirements for potential benefits prohibited them from proceeding.

The participants reported common issues in which they perceive CVD to affect their lives. A common problem was colour-coded indicators. One participant mentioned trouble with car warning lights that could be critical or cautionary. Participants also noted a need to double check traffic lights and problems when lights were placed horizontally as opposed to vertically. Other participants recalled problems when colour was used as an identifier, e.g., "green stickers", "green glass bottles". This issue was not restricted to specific applications and is critical particularly in unknown environments. Participants noted that education tests and posters would sometimes utilise colours for graphs and images that they could not distinguish. Even when teachers were aware of the problem, they did not adjust the educational material. Participants also mentioned videos and computer games not supporting CVD adjustment, and losing golf balls in grass due to inability to distinguish them. Cooking was also an issue as participants could not easily determine if things were cooked properly (e.g., chicken) or the freshness of ingredients. Interestingly, although absolute colour identification was raised as problematic, i.e., being asked to bring the red bucket, colour matching did not tend to be so as participants could compare the hues to do so.

Discussion: Drawing from the results of our study we find several points of discussion with relevance to future developments of Computational Glasses, AR compensations for CVD, and CVD aid in general. From our study we see the need for considering context-aware compensation for CVD. For example, whilst compensation was beneficial in some areas of the poster it caused problems in others, and more targeted solutions were requested by the participants. The same is true not only for the technique used but also for the overall strength of the compensation so as not to create visual obtrusion thus, needs to be context aware. Whilst the efficacy of using patterns was less than spectral-based shifts in our prior studies, participants expressed an interest in the use of these in certain areas, so using patterns and textures warrant further investigation, in particular the more commonly demonstrated hatched overlays [29, 37, 44, 110]. The feedback highlights the known issues to perceived latency. This is a general challenge in Augmented Reality and OSTHMDs [52, 73] and thus anticipated. We argue that higher integration of the components would easily allow for acceptable latency that is on par with existing OSTHMDs used in AR but would be an issue for the engineering and cost of the prototype as we used off-the shelf hardware where possible. Similarly, using higher resolution cameras that are available but costly when bought in small numbers would alleviate the identified issues when preserving or highlighting small details. An interesting point from the interviews was the potential of only highlighting the areas where issues for people affected by CVD might arise so they can deal with them as needed. Whilst many of the works in literature highlight areas of difficulty inherently by changing them, future work might consider to only highlight but not change or compensate which opens interesting research questions.

Finally, the exploratory study provided encouraging feedback when moving forward with compensating CVD using Computational Glasses. Most participants did view themselves as people

[6]https://enchroma.com/

who could most benefit from glasses despite the mild nature of CVD. Participants pointed towards careers that they would not be able to participate in and issues early in their lives. We generally noted a consensus that glasses style compensation for CVD would be of interest to participants, either as specific glasses or as an additional feature to current glasses even when compared to a hypothetical surgery. Such surgery does not currently exist, although gene therapy has shown promising results in introducing new colours to red-green colour-blind monkeys[7]. However, the desirability of such solutions was very low and participants were much more open to the idea of a glasses based solution.

9 STUDY 5: COMPENSATION TECHNIQUES ON COMPUTATIONAL GLASSES FOR CVD

Whilst our initial studies had shown that Computational Glasses could indeed improve the participant's ability to distinguish between colours, we saw a need to further develop techniques that can be properly applied to long term usage and are less obtrusive. This was supported by the feedback from our exploratory study in which participants expressed their interest in having different compensations depending on the current context. So far, we had only explored a small subset of possible compensation techniques. We thus decided to investigate which of the techniques currently present in literature could be adapted for use with Computational Glasses. We saw this as a required step to explore promising future research directions for CVD compensation techniques as well as to have a set of known and working techniques that can be applied depending on user preference or context. Consequently, as our initial tests only investigated user performance in a standard colour blindness test (Ishihara plate), we also aimed to incorporated natural images in our evaluation of different compensation techniques for CVD.

9.1 CVD Techniques

We have showed in our discussion on related works and background technologies that there are many techniques that produce a viable compensation for users affected by CVD. For our final study on compensation techniques, we opted not to test all the presented techniques but selected a representative subset of the three main directions we identified in our related work review: Colour adjustments (Spectral and Amplitude), Pattern effects, and Visual Effects.

Selection: To select suitable techniques for our comparison, we initially considered all presented techniques and selected a subset that we 1) believed can be implemented in real time based on what was reported in the original works, 2) could be implemented in an additive manner as required to achieve an effect in Computational Glasses, 3) produced sufficiently different output to those already included, and 4) had sufficient implementation details provided for us to replicate them. We applied constraints to the techniques; being able to run interactively on a stream of camera frames, and be implemented in an additive manner as our Computational Glasses can only add light. We also decided to exclude techniques that relied on user adjustments due to the desired pervasive nature of Computational Glasses and existence of non-computational filters. Whenever possible we only looked at the most current forms of the techniques, with techniques that have been shown to update and outperform older techniques being selected. Techniques that were designed for scenarios outside of Computational Glasses use, such as working for both CVD and normal viewers were also excluded due to the drastic differences in their design goals. We also avoided flicker techniques as we were concerned about their suitability for non-static scenes and potential adverse effects on users. The final constraint we applied was to only include techniques that were designed

[7] http://www.neitzvision.com/research/gene-therapy/

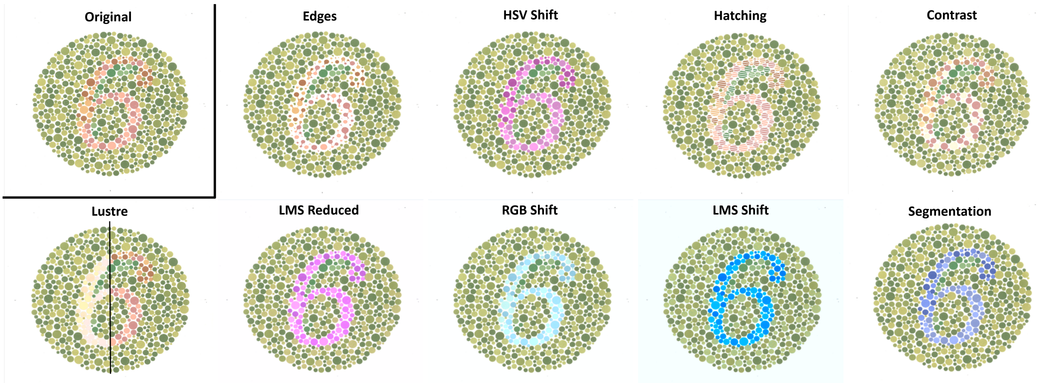


Fig. 18. The various techniques implemented for the comparison study. Top Left: the original image before modification. Bottom Left: *Lustre* is split to show the modification presented to each eye respectively.

to work for all forms of red-green colour blindness as this would be the pool of participants that we expected our recruits to belong to, and we wanted to be able to utilise all of them.

This left us with 28 works presenting 15 techniques. As several of the remaining 15 techniques performed similarly, we selected a subset of 9 unique techniques to avoid participant fatigue from comparing repetitive techniques that present little to no new insights.

Techniques: Unless otherwise stated, we implemented the remaining techniques using the equations provided by the authors and readers should refer to the referenced works for full implementation details.

RGBShift, LMSShift, Edges: These techniques were already implemented in our existing prototypes as previously detailed in Section 5.

HSVShift: The selected *HSV* effect uses a skillet adjustment to shift H. If colours are considered "red" H is adjusted based on H and maximum S, V as detailed by Riberio et al. [106].

Craik-O'Brien Effect: We implemented a modification of the original technique presented by Bao et al. [8]. This technique looks to ramp pixel intensity up around pairs of colours which are perceived as different to normal sighted viewers but similar to CVD, creating the Craik-O'Brien effect. However, during implementation and initial pilot tests, we found that we were unable to reproduce the effect on the Computational Glasses given that we only were able to add light intensities and wanted to be able to compensate smaller details (the original work by Bao et al. changed larger image areas). Instead, we included the variation of the *LMSShift* technique *LMSReduced* where we reduced the effect size, as we knew this technique to work well based on our previous studies and it had been noted that the techniques could be considered excessive. We thus looked to investigate its effectiveness at reduced levels to see if it would better achieve the goal of an unobtrusive compensation for ubiquitous use.

Contrast: Whilst none of the presented intensity adjustment techniques completely met our criteria, we chose to include an example from this category of techniques for completeness and modified the work of An and Park [2] only including the additive components. Based on the H value we modified S, V using the input S, S_{max} and $S_{average}$.

Segmentation: We also included a segmentation algorithm as these algorithms pay attention to the current colours in the image to avoid introducing new issues. To this end we included the work by Park et al. [98] whose algorithm works by clustering all colours in an image into patches and testing for colour patches that lie on confusion lines. One colour in any pair that lies on a confusion line is adjusted in *Lab*.

Hatching: We implemented the hatching technique presented by Sajadi et al. [110] that presents hatching line angles based on the input colour and scaled based on the perceptual difference between dichromats and trichromats. *RGB* values are adjusted towards white based on α, the colour difference for dichromats. Unlike the original work where a grid search was used to create optimal pattern layouts, we utilised a sin function to ensure real time operation.

Lustre: This technique was presented by Chua et al. [22] and works by showing a different image to each eye. If these images are significantly different the brain will be unable to fuse the images and a lustre is seen on affected areas. This is seen as a shimmering effect where the areas of difference shift between the colours present in each of the two images. Whilst the original technique was designed for 3D shutter glasses and used both positive and negative components on multiple levels, we adapted it to account for not being able to subtract light intensities in Computational Glasses. We increase the brightness of affected areas for one eye to produce this effect and used only one level. The level was set using the optimal delta report by Chua et al. [22].

Our final selection of techniques was: *RGBShift, HSVShift, LMSShift, Edges, Contrast, Segmentation, Hatching, Lustre,* and *LMSReduced.* Example output of each of these techniques can be seen in Figure 18 with an uncompensated Ishihara plate for reference.

9.2 Study

In the following, we describe the study for evaluating the different compensation techniques within our Computational Glasses prototype.

Design: As with the efficacy studies, we designed a within-subjects experiment with different images to view for each algorithm. Rather than simply showing the Ishihara plates as before, we also included natural scene images, resulting in a total of 4 tasks (2 on Ishihara plates and 2 on natural scenes) that participants would complete for each condition. The two natural scenes represented different scenarios participants may encounter in real life and participants were asked to either count the number of red flowers in the image, or identify which of the labelled fruits was red. These images were the same as those used in Study 3 (Section 7), *"Identifying Fruit"* and *"Counting Flowers"* (Figure 14). As our related work review identified, these were among the most common tasks in user studies. For the plates, we included those from two different palettes that needed to be read. For each task, we included two images that a researcher who was affected by CVD judged to be of similar difficulty. The correct answers for the natural images was determined by researchers with colour vision measured as normal.

As our dependent variables we collected the success rates and confidence scores when giving an answer. The success rate for the plates and the counting task was measured as in the previous studies. The identification task success rate was measured as the ratio of correctly identified items (0.0 no items identified correctly, 1.0 if all items correctly identified). For the plates and counting tasks we measured the confidence scores in the same manner as in the prior efficacy studies. For the identification task it was measured as the confidence scaled by the success rate. As our review and first study showed that all systems would likely perform well compared to the baseline, we also asked participants to judge the obtrusion of each technique on a 5-point semantically anchored scale (5=most obtrusive).

Apparatus: We used the stereoscopic prototype with the same environment setup as in Study 2 (Section 6).

Task: The tasks for this experiment were to correctly answer questions regarding the image being shown, with the questions being dependent on the image shown. When the image was an Ishihara plate the participant was asked to identify what they saw on the plate. When the image was a natural scene from *"Identifying Fruit"* the participant was asked to state all letters that were placed on top of 'red' fruit. When the image was a natural scene from *'Counting Flowers'* the participant was asked to select the letter which corresponded to the range in which the number of perceived flowers fell. After answering the question the participant was then asked to rate their confidence in their answer on a 5-point semantically anchored scale. If the task was completed under a compensated condition then the participant was also asked to rate how obtrusive they found any perceived compensation.

Participants: For this study, we recruited 10 participants from around the University using the same approach as before. We also reached out to participants from our prior studies and included 4 of them. We only included 10 participants in this study because we felt that our limited recruiting pool was being overtaxed through repeated recruitment, reducing the efficacy of each attempt. This reduces the impact of results but based on our previous results and observations from related work, we expected readily working algorithms to be clearly apparent even with reduced numbers of participants. We removed one participant because their CVD was limited to a level that they could answer plates without aid. We also noted that all, bar one, of the participants for this study presented only minor symptoms, which is in contrast to our prior studies where we had a distribution of both mild and more severe cases.

Procedure: As with the previous studies, each participant read and signed a consent form then completed a non-identifying demographic questionnaire before beginning the study. We screened participants for CVD using Ishihara plates not included in the study. For the actual study the participants were seated in the apparatus and instructed on the calibration of the system. We completed the calibration only once at the start of the study. To familiarize participants with the techniques used in our experiment, we showed them a coloured grid and then applied each technique in turn explaining the effect to them. This enabled them to see how the techniques would or would not affect various colours. Subsequently the participants were shown the first task. The order of the conditions the participant completed each task in was randomized such that the task is completed on each image used for the task in the uncorrected condition first. This allowed for the collection of a baseline and provided participants a baseline for the obtrusiveness of compensations. The task was then completed in each condition on one of the two images in a random order, with the occurrence of each image balanced. The order in which the tasks was completed was randomised. After all the tasks had been completed, the participant was then asked to rate the overall obtrusiveness of each compensation technique on a final image. During this stage the participants were shown the compensation on each of the previous images and allowed to switch between images and compensations to compare them. Throughout the study participants were encouraged to voice their thoughts and these were recorded.

Results: To evaluate the efficacy of the techniques we calculated the ratio of correct answers given for each task. Confidence was then calculated per our prior studies. We then treated obtrusion as a semantically anchored 5-point scale. Shapiro Wilks tests showed our data to be non-normally distributed so we tested for differences in score and confidence between each technique and the unmodified condition using Wilcoxon signed rank tests. We also tested obtrusion between each technique using Wilcoxon signed rank tests.

Score: Results for the success rate showed significant improvements for *LMS*, *RGB*, *LMSReduced*, *Segmentation*, and *Lustre* (Figure 19 Left). Notably scores were lower in this study than in the prior efficacy ones, and *Edges* no longer showed a significant improvement. To investigate this effect, we split the results for the Ishihara task and the natural image tasks. Here we see an interesting effect. Alongside the previously mentioned techniques, *Edges* also significantly improved the participants success. However, when looking at the natural images we see that no technique has a significant effect on the scores. We show a detailed breakdown of the statistical results in Table 1 Left.

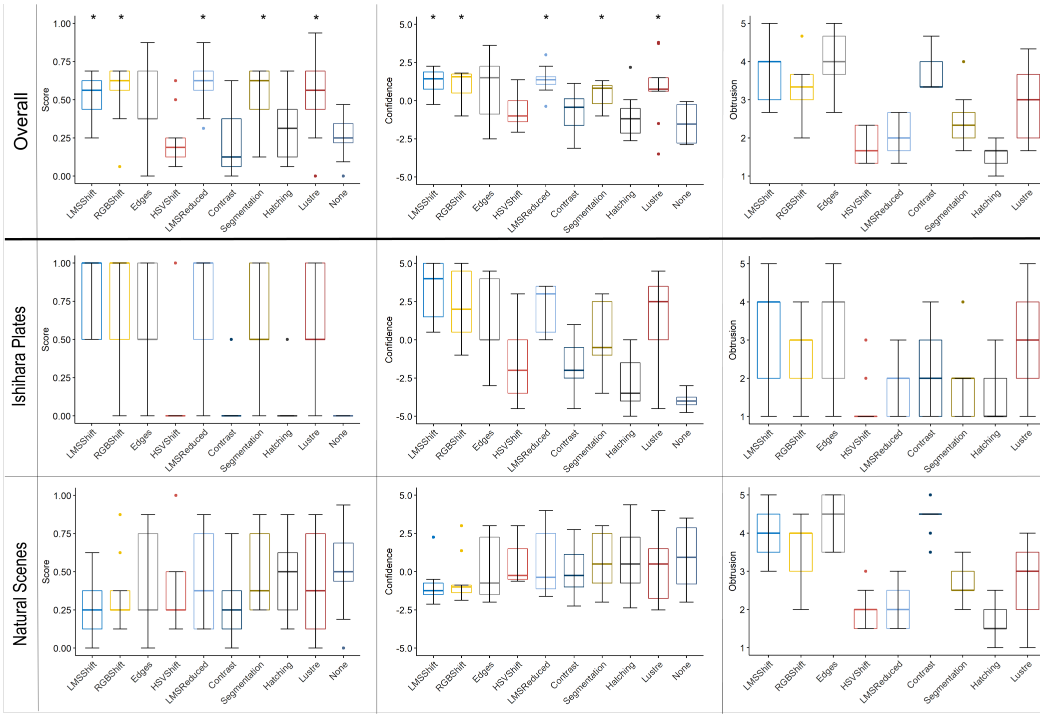


Fig. 19. Boxplots of the results. From Left: Score, Confidence, and Obtrusion for each of the display compensation techniques. The top row shows the overall results. The subsequent rows split the results by answers for the Ishihara plates and the natural scene images respectively.

Confidence: The results for the confidence again showed significant improvements for *LMS*, *RGB*, *LMSReduced*, *Segmentation*, and *Lustre* (Figure 19 Centre). We also looked at the separated results for the confidence and saw significant improvements for *Contrast* and *HSVShift*, however did not see it for *Lustre*. For the natural tasks we once again saw no significant effects. See Table 1 Right for relevant statistics.

Obtrusion: As we were interested in exploring the potential for long term use and unobtrusive compensation, to compare between the techniques we looked at the obtrusion of each technique (Figure 19 Right). We found that the *HSVShift*, *LMSReduced*, *Segmentation*, and *Hatching* were all rated lowest with mean values less than three (1.8, 2.1, 2.4, 1.5 respectively). After a Holm-Bonferroni correction *Hatching* was considered significantly less obtrusive than all the techniques except *HSVShift* and *LMSReduced*. *HSVShift*, *LMSReduced* and *Segmentation* were not considered significantly different. The original three techniques tested; *LMSShift*, *RGBShift*, and *Edges*, alongside *Contrast* were all considered the most obtrusive, with no significant differences found between them. See Table 2 for relevant statistics.

Discussion: Overall, our study comparing compensation techniques on Computational Glasses for CVD delivered mixed findings. Most importantly, we showed that compensation techniques such as *LMSShift*, *RGBShift*, *LMSReduced*, *Segmentation*, and *Lustre* were able to aid people affected by CVD. In general that would make them suitable candidates for a context-aware compensation of CVD in Computational Glasses. However, we need to state here that those overall positive results were biased by the Ishihara plates and do not hold true when looking at the natural scenes in

Technique	Full (*p*,W)	Ishihara (*p*,W)	Natural (*p*,W)
LMSShift	0.0124, 16.5	0.0005, 07.0	0.0808, 73.5
RGBShift	0.0225, 19.5	0.0016, 11.5	0.1283, 70.5
Edges	0.1598, 31.0	0.0064, 17.0	0.2870, 64.5
HSVShift	0.6762, 56.0	0.5828, 45.0	0.3420, 63.0
LMSReduced	0.0071, 14.0	0.0016, 11.5	0.8791, 52.5
Contrast	0.4947, 59.5	0.3573, 41.0	0.1831, 68.0
Segmentation	0.0187, 18.5	0.0054, 16.5	0.7324, 55.0
Hatching	0.7329, 45.0	0.3573, 41.0	1.0000, 50.0
Lustre	0.0406, 22.5	0.0054, 16.5	0.7326, 55.0

Technique	Full (*p*,W)	Ishihara (*p*,W)	Natural (*p*,W)
LMSShift	0.0045, 12.0	0.0005, 04.0	0.1037, 72.0
RGBShift	0.0112, 16.0	0.0007, 05.0	0.1208, 71.0
Edges	0.0537, 24.0	0.0011, 06.5	0.2563, 65.5
HSVShift	0.1402, 30.0	0.0487, 23.5	0.9397, 51.5
LMSReduced	0.0046, 12.0	0.0021, 09.0	0.9096, 52.0
Contrast	0.4720, 40.0	0.0189, 18.5	0.3843, 62.0
Segmentation	0.0090, 15.0	0.0031, 10.5	0.8796, 52.5
Hatching	0.6229, 43.0	0.2710, 35.0	0.6500, 56.5
Lustre	0.0210, 19.0	0.0535, 24.0	0.9698, 51.0

Table 1. Statistical results for Wilcoxon signed rank tests comparing techniques against the unmodified condition for success rate (Left) and confidence (Right). Significant values are in grey. The first columns show the results when evaluating on the full result set, the second if we only consider answers regarding the synthetic Ishihara plates, and the third for only the natural images.

Technique	LMSShift (*p*,W)	RGBShift (*p*,W)	Edges (*p*,W)	HSVShift (*p*,W)	LMSReduced (*p*,W)	Contrast (*p*,W)	Segmentation (*p*,W)	Hatching (*p*,W)
RGBShift	0.3025, 64.0	-	-	-	-	-	-	-
Edges	0.4438, 39.5	0.0732, 26.0	-	-	-	-	-	-
HSVShift	0.0002, 100	0.0004, 97.0	0.0002, 100	-	-	-	-	-
LMSReduced	0.0002, 98.5	0.0012, 93.0	0.0002, 98.5	0.1984, 33.0	-	-	-	-
Contrast	0.9077, 48.0	0.2147, 33.5	0.2837, 64.5	0.0001, 00.0	0.0002, 00.0	-	-	-
Segmentation	0.0019, 91.0	0.0119, 83.5	0.0012, 93.0	0.0252, 20.5	0.3561, 37.5	0.0010, 93.5	-	-
Hatching	0.0001, 100	0.0002, 99.5	0.0002, 100	0.2950, 63.5	0.0351, 77.5	0.0001, 100	0.0014, 91.5	-
Lustre	0.0468, 76.5	0.2081, 67.0	0.0122, 83.5	0.0189, 19.0	0.1469, 30.5	0.0378, 77.5	0.5379, 41.5	0.0015, 08.5

Table 2. Results for Wilcoxon signed rank tests between each technique. Grey results show significant effects after a Holm-Bonferroni correction ($p = 0.05$)

isolation. In fact, when only looking at the selected natural scenes we could not see these positive effects.

There is probably a good explanation for these results. Foremost, the Ishihara plates are designed to be extreme examples. Even those with mild forms of CVD usually struggle with correctly identifying those plates. Thus, it is encouraging to see that the techniques *LMSShift*, *RGBShift*, *LMSReduced*, *Segmentation*, *Lustre*, and *Edges*, performed well when considering Ishihara plates in isolation. Given that the overwhelming majority of our participants presented as mild cases, we argue that they had less problems with the natural scenes which is evident in the number of correct answers without any compensation technique. Thus, there is less opportunity for improvement. We saw further evidence by looking at the natural scene where participants struggled initially, where we could still see that they improved but the datapoints are too sparse for proper analysis. For example, we saw a change in the items identified in the identification task with one item ('e' in image one) only being identified by one participant unaided but identified by all but one under one or more of the compensation. A reduction in the subjective evaluations of techniques for milder cases of CVD has been previously reported [132].

Of the techniques that did not appear to have an effect on the user scores for Ishihara plates (*HSVShift*, *Contrast*, *Hatching*), we noted potential reasons for each. *HSVShift* represents one of the smallest colour shifts, and was one of the least obtrusive shifts indicating it may been under-tuned for Computational Glasses. Likewise, *Hatching* was considered to be amongst the least obtrusive and has a large parameter space that may warrant further exploration when used in Computational Glasses. Finally, *Contrast* was included for completeness and did not completely match the requirements of Computational Glasses, therefore custom intensity adjustments for Computational Glasses need to be developed before this avenue can be properly explored. That said, a further interesting point on the efficacy of these techniques is the application of *Lustre*, which proved to be an effective visual effect at compensating CVD on Ishihara plates. It must be noted that we did not formally verify whether binocular fusion was being avoided, in which case *Lustre* would have presented as an intensity shift.

When looking at the confidence scores we again saw the same techniques significantly affect the participants' confidence. This would indicate that using these algorithms enables participants to give correct answers with a higher confidence while being less confident in incorrect ones. Interestingly, whilst we do not see a significant effect for $HSVShift$ or *Contrast* in the success rate on Ishihara plates, we do see one in the confidence. This would indicate that whilst the techniques were unable to properly aid participants in reading the plates, they did reduce confidence on incorrect answers and increase confidence in correct ones. Lustre showed a significant effect in success however did not show one in confidence, indicating that whilst participants were able to better answer the plates, they were not more confident in presenting correct answers or less confident in presenting incorrect ones.

The final component of our results provided our second important finding from this study. When looking for an unobtrusive technique to compensate for CVD we found that reduced or image dependant colour shifts (*LMSReduced*, $Segmentation$) seemed to prove to be both effective on Ishihara plates and to have low obtrusion. Interestingly, $HSVShift$, whilst not being highly obtrusive, was ineffective on Ishihara plates, whilst colour effects such as $LMSShift$ and $RGBShift$ were effective but also rated amongst the most obtrusive. We take this to indicate that there exists a range in which colour shift techniques can be utilised to compensate for CVD over which they are effective, however, they must be appropriately tuned. We also saw the only visual effect (*Lustre*) implemented to show promising results in being effective whilst there being no evidence to support them being more obtrusive than the colour shifts, and so view this as a promising research direction. We reiterate again that this result may speak more to the promise of intensity adjustment, rather than that of the intended visual effect, as we did not verify we achieved a lustre. Furthermore, although not reported by our participants, the original work [22] observed that lustre could result in discomfort.

Overall, this study represents, so far as we are aware, the first time these methods have been tested for efficacy using the same test, and that all styles of CVD compensation (*Spectral, Intensity, Patterns, Visual Effects*) have been tested on the same test. Despite most works looking to create spectral based adjustment techniques, as we see several of them working, we also show other approaches are viable avenues for creating compensation techniques. We saw that pattern based techniques, although only in extreme cases, and visual effect techniques also worked. Intensity based techniques have been rarely explored and we saw no evidence that current approaches based on this are viable. As a further point we tested for first time *Contrast*, $Segmentation$, or $HSVShift$, which were not tested for efficacy when originally published. Of these techniques we found that only one of them proved to work as an aid in our Computational Glasses. Whilst this might not be the initially intended environment for these techniques, we believe it reinforces the need for techniques to be properly tested for efficacy using common tests.

We would note that $Segmentation$ provided little benefit when compared to other colour shifts, in particular *LMSReduced*, despite high performance costs and while still generating similar shifts. We would propose that for pervasive compensations, further developments in efficiency and effect should be investigated before $Segmentation$ can be utilised over a technique like *LMSReduced*.

In conclusion, our study into compensation techniques on Computational Glasses for CVD has shown several viable approaches that can be drawn from current literature ($LMSShift$, $RGBShift$, *LMSReduced*, *Segmentation*, and *Lustre*), and identified those of which were considered to be the least obtrusive and therefore most viable for long term use (*LMSReduced*, *Segmentation*, and *Lustre*). In doing so we have provided the first instance in which several of these techniques have been tested with CVD participants (*Contrast*, *Segmentation*, and *HSVShift*). We can see from our results research gaps in creating effective intensity based shifts, and a reiteration of the need to make techniques context aware and tailored to users. At the very least user control, as demonstrated in our prior studies, and shown by Jefferson et al. [56] is required to enable users to adapt compensations to their needs. Further research is needed into the efficacy of techniques in more natural settings with a larger, fresh pool of participants.

10 CONCLUSION AND FUTURE WORK

Prescription glasses have been used as a fashionable and simple way to correct for visual impairments caused by refractive issues. While glasses are widely socially accepted there remains a large number of visual impairments that cannot be fully corrected with traditional glasses or optics alone. In this work we showed the potential of utilising OSTHMDs traditionally used for Augmented Reality to create Computational Glasses that can compensate for one such impairment, Colour Vision Deficiency. In this work we provided a detailed view into our works including the developed prototypes and studies providing encouraging insights into this technology showing that this technology works and is effective. Our later studies also provided feedback on next steps that would be required to make this approach more mature including addressing latency and context awareness to support continuous usage.

Contribution 1 - Literature review:
Given the lack of surveys or meta-studies on techniques compensating CVD, we completed an exhaustive literature review. In doing so, we not only were able to compile a list of the techniques present, but also noted some limitations in the literature that we presented here. These include a lack of comparative studies allowing for the various techniques to be compared, either generally or within the given design space utilised by individual techniques. There is also a lack of a consistent, or even publicly available, dataset usable for testing and verifying techniques that extends beyond the highly tailored and unreal pseudo-isochromatic plates. Whilst we did not overcome the problems presented by these limitations in our subsequent studies as that was beyond the scope of this work, these current limitations are important to understanding some design decisions taken during our research. More importantly, we think the summary of related works is important for other researchers in the field.

Contribution 2 - Computational Glasses for compensating CVD:
We proposed the idea of utilizing Computational Glasses built on top of OSTHMDs, enabling a pixel precise compensation of the perception of colours in the environment, to aid CVD. Critical colours are identified in the camera view and the mapping from the camera to the semi-transparent display allows for those colours to be adjusted in the user's point of view. To demonstrate Computational Glasses we created a series of prototypes. These prototypes allowed for a varying trade-off between control of external factors and real-world applicability. An initial monocular benchtop prototype, where the user's view through the glasses, and therefore of the compensation, was mediated by a camera, allowed for complete control of the system. This meant that we could know exactly what the user was seeing and ensuring pixel precise compensation. This allowed for the removal of various confounding factors such as user-specific calibration errors, however, forced the world to be mediated by the camera, reducing the perception of the world to that facilitated by the camera. The second prototype we created was a stereoscopic setup that enabled users to look directly through the system while still being stationary. This removed the limitations of the camera when users viewed the compensation, allowing for proper interaction between the user's vision and the

compensation. However, it required user-specific calibrations, and removed the ability to know exactly what the user was seeing. The final prototype created was a portable prototype. Whilst tethered to a computer and limited by cable performance, this prototype enabled the testing of users that could freely move around and look where they desired. The prototype introduced issues that are likely to happen in the real world such as a more unstable calibration (because someone scratched their nose or moved the glasses) as well as issues that are caused by current hardware such as latency. It did however allow for exploration in a less restricted and more open space and shows the potential for miniaturisation similar to existing glasses.

Contribution 3 - Studies on CVD compensation using Computational Glasses: We provided a series of studies to prove the efficacy of Computational Glasses. These studies were overall positive. They showed the efficacy of the system in several prototypes, each compensating for different external parameters and with different participants. This contributed to the high internal validity of our findings.

3.1 Efficacy With the two efficacy studies we were able to show that using Computational Glasses significantly improved the ability of those with CVD to correctly read example material from a standard test in the form of Ishihara plates in regard to both success rate and confidence in answering. All techniques tested during our efficacy tests showed significant improvements and allowed participants to read the plates more confidently. We found the colour shifts tested to be more effective than outlining in this situation and saw further improvements in participant's scores when we allowed them to adjust the compensation to best allow themselves to read the plates. There was however no correlation between the shifts. We also showed that Computational Glasses were able to assist participants affected by CVD with default compensations and this effect could be further improved with user-customised compensations. The lack of statistically significant improvements on natural scene images in our final study indicates a need for further efficacy testing in more general scenarios but also reflects on a more general issue: The interpersonal differences in severity of CVD and strategies used to cope with CVD allows participants to deal with natural scenes better than with specific patterns developed to emphasise CVD. As such we do not think the lack of significance is a shortcoming of our Computational Glasses (as highlighted with the Ishihara plates) but reflects on the improved performance even without any compensation for CVD. Better datasets of natural scenes and long term usage of Computational Glasses in realistic environments would provide a more realistic picture of the performance in practical scenarios. Also a more focused recruitment of participants, e.g. screening for severe forms of CVD could have further improved the results for natural scenes. Finally, as we saw in our efficacy studies, individual improvements could be found by adjusting techniques to each participants optimal settings for each test plate. Without any evidence of consistency in optimisation this indicates a need for inter-personal, alongside situational and environmental, factors to be considered. Whilst the Computational Glasses demonstrated efficacy, compensation techniques still require further development regarding when to employ them and how they are optimised.

3.2 Comparisons Our findings showed that many developed techniques could be deployed on Computational Glasses, although issues arose when considering how well the techniques work on natural images, and the obtrusion of compensations as perceived by the participants. We also tested our approach against a current state-of-the-art device and found Computational Glasses performed on par, if not better than, the comparison.

To Google Glass: When comparing our system with an off-axis display that shows a compensated image we found that directly compensating the scene did not result in an increased workload and in cases where participants had to distinguish between small details even required less mental demand, once again highlighting its potential for spontaneous or even potentially uninterrupted continuous use. We did not find significant differences in the usability between corrections by

Computational Glasses and Google Glass, which we hypothesised due to the fact we had to modify the content shown on the Google Glass to make it more accessible, and that such a system allowed retention of personal cues used to differentiate colours whilst participants had limited time with Computational Glasses to learn the new ones. If participants had to zoom in manually or could use it only with objects held in their hand the results could have been different. An alternative explanation for there being no significant difference between the two conditions can be found in our final study. There we saw that the compensation used did not in fact provide statistically significant assistance on the natural images, only being assistive in anecdotal cases, and therefore it may have increased the workload and hindered usability when not providing significant benefit.

Techniques: We explored existing compensation techniques addressing CVD for their suitability to be applied within Computational Glasses and eventually context-aware Computational Glasses. In general we found most techniques applying a spectral shift perform well. This is also true for the technique using a visual effect (Luster effect). However, as previously pointed out we saw the biggest gains mainly in extreme scenarios such as all the Ishihara plates. Expanding on the lack-of notable gains on natural images, we attribute much of this to our participant pool, and the smaller opportunity for improvement. However, many of these techniques have been demonstrated to work previously, including in our own studies. This disparity in results further highlights the need for natural image datasets for CVD research that show realistic everyday issues for people affected by CVD that are also validated. Many of the purposed techniques in literature rely on spectral shifts or have significant impact on the original scene. This is fine in extreme cases, and when the semantic meaning of colours is not required, however produces issues in more natural scenes. Techniques also rely on implicit understanding of compensations, such as the angles of hatching patterns. Further research is needed optimizing effectiveness together with minimal obtrusion.

3.3 Portability We also conducted an exploratory study with our portable prototype showing the potential for Computational Glasses to be extended beyond the restricted lab prototypes previously used. Whilst the results of this study were intentionally of a qualitative and exploratory character, we still saw similar effects of the compensation on the participant's ability to discern previously indiscernible colours. Viewing pseudo-isochromatic plates was greatly assisted, whilst other images saw lesser effects. Latency was still a problem with the portable prototype, exacerbated by having the prototype tethered to a desktop computer. The primary component of this study was the qualitative data given by participants about the desire to correct for CVD and how it affects their live. To this end we received very positive feedback to the notion of compensating for CVD with devices with a form factor similar to glasses, a feature of Computational Glasses. We also produced further findings regarding how those affected by CVD view its effects on their lives and who might benefit from assistive technologies. Further points raised show the need for customised, application cognisant compensations.

10.1 Limitations

Several limitations for this research should be mentioned.

Lab prototypes: Although we tested with varying prototypes which were increasingly closer to a real-world device, we only tested Computational Glasses within static environments so it remains to be explored whether our findings can be replicated in dynamic scenarios, e.g., while driving or walking down a street. Nevertheless, if latency is minimized we are confident that Computational Glasses could be used in these scenarios as well as we did not restrict the participant's head movement in our evaluation with the portable prototype. Deploying Computational Glasses in daily life would require advances not only in the form factor, weight, and battery life of the device, but also with respect to lower camera latency [51] and integration into an untethered version of the system. As such, the developed prototypes are still not viable for longer term everyday use with problems such as size and comfort, as well as with currently remaining tethered to a static computer rather than a mobile computing unit.

Number of participants: We managed to recruit between 10-19 participants for each study which can be considered as a limited sample size. However, we must mentioned that we were limited here by the general prevalence of CVD that is between 5-10% of the male population. Additionally, we observed a general hesitation of acknowledging any form of impairments which can be easily explained by prior experiences such as those mentioned during study interviews. Anecdotally, we had to personally talk to more than 1200 students (visiting their lectures) in addition to university-wide advertisement via email to recruit the participants for the first two studies demonstrating the practical hurdles. Furthermore, whilst targeted towards general CVD, we limited participants to those with less sensitivity in the red-green spectrum of CVD as this represents the vast majority of cases (we accepted more rarer forms of CVD into the study but did not use them when reporting on the study, only using them for their exploratory feedback). It should still be emphasized that to our knowledge, our studies are among the largest exploring compensating techniques of CVD. Lastly, as we repeated similar studies with mostly different cohorts and prototypes, we think we further increased internal validity beyond what the numbers of individual studies indicate.

Limited exposure time: While we performed an initial exploration of potential situations where participants could benefit from the system, and postulated its long-term use, we did not deploy it over a long duration to explore how users would utilize it in daily situations.

Specific CVD calibrations: Throughout our work we did not look to fully diagnose participants, nor look to explore the various CVD simulation calibration techniques so utilised the simpler, and computationally efficient simulations provided by Brettel et al. [13].

10.2 Future Work

There are various potential areas of research that could be explored building on from this research.

Further miniaturisation/mobilisation: From a practical position, whilst we showed first steps towards a mobilised and fully functional prototype, further work towards a fully portable and longer-term deployable prototype is needed. Doing so would help evaluate techniques in more realistic scenarios and longitudinal studies, improving generalisability of the research. It would also help to further research in the general field of providing vision augmentations. Here we hope in particular to benefit from industry efforts in miniaturising and improving OSTHMDs used for AR.

Creation of a dataset: As noted several times, a comprehensive dataset for testing compensations still needs to be created. We saw in our final study that compensation techniques struggled to provide notable assistance on the natural scene images. We believe this to be due to the limited room for improvement on these images for our participants. In order to better develop and tune compensations techniques such that they might provide assistance in such scenarios, a finely tuned and verified dataset is needed to enable evaluation of techniques as to their applicability to the real world.

Comprehensive comparisons: Whilst we looked at various kinds of techniques to be applied on the Computational Glasses, a more comprehensive set of comparisons between the techniques on some of the various metrics supplied, such as maintaining naturalness, efficiency, or effectiveness, would better enable future works to draw on prior studies when looking to create new and improved compensations for CVD.

Context awareness and continuous use: On the note of improved compensations, during our research we clearly see a need for further development of context aware techniques for compensation. As evidenced by our portable and comparison study, introducing context awareness to the system should improve generalisability and use in real-world scenarios. However, this remains an emerging research topic even in the field of AR [35] but the use of these devices as vision aid demonstrates the need for it. An adaptive user interface is one that "remains well designed even as its world changes" [14] . For Computational Glasses to be use in a generalised scenario of continuous use they need to provide such an adaptive interface, enabling them to adjust to the needs of the user. A simple solution to the need for adaptation in algorithms is to provide simple user control (adaptability) [35]. As mentioned in the related work, several papers have covered the introduction of adaptable parameters for techniques [56, 70]. In our own studies we also saw the advantages that this could provide. Enabling users to adjust compensation degrees, styles, and enable/disable compensations (particularly if other assistive aids are also to be provided on the Computational Glasses) as desired would help alleviate the aforementioned issues. This does however place the onus of use on the user. As with the use of phones to aid CVD this produces problems for a constant persistive aid and requires users to know when they require assistant, even when their needs preclude them from knowing so. As such, we believe that ultimately a context aware solution for Computational Glasses that adjusts the interface implicitly (adaptivity) [35], whilst still allowing for adaptability by the user, is needed.

Individual vs combination techniques: Another largely unexplored component of the field is the ability to utilise multiple styles of compensation such as patterns and colour shifts to enable better compensations in conjunction with utilising different styles within different contexts. As noted by the participants in our explorative evaluation, some wanted stronger shifts on the plate whilst also asking for different styles of shift on the rest to reduce obtrusion.

User-specific compensation: To reduce the potential impact of poor personal calibrations for simulations and compensation levels we largely looked to avoid this throughout our research. This allowed us to ensure that all participants were exposed to the same conditions, allowed for easier replication of our studies and results, and avoided the need to individually optimise everything without a baseline to optimise against. However, as noted in our efficacy studies, individualisation of compensations does have an effect on the results of compensations and furthermore CVD is inherently variable between people so adjusting simulations to suit individuals may change the results. How best to individualise masks/simulations and produce tuned parameters for individual preferences and requirements is still an open and interesting area of exploration, although some works have made inroads in this direction.

Exploration of simulations: As a final note, alongside user-specific compensations, there is a need for an exploration of simulations and tailoring these to the user's condition, the situation the user is in, and the compensation being used. For our studies we stuck with the simplest forms of simulation to ensure real-time operation and to prevent a confounding variable.

In summary, we believe in the potential for Computational Glasses to be used as visual aids for CVD by compensating the view of users with augmentations. Whilst further work is needed for long term use, our results show promise. We saw that the Computational Glasses could assist those with CVD, however saw issues with the compensation of natural scenes where improvements were not apparent. Given the generic settings used for our compensations and the limited dataset available for testing natural scenes, we firmly believe that the creation of tailored, user-specific, adaptive, compensations evaluated using a comprehensive dataset is needed to alleviate these issues. This research has strong implications for the ability of Computational Glasses and Augmented Reality to further aid human vision and we would even go so far as to indicate implications for amplification of unimpaired vision, or contribute to an Augmented Human with real-time compensations based on image analysis providing additional visual information.

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