30 Years of Solving the Wrong Problem: How Recolouring Tool Design Fails those with Colour Vision Deficiency

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ABSTRACT

By far the most available assistive tool to assist people with Colour Vision Deficiency (CVD) is recolouring. However, despite over three decades of research designing and developing recolouring tools, no work yet has looked to understand how these tools are actually used or perceived by people with CVD. To address this, we first analyzed posts and comments from the r/colorblind subreddit in order to get an unconstrained understanding of the perspectives people with CVD have on recolouring tools. We then conducted an observation study with follow-on interview to further understand how people with CVD use and perceive these tools in a more controlled setting. Our findings suggest that recolouring tools are rarely used how their designers intended and that a better future solution is to design with true inclusivity by solving the actual problems people with CVD have, rather than attempting to 'fix' CVD.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility**.

KEYWORDS

Colour Vision Deficiency, Recolouring, Colour Filter, Daltonization

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1 INTRODUCTION

For over thirty years, researchers, designers, developers, and even those who have Colour Vision Deficiency (CVD) have been designing and developing *recolouring tools* (also called *recolouring filters or colour filters*) in an effort to assist those with CVD. A wide variety of recolouring tools have been developed with different goals and with differing implementations. Perhaps the most available recolouring tools are the macOS [1] and iOS [2] colour filters, the Android [20] colour correction filter, and the Windows [40] colour filter.

Over these 30 years, three requirements for creating 'optimal' recolouring tools for those with CVD have become dominant: 1) Maintaining Colour *Naturalness*, 2) Maintaining Colour *Consistency*, and 3) Enhancing Colour *Contrast* [46]. In the pursuit of these requirements, researchers often conduct evaluations that rely solely on the author's judgement, quantitative formulas representing colour differences, CVD diagnostic tests, or ranking of images by those with CVD [60]. Unfortunately, these popular approaches largely prevent the researchers from truly understanding how these tools are used and perceived by those with CVD, as they do not actively engage people with CVD in open-ended dialogue.

A very limited number of studies have involved CVD participants to help understand how recolouring tools affect the aesthetics of websites [9, 16], understanding the usability of websites with the Windows 10 colour filter [43], with more recent research investigating CVD participant thoughts on recolouring via computational glasses [52]. However, a major limitation of this research is that it relies on unstated assumptions about how the recolouring tool will be used (i.e., always-on), leading to a lack of understanding in how people with CVD generally feel about recolouring tools.

To address this lack of understanding of the perspectives people with CVD have on recolouring tools, we first looked to investigate posts and comments from r/colorblind relating to recolouring tools. We intentionally started with a public social group like r/colorblind so that we could understand the broad perspectives on recolouring tools that people with CVD have in a setting we had no influence over. We then used this understanding we gained from r/colorblind to inform an observation study with follow-on interview where we could more deeply investigate how those with CVD use recolouring tools to perform colour-related tasks, thereby shedding light on the perspectives those with CVD have on recolouring tools.

Overall our findings advise against the idea that a recolouring tool can be used in a pervasive way to passively and constantly correct colour difficulties for those with CVD. Both our r/colorblind study and our follow-on study indicate that recolouring tools make colours unusual and ugly to people with CVD and that recolouring tools cannot address all colour-related challenges they experience.

However, while we do uncover many shortcomings of recolouring tools, we still believe that recolouring can assist people with CVD. As we found in both our analysis of r/colorblind and in our observation study, those with CVD have developed strategies for more effectively using recolouring tools. For instance, many r/colorblind posters and commenters described that they 'toggle' their recolouring tools on and off, and in our observation study, we saw that

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participants would use information from all states (on/off and different recolouring tool modes) in order to make informed opinions based on how they believed colours were transformed during recolouring.

Finally, we argue that if future research is to genuinely progress in creating assistive tools (i.e., recolouring tools) for those with CVD, more honest effort must be made to truly involve them in this research. Furthermore, this involvement needs to go beyond just using their eyes to 'prove' the effectiveness or aesthetics of a method. We do believe that the current shortcomings and misconceptions of recolouring tools are a direct result of the large body of research in this area that has historically avoided open-ended dialogue with those with CVD in favour of less-demanding evaluation methods (e.g., CVD simulations) due to apparent reluctance to recruit CVD participants.

This paper makes the following three contributions: First we contribute a thematic analysis of posts and comments on recolouring tools collected from r/colorblind. Second, we contribute a thematic analysis of a follow-on observation and interview study with 21 participants with CVD to more deeply understand how they use and perceive recolouring tools. Third, we provide direction on how future research and design can genuinely assist those with CVD.

2 RELATED WORK

2.1 Colour Vision Deficiency

We owe our colour vision to three retinal cone cells (or cones) in our eyes, each of which is sensitive to different wavelengths of light. Each cone is typically classified by the wavelength it is most sensitive to, giving Long (L or Red), Medium (M or Green), and Short (S or Blue) wavelength-sensitive cones [7]. The presence of three cones defines human colour vision as trichromatic (or three-dimensional). However, if one (or more) cones is missing or has an irregular sensitivity, it results in Colour Vision Deficiency (CVD) [3]. There are varying classifications of CVD based on which cone(s) is/are affected and how many cones are affected.

When one cone type has an irregular sensitivity, anomalous trichromacy results, leading to a diminished perception of colour. Dichromacy is when one cone type is missing, resulting in the loss of one of the three dimensions of trichromatic vision. For anomalous trichromacy and dichromacy, CVD types can be further classified by the cone that is affected: protanomaly or protanopia for the the L cone, deutranomaly or deutranopia for the M cone, and tritanomaly or tritanopia for the S cone. When referring to anomalous and dichromatic CVD types, we will shorten the name to mostly focus on the cone affected (e.g., Protan for referring to individuals with an affected L cone). Finally, if two or three cones are missing, this results in monochromacy or achromatopsia (respectively) - the complete loss of chromatic vision.

2.2 Recolouring

The most popular assistive tools developed in an effort to assist people with CVD are recolouring tools. Recolouring tools have been developed and proposed within academia, by industry, and by members of the community at large, with tools often released on app stores. A recolouring tool is any filter that remaps colours in such a way as to assist people with CVD to detect colour differences they would have been unable to see otherwise. Recolouring tools are typically designed to adjust all colours on a screen (i.e., full-screen) and to be constantly on and 'correcting' the vision of someone with CVD (i.e., always-on).

Recolouring methods usually employ CVD simulation models to identify confusing colours that are then altered (recoloured, e.g., by shifting some hues) in an attempt to remove the confusion. Recolouring can make coloured content more differentiable, but can also result in original colours being mapped to new, differently-named colours, thus introducing new difficulties. As a result, alternatives to recolouring have also been proposed (see Section 2.3).

2.2.1 Academic. A variety of recolouring tools have been developed and published in academia. Often considered to be the first work in the space of recolouring tools, Meyer and Greenberg [39] proposed that the colours presented on a monitor could be shifted perpendicular to confusion lines to improve colour differentiation for people with CVD. Rasche et al. [45] developed the first method that utilized a simulation as a mask to determine specific problematic colours in an image that would then be adjusted. Jefferson and Harvey created a recolouring method that attempted to maintain colour difference values when making adjustments [31] and an interface to enable real-time colour adjustments for users with CVD [32].

SmartColor [56] allowed a designer to annotate the intentions of colours and then adjusted the colours to improve accessibility for people with CVD while retaining each colour's intended effect. Kuhn et al. [33] developed the first recolouring method that attempted to maintain the 'naturalness' of the image. Huang et al. [27] created a rotation-based recolouring method that features parameters to control the amount of the rotation. SSMRecolor [14] was a recolouring method that required users to complete a calibration process that was used to create a custom recolour mapping for each user based on their type and severity of CVD under their specific viewing conditions.

Hassan and Paramesran [22] created a method that attempts to maintain the naturalness of the image by only adjusting the chromaticity of the colours. Tseukouras et al. [55] created a method that utilizes fuzzy clustering to extract key colours and then makes ranked adjustments to colours determined to be confused via confusion lines. Zhu et al. [61] created a method that attempted to personalize a recolouring tool to an individual based on the CVD simulation method developed by Machado et al. [38].

2.2.2 Commercial and Community. Many commercial recolouring tools have been developed for all major platforms. Microsoft offers a recolouring tool for the Windows operating system [40] that includes three filters, one each for protan, deutan, and tritan CVD types. Apple also has recolouring tools in both its iOS phone [2] and on the MacOS computer [1]. Apple offers filters for protan, deutan, and tritan CVD types, but unlike the Windows filter it also offers a severity slider to increase or decrease the strength of the filter. Finally, Android also includes a recolouring tool [20] that, similar to iOS's filter, provides options for protan, deutan and tritan CVD types and also features a severity slider.

Community recolouring tools have also been developed by the community and also (somewhat infrequently) by people with

Colour Vision Deficiency in an effort to provide assistance. Daltonize.org [8] developed an open source recolouring tool that looks to provide assistance by adjusting all the colours on the screen to reduce confusion colours. Dalton-Bot [25] is an open source recolouring tool that provides assistance to Reddit users, and is often used on the r/colorblind subreddit by commenting 'u/Dalton-Bot' to recolour a posted image.

2.3 Alternatives to Recolouring

Techniques have been developed that look to overcome recolouring's limitation of transforming colours to potentially unknown colours. One common alternative makes use of pattern overlays, in which symbols are overlayed on an image to communicate the colour underlying each symbol. Overlay patterns can map each colour to lines representing that colour's hue angle [15, 48], or provide an analogy to the underlying colour using symbols [18]. Other methods use a visual effect to communicate colour to a user by highlighting a chosen colour [15], varying the amount of perceived lustre for confusing colours to make them differentiable [24], or producing a lightness difference between confused colours [37, 51].

There are also assistive tools that provide multiple methods (including recolouring) to try to help with a larger variety of colour-related tasks than just recolouring can handle. Chroma [54] is a Google Glass app that provides recolouring, outlining specified colours, and highlighting colours by name. ChromaGlasses [34] investigated how computational glasses could be used to assist those with CVD using similar techniques as Chroma. DaltonLens [5] is a desktop colour identification tool that provides a colour namer, recolouring, colour highlighting, and customized recolouring via user-directed colour property adjustments. ColourBlind Pal [13] features a pattern overlay for one user-selected hue value, user-selected popout via hue values, and a recolouring option in its 'filtering' mode, plus a colour picker in its 'inspecting' mode.

In spite of these attempts at providing alternatives, recolouring tools still dominate the academic landscape; from 2018-2022 (by our count) there were 56 recolouring papers published[1], but only four papers published that developed alternative techniques [12, 18, 21, 37].

2.4 Evaluation of Recolouring Tools

When evaluating recolouring tools, three general requirements have been suggested for creating optimal results [46]:

(1) *Colour Naturalness*: Recoloured colours must retain a natural appearance.
(2) *Colour Consistency*: All colours of the same original hue must be recoloured consistently.
(3) *Colour Contrast*: Recoloured colours must have enhanced contrast for an individual with CVD.

Below we summarize and categorize the most common approaches taken to evaluate recolouring tools, usually to satisfy the three goals mentioned above. We note that authors will sometimes combine the methods below to show the effectiveness of their technique.

[1]List available in supplementary material.

2.4.1 Author Judgement and Automatic Formulas. One way researchers evaluate recolouring tools is simply by qualitative assessment of how their recolouring method assists people with CVD by using CVD simulations [10, 27, 28, 41, 45, 47, 53, 58–61]. Authors do this by describing how their method satisfies the three requirements listed above or by visually comparing their method to existing methods.

Another common way of determining whether these requirements have been satisfied is via quantitative formulas that measure Euclidean distance (typically in a perceptually uniform colour space like CIE L*a*b* or L*u*v* [57]) between image pixel colours. For colour naturalness, the Euclidean distance is often calculated between corresponding pixels in the simulated original and the simulated recoloured images (or between the original and recoloured images), with the goal of *minimizing* the sum of all such distances (e.g., [23, 27, 47, 49, 60, 61]). For colour contrast, the same distances are calculated but with the goal of *maximizing* the resulting sum (e.g., [23, 60, 61]). More details on using such formulas for recolouring tool evaluation can be found in [60].

2.4.2 Diagnostic Tests and Image Ranking. Diagnostic tests such as the Ishihara Plate Test [30] and the FM-100 Hue Test [11] are also commonly used when determining the effectiveness of a recolouring tool. Evaluations using Ishihara Plates tend to be the most common, typically showing that the proposed recolouring tool makes the underlying (usually invisible to people with CVD) number visible under CVD simulation. However, there are some studies that have recruited participants with CVD to conduct a user study with the use of the Ishihara Plate Test (e.g., [32, 34, 49, 61]). Studies using the FM-100 (e.g., [61]) or other diagnostic tests are more rare, but they are usually conducted with the recruitment of participants with CVD and attempt to show that error scores are decreased when using the recolouring tool.

Finally, another common method used in the evaluation of recolouring tools is natural image interpretation, which requires those with CVD to rank several images generated using different (often competing) recolouring algorithms, based on which looks the 'best' (e.g., [29, 35, 36, 42, 49, 58, 61]).

2.4.3 Conducting Studies with CVD participants. Unfortunately a rather unsettling observation of many of these evaluations is that those with CVD often do not get included in the evaluation. Sutton et al. [52] highlights that only 57 of the total 101 papers they reviewed have actually conducted research with CVD participants with only 29 of those having a participant count greater than 10. Furthermore, Sutton et al. [52], in reviewing the types of user studies conducted, state that *only four papers reported any user feedback*, showing the clear lack of attention given to the experience of those with CVD in using an assistive tool to assist them. This, along with the most popular methods of recolouring tool evaluation outlined above, highlights how current research has missed the opportunity to understand how those with CVD use recolouring tools and their perspectives of them.

2.5 Research Questions

Despite decades of research looking to develop better recolouring tools, to date there has been very little research that seeks to

formally understand how those with CVD use recolouring tools. As such, we started with an intentionally broad research question (RQ1): "Does the current design of recolouring tools support people with CVD?", which guided our analysis of the data we collected from r/colorblind. After uncovering the broad stroke opinions on recolouring tools from r/colorblind posts and comments, we focused on two specific questions in follow-on observation study and interview (RQ2): "How do people with CVD actually use recolouring to solve a variety of colour-related tasks?", and (RQ3): "What opinions do people with CVD have on the design of recolouring tools?".

3 R/COLORBLIND STUDY METHODS

To get an initial understanding of perceptions and uses of recolouring tools by people with CVD, we scraped posts and comments from Reddit. This enabled us to understand opinions and potential methods of use in a way that would minimize researcher influence while including a wide variety of responses.

3.1 Data Collection

We used the search functionality of PRAW (Python Reddit API Wrapper) to obtain r/colorblind (a group predominantly populated by members with CVD) content relating to recolouring tools. As the most commonly used recolouring tools (i.e., Windows, Apple, and Android), all feature the term 'filter', we used the query term 'filter' & 'recolor'. We performed an initial query on June 15th 2022, which we scanned to ensure our search query terms were valid, and a second query on August 13th 2022 to capture up-to-date posts and comments for full analysis. We obtained a total of 235 posts and 1442 comments and recorded the post title, post body text, and the top level comments for each query result.

3.2 Analysis

To analyze our data collected from r/colorblind, we used Braun and Clarke's thematic analysis approach [4]. We first combined all post titles, posts, and comments into a single text document using a custom Python script (available in our supplementary materials). The first author then read the entire file to familiarize themselves with the data. The first author then reread the file again while identifying and assigning initial codes relevant to RQ1. Once this was complete, the first author copied all initial codes and their corresponding r/colorblind data into an Excel spreadsheet for further refinement.

Identifying redundant initial codes in the spreadsheet, the first author then reduced the number of codes by combining them by similar use, which also helped form initial definitions for each code. Finally, after refining the definitions for our final codes, the first author grouped and categorized codes and definitions into themes and subthemes, again using Excel. When grouping and categorizing the codes the first author checked with the second author to discuss whether the developing themes adequately covered all generated codes. Once the thematic map stabilized, all authors double-checked the map to ensure it sufficiently covered and captured the final codes. We do note that, although the first author did most of the thematic analysis alone, Braun and Clarke do not call for multiple coders or endorse inter-rater reliability measures for a good thematic analysis [4].

3.3 Ethical Considerations

Given recent discussions on data collection involving social media groups such as Reddit [44], we opted to paraphrase all quotes that we include below in support of our themes. Furthermore, we also chose not to include coded posts and comments in our supplementary material, opting instead to provide the python code we used to obtain our data.

4 R/COLORBLIND STUDY FINDINGS

We identified two major themes that help answer RQ1: 1) Frustrations and Benefits of Recolouring, and 2) Unique Strategies of Use. We will now discuss the narrative surrounding each theme.

4.1 Frustration and Benefits of Recolouring

Across the posts and comments, there were both negative and positive opinions towards recolouring tools. The negative opinions are best captured by our subthemes 'Filters create new problems' and 'Full screen filters look ugly'. Positive opinions are represented by the single subtheme 'Only change what matters'.

4.1.1 Filters create new problems. It is interesting that posters and commenters reported that they experienced new problems in differentiating colours using recolouring tools. This seems counterintuitive for a filter specifically designed to improve colour differentiability. One poster reported:

> " Are these color filters meant to help or not? I've used color filters on all my devices, and I've noticed it causes me to make a lot more mistakes in naming colours. Like I feel I confuse colors now because I lost a bit of my previous perspective of colors, no matter how inaccurate I was before."

From this post we can see that the colour filter changed colours so much that it affected the poster's knowledge of how specific colours should appear. Another similar comment described the importance of objects retaining their natural colour:

> "[...] Colors should not be remapped. By remapping colors you are changing how we normally see things. If you make reds and greens easier to tell apart by remapping them, I can now tell grass from fire much easier. But grass is no longer colored like grass and fire is no longer colored like fire. What should be done is understand the specific issues causing confusion and fix those. [...]"

As can be taken from this post, filtering or adjusting all colours changes how those with CVD see the world but not necessarily for the better. This highlights the (false) assumption that the ability to differentiate colours is more important than seeing colours naturally. Another very important issue is also raised – that the specific problem(s) encountered by someone with CVD should be addressed, and not by applying a generic filter to the entire interface (see Section 4.1.3).

4.1.2 Full screen filters look ugly. There were also very frequent posts and comments describing how recolouring tools made an image, the real world, or a game look 'icky', 'ugly', or even 'unnatural' as highlighted by this post:

> "Am I the only one that hates colourblind filters? Often I see a game or program that tries to assist the colourblind by adjusting the colours of the entire image to try to help. I really don't like them, they may help with identifications, but they make the entire image gross. I played this game once I think it was a Call of Duty, and it had a colourblind option, but it was so distractingly ugly to look at that I had to turn it off. [...] "

We can see that even if a filter assists with colour differentiation, that filters must consider the effect they have on how users perceive the content that is being filtered.

4.1.3 Only change what matters. Posters and commenters expressed a great deal of frustration towards interfaces and games that employ all-or-nothing full-screen recolouring tools. Many described how they wished that they were given the ability to change key colours or core UI components in the game instead of a filter that arbitrarily changed all colours to unusual or unnatural colours:

> " Colour filters can be useful if only applied to the UI, such as changing the colour for the typically green (ally) and red (foe) markers. But too often a blanket filter is applied over the whole screen. I still want to see the world as I would normally see it, but what I want is for the UI to be as usable to me as for non-colorblind people. That's all I need. "

This commenter described how they only want UI components to be corrected – versus modifying the entire screen – as the broader approach adjusts coloured components that do not pose any problems. Another commenter described the specific assistance they would like to see in games:

> "Give us the ability to customise everything. If a game uses item rarity do things like making the frame of the item different. Like different line outlines for each rarity. If thats not possible, tell us the rarity when we hover over it. Provide a name for all colours if there is colour customisation for items/clothing. Avoid colouring buttons in important puzzles, use stuff like different shapes instead. Essentially it should be playable in greyscale. "

A commenter to a post on colour filters highlighted some benefits of adjusting colours through a specific example that showed the idea that colour filters do not have to be full screen to provide assistance (i.e., limited recolouring):

> "I tend to avoid them [colour filters]. But, a game I play called World of Tanks, has a good colour blind option. When you use it, it changes the enemy outlines from red to blue, which for me makes it easier to see [...]."

What we can take from this comment is that there is benefit to be had from recolouring, just not necessarily full-screen recolouring. What this also highlights is that colours need to be carefully chosen for software that is complex, such as games. Those with CVD should be able to experience the same intent as those without, and it should never be about just applying the latest filter 'proven' to solve the Ishihara Plate Test. Colours need to be carefully chosen, and if user interface components are important they need to be easily differentiable. Also, as the second quote above highlighted, it is not required that colours be adjusted to improve their differentiability, as alternative assistance (such as outline thickness or colour names) can be added instead.

4.2 Unique Strategies of Use

We also saw many examples of those with CVD either: 1) Applying strategies to more effectively use a full-screen filter, or 2) Developing unique solutions to assist them in determining colours. We discuss the narratives around those two subthemes below.

4.2.1 Strategies to more effectively use full-screen recolouring. Many posters and commenters discussed shortcut options to quickly toggle full screen filters on and off – an interesting use case that was not immediately obvious:

> " [...] That's exactly why I don't leave my filter on, as games and videos would just look odd. I am very grateful for the shortcut option for when I am looking at an image and need to quickly interpret it. I would say if you can switch the filter on and off on a colored image and not see the difference, that you are using the wrong filter. "

This poster discussed how they would never leave a filter on, which goes against the common design goal many researchers are pushing towards with recolouring tools – always-on filters. Many publications feature either devices (e.g., smartglasses) or algorithms that were purposefully designed with the goal of fully replacing the vision of an individual with CVD. However, it seems that these same filters should instead be extended to allow quickly toggling filters on and off to help CVD users find colour differences:

> "I have the accessibility shortcut set up on my iphone (triple tap home button), and only apply it when I need it. Most of the time its off, but as a deutan it can help for some of the colors I confuse. But, I wouldn't use it all the time, since I don't know what the "new" colors are. [...] "

This comment again highlights the benefit of the on and off shortcut functionality for toggling a recolouring tool. This commenter described how they leave it off most the time and only turn it on when they need assistance, and not using it all the time due to the colours looking different to them under that filter. It seems that this individual would rather see colours as they have always seen them rather than have the filter replacing their vision, and only employs the filter for quick colour differentiation problems. Another commenter described this same idea of only using the filter when they need it, but adds another interesting insight that the filter designed for their specific CVD type was not ideal for them:

> " When I am having difficulty telling colours apart, what works best for me is to utilize the windows colourblind filter. Oddly, I found that the protan filter works better for me, even though I am a deutan type colorblind. "

This idea that users were using filters not specifically designed for their CVD was seen in several other posts as well:

> " Using the tritan filter doesn't adjust things to an unnatural colouring. Unfortunately, it doesn't allow me to pass colorblind tests and I'm still diagnosed as a protanope. "

This user discussed how a filter not designed for them assisted them better than a filter specifically designed for them, despite the drawback of not being able to pass a CVD test (e.g., Ishihara Plate Test). As mentioned in Section 2.4 many recolouring tools are specifically designed to pass a CVD test like the Ishihara Plate Test as this is often seen as the gold standard in 'curing' CVD. Unfortunately, tests like the Ishihara Plate Test do not present sufficiently realistic scenarios to show that adequate real-world assistance can be provided to people with CVD via recolouring.

4.2.2 Unique solutions for determining colours. Solutions and techniques have been developed by CVD individuals from r/colorblind that have a similar functionality or purpose to a filter. The first is from a commenter that describes a unique solution once again highlighting the idea of a quick shortcut filter to tell the difference in colour:

> "[...] Being able to temporarily disable all red pixels by pressing a button, so that all red stuff becomes black, and all green stuff could stay green would make telling the difference easier. Adjusting a 3-color wheel can give alot of options to mess with, but a single option to toggle red pixels would essentially solve all digital color problems for us. [...] "

This describes how minimizing the colour in a different way as opposed to remapping could be useful. This would allow for a new way to differentiate red and green shades. Another method is described that takes inspiration from earlier CVD glasses:

> "I prefer the ability to tint the screen over the filter. It doesn't look as nice when its on, but it helps me more in differentiating colors. "

4.3 Discussion of Findings

Through our analysis of posts and comments from r/colorblind, we believe that we managed to get a general idea of how well recolouring tools assist people with CVD (RQ1). We saw a variety of perspectives that were more often negative towards recolouring tools (but there were some positive opinions as well), a variety of alternative design ideas to recolouring (e.g., only recolour UI elements, using shapes or labels to identify colours), and learned adaptions that people with CVD applied to recolouring tools in order to make the filter work for them.

However, these results were collected from r/colorblind so they only represent issues and problems that recolouring tool users deemed severe enough to be worth reporting. It is also possible that some uses of colour are simply underreported, as we had no control over the stimuli that led to these reports. As such, we opted to further investigate these insights in a controlled observation study using specifically designed colour tasks. We designed our observation study after identifying the themes outlined above, so we focused on two additional research questions (as informed by these results): RQ2) How do people with CVD actually use recolouring tools to solve a variety of colour-related tasks?, and RQ3) What opinions do people with CVD have on the design of recolouring tools?

5 OBSERVATION STUDY & INTERVIEW DESIGN

We used the results from our r/colorblind investigation to help inform a follow-on observation study and interview, which were approved by our institutional Research Ethics Board.

5.1 Materials, Procedure, and Participants

We recruited participants from Facebook and Reddit (including r/colorblind, however no participants would have known about our initial study) via a screening questionnaire. Our questionnaire gathered screening (CVD and 18+) and demographic details, and participant availability to help with scheduling. No incentive was offered for completing the screening questionnaire, however, participants in the observation study and interview received a $50 (CAD) Amazon gift card. We conducted the observation study and interview over Zoom and recorded each session after obtaining participant consent. The mean recording length was 51 minutes (min: 25, max: 76). Table 1 summarizes the self-reported demographic details for our observation study and interview participants.

5.1.1 Observation Study Details. We employed a 2015 Lenovo T450s running Windows 10 for the main Zoom host, as we incidentally found in our r/colorblind study that the Windows 10 colour filter is one of the most commonly used recolouring tools. We also chose the Windows 10 colour filter because it is applied to the entire screen ('full-screen'), and appears designed to: 1) be 'always-on', 2) maintain naturalness, 3) maintain consistency, and 4) enhance contrast, aligning with design goals common to most recolouring tools (as outlined in Section 2.4). We also joined each call with a 2019 MacBook Pro 16" running OSX 11.4 to verify that the recolouring tool was functioning properly over Zoom. Participants directly controlled the recolouring tool via Zoom's 'Remote Control' feature, however seven participants were unable to use this feature due to them being on mobile or latency issues. In these cases, participants provided verbal instructions that we followed directly (e.g., 'turn filter on/off').

Using Zoom's 'Share Screen' and 'Remote Control' features, each participant worked through the same slide show featuring 14 colour-related tasks (one per slide), each pairing a single image (e.g. a picture of a towel) with a task (e.g., determine the colour of the towel). We created our tasks such that four required naming the colour of a single coloured object, two required naming all colours present, four required colour differentiation (e.g., Are colours the same or different?), and four required determining a specific colour-based characteristic (e.g., Is the banana ripe?). These four colour task types follow recent advances in evaluating recolouring tool alternatives [17, 18].

Prior to the 14 slides described above, each participant completed four training slides (Figure 1, top row), one illustrating each task type. Participants did not use the Windows colour filter during training so they could become familiar with the study colour tasks themselves. We then demonstrated how to use the Windows

ID	Gender	Age Range	CVD Type	CVD Severity	Used Recolouring	Frequency of Recolouring Use	Remote Control
Pilot1	Male	35-44	Protan	Moderate	Yes	Once in Awhile	Yes
Pilot2	Male	18-24	Deutan	Moderate	No	N/A	Yes
P1	Male	25-34	Protan	Strong	Yes	Everyday	Yes
P2	Male	18-24	Deutan	Mild	No	N/A	Yes
P3	Male	18-24	Deutan	Moderate	Yes	Once in Awhile	No
P4	Male	55-64	Protan	Strong	No	N/A	No
P5	Male	25-34	Deutan	Mild	No	N/A	Yes
P6	Male	25-34	Protan	Strong	Yes	Once in Awhile	Yes
P7	Male	25-34	Deutan	Moderate	No	N/A	No
P8	Male	35-44	Protan	Moderate	Yes	Once in Awhile	Yes
P9	Male	35-44	Deutan	Strong	Yes	Once in Awhile	No
P10	Male	18-24	Deutan	Moderate	Yes	Once in Awhile	Yes
P11	Male	18-24	Protan	Moderate	Yes	Once in Awhile	Yes
P12	Male	18-24	Deutan	Strong	Yes	Almost Never	No
P13	Male	18-24	Deutan	Mild	Yes	Everyday	Yes
P14	Male	25-34	Protan	Strong	Yes	Once in Awhile	No
P15	Male	25-34	Deutan	Moderate	Yes	Everyday	Yes
P16	Female	18-24	Deutan	Moderate	Yes	Everyday	Yes
P17	Male	18-24	Protan	Moderate	Yes	Almost Never	Yes
P18	Male	25-34	Deutan	Mild	No	N/A	Yes
P19	Female	65+	Deutan	Mild	No	N/A	Yes
P20	Male	25-34	Protan	Strong	Yes	Almost Never	No
P21	Male	18-24	Protan	Mild	Yes	Almost Never	Yes

Table 1: Demographics for interview & observation study participants: Participant ID, Gender[2], Age Range, CVD type and severity, whether participant had used recolouring before,frequency of recolouring tool use, and whether the participant had direct control of the recolouring aid via remote control on Zoom.

colour filter, had participants set it up according to their preferences (choosing one of Protan, Deutan, or Tritan filters and starting with it on or off), and allowed participants time to experiment with the filter using the reference image on the Windows 10 colour filter settings page.

Participants then proceeded through the 14 task slides using a Think Aloud protocol. Once complete, we reviewed all of the slides with the participants, giving the 'answers' for each task while prompting participants for additional comments. We did this in an attempt to 'close the loop', so participants could be more aware of how much the recolouring tool was actually helping them. Due to the lack of feedback (prior to our review) and the relatively broad goals of our observation study, we decided to not adjust the ordering of slides between participants. However, we did make sure task types were randomly interspersed among the 14 slides (Figure 1, bottom three rows). In addition, it is unclear if Zoom provided colour reproduction consistency (e.g., via ICC profiles) between our laptop and our participants' screens. However, this study is not focused on the specific quantitative performance of participants in each task (which would require this level of control), and our 'double-check' MacBook helped ensure that colour reproduction was acceptable for each participant.

5.1.2 Interview Details. The interview started immediately after the observation study. We prepared five questions (four with follow-on components) prepared for participants who had never used a recolouring tool before. For participants with prior recolouring tool experience, we prepared six questions (five with follow-on components). Following our REB protocol, all questions were optional. Both sets of questions are available in our supplementary materials.

The first four questions were identical between both groups with the first two questions asking participants to discuss the perceived benefits provided by the recolouring tool during the observation study, with the first question related to colour naming and the second to colour discrimination. Follow-on components investigated any interesting use cases we observed earlier (e.g., a participant constantly turning the filter on and off). The last two of the four shared questions focused on the design goals and typical use cases of recolouring tools – we asked participants their thoughts on 'always-on' recolouring tools replacing their vision and the requirements listed in Section 2.4 that emphasize minimizing differences (to maintain naturalness) while maximizing contrast (to differentiate confused colours).

5.2 Analysis

We analyzed the combined data from our observation study and interview using Braun and Clark's thematic analysis approach [4]. We started by transcribing the entire recording, while simultaneously adding relevant annotations from the observation study (e.g., current slide, colour filter setting, toggling the colour filter on/off).

The first author then re-watched the recordings several times to further familiarize themselves with participant responses, behaviours, and choices throughout the study, all while updating the

[2]Male participants outnumber female participants due to the X-chromosome sex-linked nature of inherited CVD, which leads to biological males being 16-17 times more likely to have CVD than biological females.

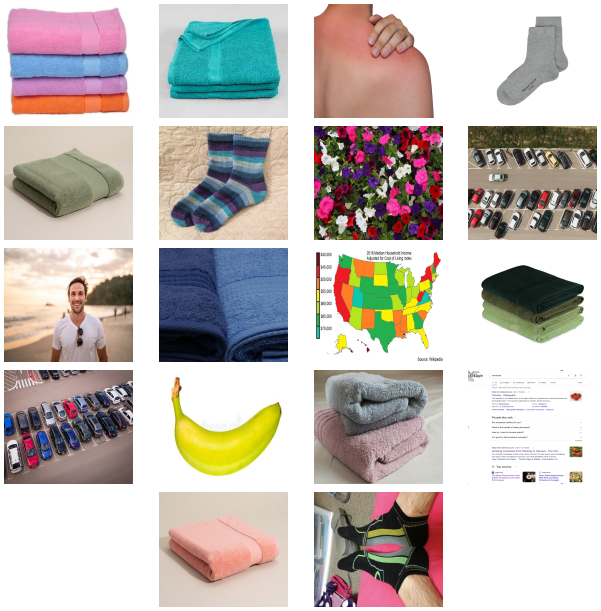

Figure 1: Images used in the study, with the images ordered specifically to indicate the order they were presented to participants. The top row of images shows the images used for the practice portion of the study (without any filter).

initial transcript with any missed details. The first author then iteratively coded the transcript by starting with fine-granularity codes applied to as many data points as possible, choosing only to not code data when the topic was clearly irrelevant to our research questions (e.g., off-topic banter with the participant). After this initial coding session, the first and second authors collaboratively assigned definitions to each initial code (similar to our r/colorblind process outline above in Section 3.2), then used these definitions to condense the initial codes to our final codes by collapsing codes with similar definitions.

The first author then printed the final codes with their definitions on paper to sort them into themes and subthemes. The initial major themes we developed ('Recolouring's Usefulness in Solving Different Colour Tasks' and 'Thoughts on Always-On Recolouring') were more akin to a summary of our data rather than the typical output from thematic analysis that should broadly reflect what we collected from our participants. As such, the first author revisited our themes and subthemes with the specific goal of breaking them away from the data and ordering of our observation study and interview. We ended up with two major themes ('Tools Used By Those With CVD' and 'Why Are You Changing What I Know & Recognize?') that we believe suitably represent the data we collected.

6 OBSERVATION STUDY & INTERVIEW FINDINGS

With the combined findings of the observation study and interview, we identified two themes that highlight how participants actually use recolouring tools and participants' thoughts on how recolouring tools should be designed. The first theme, *Tools Used By Those With CVD*, generally highlights when recolouring is deemed to be effective, how it is used in real situations, and strategies for when recolouring does not help. The second theme, *Why Are You Changing What I Know & Recognize?*, highlights participant thoughts on 'always-on' filters and describes situations (e.g., colour naming) where filters often change colours in a negative way that inhibits them from actually performing a task. We start by looking at how participants utilized the recolouring tools when solving tasks in the observation study, and then go on to discuss the narratives around each theme.

6.1 How Recolouring was used to Solve Colour Tasks

When going through the observation study, six participants (P2, P4, P10, P13, P16, P19) had the recolouring tool enabled the entire time. It should be noted that both P2 and P4 said that they completely forgot that the filter was active and P10 stated they normally would not continually use their filter in its 'always on' state, but said they wanted to experience it as they saw the study as an opportunity to experiment with an alternative view on the world.

Next, four participants (P3, P7, P12, P18) kept the filters on the entire time, but switched between the different types of filters (e.g., between Deutan and Protan filters). Four other participants (P1, P11, P15, P20) toggled the filter 'on' and 'off' repeatedly during tasks. Six participants (P6, P8, P9, P14, P17, P21) toggled the filter 'on' and 'off' and switched the filter type. Finally, P5 specifically started each prompt with the filter off and only enabled the filter after first attempting the task without it.

This diversity in how participants used recolouring tools shows that there are different preferred use cases for these types of filters. Specifically, this tells us that filters need to prioritize user-chosen manipulation in their interfaces to make toggling on/off and switching filter settings easier. However, the need to switch settings often might also indicate that the design of existing filters is simply not providing the right type of assistance to people with CVD. Put another way, if current recolouring tools are as successful as their associated evaluations suggest (see Section 2.4), why did 15 of our 21 participants feel the need to divert from the typical recolouring tool use case?

6.2 Tools Used By Those With CVD

6.2.1 When is recolouring actually used? Participants described specific situations where they have applied or tried recolouring tools. Six participants (P1, P3, P10, P12, P15, P17) said they try out filters in games to see if they would help. P15 specifically mentioned how they would really like the option to customize specific important coloured components (e.g., teammate colours) and described this as potentially better than a blanket filter. P12 and P17 described how they generally try out filters in games, but P12 tends to turn them off if they look 'gross' and P17 described how it depends on the specific filter implementation in that they usually do not want all colours to be shifted. Other application domains were visualizations (P8, P14), P6 uses recolouring to ensure content is visible to people with CVD, and differentiating coloured categories in Outlook (P16). Finally, P11 and P21 specifically stated that a lack of recolouring tool usefulness led them to abandon them altogether.

6.2.2 What colour tasks are helped by recolouring? The situations and colour tasks where recolouring is actively used and where participants find benefit from recolouring appears to be quite limited. Although nine participants (P2, P3, P5, P10, P11, P13, P15, P16, P18) provided a colour task, the only one mentioned was solving colour differentiation problems (i.e., telling colours are the same or different):

> P3: "[...] If all I'm trying to do is differentiate if two things are different typically recoloring is really useful for that [...] because it just turns up slight differences that we see up to 11 and it's usually helpful [...]"

While participants did note that colour differentiation is where they find recolouring helps, other participants also clarified that there are also limits to this usefulness:

> P9: "Well so with the filter tools they really help me confirm what I had suspected in a lot of cases. Like with the links being blue or purple you know they sort of exaggerated the colours and that helped me sorta distinguish some of them. In some cases I felt they didn't help where I need them. [...] The question about the banana is interesting because even when you turn the filter on it still looked very yellow to me. [...]"

Furthermore, some participants (P1, P6, P8, P14) also described how a single filter was often not sufficient to solve all colour differentiation problems. Several different filters would have to be used to look for slight differences between potentially different colours:

> P6: "[...] if you flip through a lot [of different filters], and even [with] one of them, [the colours] look different, then it's a good indication that they are, in fact, different colors. So that would be I think, the easiest way but yeah, you really need to have a bunch of different filters that you can use. [...]"

However, we also saw with P6 and many other participants that the filters could not provide adequate assistance in all colour differentiation tasks. P6 went on to clarify that in our differentiation task of telling if two blue towels were the same colour or not, that their typical experience with recolouring tools misled them:

> P6: "[...] I was turning the filter on and off and I thought that one was changing a lot more therefore it must have been a different hue, but that wasn't right. I don't know why that's not right?!"

6.2.3 Alternative tools used by those CVD. Participants also described other tools they used when they knew a recolouring tool would not assist them. By far the most common answer from participants (P8, P9, P10, P14, P17) was to simply ask someone else about a specific colour:

> P17: "[...] You know if a recolouring tool isn't something that I'm going to put to use, which, you know, it honestly rarely is, then it's only almost always ask a friend or you know, I've even taken a picture of something and sent it to someone for their opinion on what colour something is."

The next most common answer was for participants (P6, P9, P13) to use various colour pickers (e.g., Color Grab). P6 mentioned that for most tasks, they found that using a colour picker to grab HSV (Hue, Saturation, Value) information was more valuable, and even in tasks like comparative or colour differentiation tasks, breaking them into two colour-naming tasks was guaranteed to be more accurate. P8 described how they would specifically adjust lighting as they found this could help with colouring naming or differentiation in some cases. P9 described how they used colour naming apps (a feature provided by many colour pickers) and that they were accurate, but they felt that they did not often actually need to figure out the colour of something. P12 and P15 described how they would compare colours they definitely knew the colour of in order to obtain contextual clues.

6.3 Why Are You Changing What I Know & Recognize?

6.3.1 Distorting colours so I can't use any cues. Almost universally, participants described how recolouring tools simply cannot help with colour naming. An admittedly more disturbing finding was when we observed participants being led astray by the recolouring tool to assume that a specific coloured object was not present when it was, and was visible when not recoloured:

> P4: "It completely threw me on to the wrong track with certain images. Without the colour filter, I could at least see that three of the cars were red. Whereas it very clearly became none with the colour filter on, which was wrong. So it did not help me with naming, quite the reverse."

which stands as further evidence against using recolouring tools in an 'always-on' configuration.

One participant did note one case where they believed recolouring could help with naming, but again specified it would have to be with turning the filter on and off and effectively using information from both states:

> P1: "[...] I feel like if I couldn't toggle, I would be stuck between green and brown for this color [towel when filter is on]. But because I can toggle, I know that there's no way this is brown [towel when filter is off]. And then I flip on the toggle and because I know this can't be brown, I know this is green."

Finally, even P13, who mentioned that they use recolouring tools 'always-on' in their daily life and really enjoy it, described how filters could affect them when having to name colours:

> P13: "Well, the thing is, I'd like to think it helped me but I guess in some cases, it can be a hindrance where as a result of making things more red, it could just change the color entirely."

Several participants also discussed the importance of lightness and darkness when determining and differentiating colours. To describe this, P1 explained how they would turn the filter on and off to see whether two colours they were comparing changed equally in lightness/darkness. However, while light/dark cues are important for those with CVD, they do not appear to be deeply considered in

the design of recolouring tools. This requires adopters of recolouring tools to reject a lifetime of using light/dark cues to differentiate between colours. In our example of differentiating between two towels, it was apparent that the tool misled several participants (P1, P3, P4, P6, P8, P12, P17, P20, P21) away from their previous experiences by arbitrarily shifting colours, which also happened when trying to distinguish visited and unvisited links (P1, P4, P6, P11, P20):

> P11: "[...] this is just where previous knowledge comes into play. Usually how I identify which color or which links had been selected before is actually based on darkness and not color. [...] So the links that ended up being darker are ones I usually associate as the ones being selected, whether or not that tends to lean purple. I think this can be a common thread here – I look for anything but color."

Here P11 is explaining why they ended up selecting all the opposite links when trying to count all the links that had been visited. It appears as though the colour filter shifted visited (purple) to a lighter shade, thus destroying the natural mapping P11 had previously learned that visited links are darker and unvisited links are lighter. Preserving the cues that people with CVD rely on could be a vital design constraint for recolouring tools, however it is often missed or overridden in their current implementation. This contradiction could arise from not including people with CVD in the entire design process of these tools made specifically for them.

6.3.2 Maximizing versus minimizing colour changes. Participants often described how they believed that recolouring tools should minimize how much they changed colours so they would not be so different from how they recognize them. The following comment from a participant summarizes the general opinions:

> P13: "I think you would want to minimize the differences. Because if you overemphasize the differences, you just end up changing too many colors, and it would be harder to get used to. Okay, although I suppose it would still be possible to get used to them eventually."

However, some participants (P6, P8, P10) discussed how neither minimizing changes nor maximizing changes can fully assist them. If you maximize changes, these participants described how they would no longer be able to name colours accurately, and if you minimized changes they would not be able to differentiate between colours:

> P10: "I guess each of those have their strengths and weaknesses. Yes. If I needed to tell that two colors were different and not care about what colors they were, I think the overly contrasted would be better, more useful for me. But if I was trying to see more like a non-colorblind person, then that first one you mentioned [minimizing changes] would be just slightly correcting my vision..."

Finally, P1 and P14 both mentioned how they wanted colours to be overemphasized so that subtle (to them) differences could be very easily and quickly spotted when they use the filter in their preferred case as an on/off toggle.

6.3.3 Normal Colour Vision is NOT 'Correct' Colour Vision. Participants also discussed filters that are 'always-on' and continuously changing their vision. The way participants felt about this use case of the filter was largely negative, however a few participants were positive, but only if it was essentially a 'magical' cure. Only one participant was fully on board with replacing their vision with a recolouring tool stating: "Sign me up!", clarifying that if there were glasses that used the Windows 10 colour filter, they would wear them all the time. P2 stated they would not mind an 'always-on' recolouring tool and in general liked how recolouring looked, however, they would not seek it out. Other participants (P1, P4) stated that they would need to have control over the recolouring tool, or that it would need an on/off switch. Participants P5, P9, and P10 did not feel that their CVD was severe enough or that they did not encounter enough problems to feel that replacing their vision was warranted.

There were also participants (P3, P15, P16, P17) that simply did not like the idea of a recolouring tool that they thought produced 'ugly' or simply inaccurate results (e.g., for colour naming, as described above) when replacing their vision. An overwhelming number of participants (P7, P8, P11, P12, P14, P18, P19, P20, P21) stated that they would not adopt 'always-on' recolouring because they either like the way they see colours, do not want to adjust their vision, or have already learned ways to determine colours with cues learned over their lives. However, a few participants (P7, P16) stated that if the 'always-on' recolouring tool was a 'magical' solution or provided an exceptional experience they would be willing to try it.

One participant specifically described that they believe there is confusion in how people imagine how filters are supposed to be applied, going on to say that they only really need recolouring tools to quickly spot the difference between colours so filters should never be a whole experience changer:

> P14: "I would never leave it on because these colourblind filters...they change the colour of everything and so, I think the idea most people have about why somebody would use these is wrong. I am not trying to see something 'correctly' I already see everything correctly as my brain knows it. So when I put on one of these colourblind filters like there's a level [in a game] where lava is going by and with the colourblind filter on, it appears very bright yellow or very bright green, neither of which are correct for me. I've never played this game and went ah, the colour of this lava is not the correct red. To me when someone colours it the colour of lava it looks like lava to me. [...]"

Another participant specifically described how they would never really use recolouring tools 'always-on' and wished that accommodations did not try to 'fix' those with CVD but instead focused on getting around or designing for CVD:

> P17: "I'm sure there's a use for it [recolouring tools], but at the end of the day I don't want to feel like I'm dependent on a technology. I would rather see change in society where we are a bit more accessible for people that can't differentiate colors and even though color [can be] convenient, ... I still think that

> there are ways to go around color blindness rather than you're trying to fix it. "

Many of our participants' thoughts on the idea of 'always-on' recolouring being used to replace the vision of people with CVD highlights the problem that recolouring tool designers and developers appear to want to 'fix' colour vision deficiency. However, as was mentioned by P14, people with CVD already see colours correctly as they know them, so arbitrarily shifting colours is always going to cause problems. Given that the most common use case for recolouring tools appears to be the real world, it seems that researchers are really missing the mark on understanding actual use cases for recolouring tools *according to people with CVD*.

6.4 Discussion of Findings

Our observation study and interview uncovered four important findings: 1) those with CVD rarely use recolouring tools in an 'always-on' fashion, 2) recolouring is useful for confirming suspicions by "turning up slight differences to 11", 3) recolouring can inhibit coping mechanisms people with CVD have developed over their lives by transforming known colours to unknown colours, and 4) people with CVD do not want recolouring as a pervasive or corrective tool because they prefer the appearance of unmodified colours, they think recolouring makes the world 'ugly', and the costs (living with CVD) do not outweigh the benefits (of potentially improved colour differentiation).

Overall, we saw that people with CVD employed different strategies when using recolouring tools to solve colour tasks (RQ2), including toggling the filter on and off and/or switching between different CVD modes. It is clear that those with CVD are trying to use as much information as possible from all of the tools available (including their own vision) to try to complete colour tasks, but also that recolouring tools, as currently designed, are not sufficient to solve all colour tasks. In particular, we saw that recolouring was universally described by our participants to be useless in assisting with colour naming. Finally, we saw that those with CVD had mixed advice when it came to whether a recolouring tool should maximize or minimize colour changes (RQ3, specifically maintaining naturalness and enhancing contrast). Participants who wanted minimization described not wanting to change how they inherently see the world, whereas participants who wanted maximization described how recolouring would provide no benefit unless it maximized differences – the benefit of recolouring is to quickly distinguish confusing colours.

7 DISCUSSION

Our findings should sound a warning to recolouring tool researchers and developers that they need to better understand the dangers that recolouring can present. However, our findings also hint at future directions for assisting people with CVD based on our r/colorblind, observation, and interview studies with those with CVD.

As confirmed by both our studies and the popularity of r/colorblind's Dalton-Bot tool, we acknowledge the benefits that recolouring can provide. However, we also emphasize that our findings and Dalton-Bot underline the utility of recolouring as an *on demand* tool, where CVD users choose to apply it when they decide there is something they are having trouble interpreting or differentiating. This contradicts the current design assumption of providing recolouring in an 'always-on' configuration.

We also found that recolouring is simply not sufficient to help with all CVD-related challenges (e.g., colour identification). As discussed earlier, Colorblind Pal [13] and DaltonLens [5] are popular publicly available CVD tools. The popularity and utility of these tools likely benefit from the lead developers of each tool having CVD themselves, so they built tools specifically to assist them with challenging tasks they themselves identified. As a result, both tools comprise multiple modes (not just recolouring) for both differentiating and determining colours.[3]

Given both of these findings (recolour toggling and insufficiency of recolouring), we encourage future researchers to:

(1) Build recolouring tools that allow efficient toggling on and off or otherwise support on-demand use.
(2) Understand the most useful tools/modes to assist people with CVD in a variety of *real world* colour challenges.
(3) Work closely with people with CVD to build and validate new multi-mode tools.

As noted earlier in Section 2.3, alternative approaches to recolouring are rarely researched. As such, we also recommend that researchers look further into the feasibility of alternative methods such as applying redundant encoding via colour patterns [15, 18, 26, 48]. There still appears to be important outstanding work in this field, such as understanding the long-term effectiveness of these alternative methods and exploring how useful they are in everyday digital and real-world colour tasks.

Various requirements for recolouring tools have been proposed, including the three attributes of 'naturalness', 'consistency' and 'contrast' [46] discussed above, a set of nine guidelines from Simon-Liedtke et al. [50], and most recently a standard from the Commission Internationale de l´Eclairage (CIE) [6]. The guidelines provide by Simon-Liedtke et al. [50] are the earliest and most strict, focusing on satisfying a checklist. The three requirements [46] and CIE's standard [6] are most similar, however the recent CIE document includes the substantial clause: "There is no unique technique that can cover all cases.". Given our findings around the insufficiency of recolouring and the potential for CVD multi-tools, we find this warning from the CIE to ring true, and clarifies the need for multiple tools to cover the large variety of real world colour challenges actually experienced by people with CVD.

When researchers evaluate the effectiveness of their recolouring tools, the Ishihara Plate Test appears to have become the 'gold standard'. Furthermore, other CVD assistive aids, such as the Enchroma glasses, are often deemed to be ineffective due to their inability to allow someone with CVD to pass the Ishihara Plate Test [19]. However, as we saw in our r/colorblind study, there was a particular comment illustrating how a user picked a specific recolouring tool not because it allowed them to pass the Ishihara Plate Test, but because it disrupted their vision the least yet still provided benefits to them. It seems that passing the Ishihara Plate Test is barely relevant to any realistic challenges with colour those with CVD may face, and given that there are numerous claims of the benefits of

[3]Details for each app can be found on their respective websites as linked in our References.

the Enchroma glasses, we genuinely believe that the Ishihara Plate Test is a poor evaluation method and should be retired as such.

Finally, another evaluation method recolouring researchers often use is validation by quantitative (or 'objective') formulas to calculate attributes like 'naturalness', 'consistency', and 'contrast'. We believe that these formulas, while an attractive quantity to show success or improvement of a recolouring tool, do substantially oversimplify human colour perception, and are themselves based on CVD simulations that have yet to be empirically validated. We counter this approach by emphasizing that research looking to assist people with CVD should seek to genuinely assist *them* by emphasizing designing 'with' rather than 'for' and incorporating open-ended evaluations with people with CVD.

8 LIMITATIONS AND FUTURE WORK

In our observation study, participants were completing colour-related tasks with a recolouring tool via a remote connection. It is important to note that uncontrolled factors such as environmental lighting, screen brightness, screen size, distance from the screen, and unknown colour reproduction consistency over Zoom could all influence how our participants perceived each colour on their end. Furthermore, we employed a single recolouring tool in our study – different results may arise from different implementations and types of recolouring tools. However, for reasons outlined in Section 5.1.1, we are reasonably confident that: a) the Windows 10 colour filter is a suitable representative of recolouring tools, and b) any variance in colour perception experienced by our participants (due to the factors listed above) is within the range of noise in which recolouring tools would be used in day-to-day life (e.g., few people view colour on lab-perfect colour-calibrated screens in controlled environmental lighting [14]). As such, we are assured that our findings are legitimate, especially those findings consistent across most of our participants, such as those supporting a move away from 'always-on' recolouring and the insufficiency of recolouring for all colour tasks. Regardless, further research is needed to more deeply investigate recolouring in genuine daily use (rather than our generated colour tasks) to validate our findings. In addition, our formative study only investigated posts and comments on the r/colorblind subreddit, so this work could benefit from gathering the perspectives of other social groups (e.g., Facebook's Color Blindness/Color Vision Deficiency Awareness group).

9 CONCLUSION

Enabling those with CVD to identify and differentiate colour is important, however, efforts need to go beyond applying a filter that arbitrarily changes colours. Decades have been spent researching and developing filters in the pursuit of one that can preserve both naturalness and consistency, while simultaneously enhancing contrast [46]. However, our findings suggest that such an approach can seriously detract from the experience of someone with CVD (e.g., by making coloured content ugly to the CVD viewer), or even worse, inhibit a coping mechanism that designers or developers were not aware of (e.g., differentiating light and dark to determine hue). We believe that these limitations are a direct result of research that historically valued quantitative formulas, image comparison and simulations over open ended evaluations involving people with CVD. Given this we call for future research that is looking to assist people with CVD to involve them directly in the entire process of creating tools for them.

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