ColourID: Improving Colour Identification for People with Impaired Colour Vision

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Figure 1. Left to right: "Grab the yellow pencil.", CVD simulation showing difficulty, our ColourNames, ColourMeters, and ColourPopper techniques.

ABSTRACT

Being able to identify colours is a fundamental human activity; colour identification helps us work, get dressed, prepare food, and keep safe. But for the 5% of the world with impaired colour vision (ICV), colour identification is often a challenge, resulting in frustration and confusion with sometimes dangerous consequences. Colour namer tools have been proposed as a solution, however these are often slow to use and imprecise. To address these shortcomings, we developed three new colour identification techniques (ColourNames, ColourMeters, ColourPopper) using a new colour name dictionary based on the largest colour naming experiment to date. We compared our techniques to colour namers using participants with ICV in desktop and mobile conditions, and found that ColourNames and ColourPopper resulted in ~99% colour identification accuracy (10% higher than the colour namer), and ColourMeters and ColourPopper were three times faster, and ColourPopper had lower perceived effort and was ranked significantly higher. With the benefits provided by our new colour identification techniques, people with ICV are one step closer to seeing the world like everyone else.

Author Keywords

Colour identification; impaired colour vision; colour vision deficiency; colourblindness; colour namers

ACM Classification Keywords

K.5.2. Social Issues: Assistive technologies

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INTRODUCTION

Colour identification is a fundamental human ability we use on a daily basis. We use colour identification to tell the ripeness of fruit (e.g., green and yellow bananas), to coordinate clothing and jewellery, to determine whether meat is cooked ("Any pink in that chicken?"), and for diagnosing rashes and burns. In digital environments, colour identification helps us distinguish between visited (purple) and unvisited (blue) website links, read data from visualizations, and to find missing information in web forms (often marked in red).

However, for 5%-10% of the population who have impaired colour vision (ICV) [26], colour identification is often a challenge, and sometimes impossible. As shown in the two left images in Figure 1, people with inherited Colour Vision Deficiency (CVD – or colourblindness – a common form of ICV) often see one colour, but everyone else will call that same colour multiple names (e.g., brown, green, orange), leading to confusion and frustration [4], and sometimes danger (e.g., unnoticed sunburn or eating raw meat) [25].

To help address this problem, tools that identify colours on-screen and using mobile phone cameras (*colour namers*) have been developed, however they have two major limitations:

1. *Speed*: Colour namers typically provide colour identification for the colour under the cursor (desktop) or a crosshair in the center of the screen (mobile). This works when a person wants to know the colour of a specific item, but fails when the user needs to find an object with a specific colour (e.g., "Quick, grab the green folder!", "Cut the red wire!") or needs to get the general sense of the colour of something (e.g., "Is there any pink in that meat?", "Is this bread moldy?"). Compared to people with typical colour vision, people with ICV using colour namers will take much longer to answer these types of questions.

2. *Precision*: Colour namers condense numerical colour information (e.g., RGB values) to human-readable colour names, which is typically lossy (e.g., 24-bit RGB has 16.8 million colours, English only has 11 basic colour terms [2]). As a result, designers need to make decisions about the number of colour names provided by their colour namers, as well as the mapping from RGB to colour name. To solve this, *colour name dictionaries* are often used (e.g., X11 colour names), but currently-available colour name dictionaries contain colour names that are imprecise or difficult to understand (e.g., ‘peru’, ‘papaya whip’).

To address these two limitations, we first developed a new colour name dictionary based on the large set of colour-name pairs collected from the readership of the popular online comic, XKCD (www.xkcd.com), and refined by Heer and Stone [11]. This data set is based on over three million unique colour-name pairs, and reflects the commonly-accepted colour-naming conventions found in English (eleven basic colour terms: black, white, red, green, yellow, blue, brown, pink, purple, orange, grey) [2].

We then employed our new colour name dictionary to develop three new techniques to help people with ICV identify colours. First, we developed *ColourNames* – a direct extension of existing colour namers that tiles colour names across the entire screen. *ColourNames* (Figure 1, centre) replaces the physical search of colour namers with a visual search task – users scan with their eyes, rather than scanning physically. Second, we developed *ColourMeters* – a simplification of the *ColourNames* approach that replaces tiled colour names with a visualization using tiled colour meters. *ColourMeters* (Figure 1, centre right) replaces the high load of linearly reading English colour terms in *ColourNames* with scanning for simple visual patterns. Third, we developed *ColourPopper* – an extension of the *ColourMeters* technique that maximizes the popout effect of some visual patterns in *ColourMeters*. *ColourPopper* (Figure 1, right) replaces the *ColourMeters* visualization with a user-directed colour highlighting effect.

We evaluated our new techniques by comparing their performance to traditional colour namers in desktop and mobile colour identification tasks for people with inherited CVD. On the desktop, our techniques enabled almost 100% colour identification accuracy, and were two-three times faster than our test colour namer. *ColourNames* achieved 99.1% accuracy, with a mean completion time of 8.0s. *ColourMeters* achieved 94.5% and 5.7s. *ColourPopper* scored 98.6% and 5.2s. The colour namer performed worse than our techniques, with 90% accuracy and 15.7s mean completion time. Compared to our 100% accurate non-CVD control group (1.6s), the colour namer took 9.9 times longer, *ColourNames* took 5.0 times longer, *ColourMeters* took 3.6 times longer, and *ColourPopper* took (a relatively fast) 3.3 times longer. The mobile evaluation results supported some of these findings, with CVD participants ranking the mobile versions of *ColourMeters* and *ColourPopper* higher than a commercially-available Android colour namer, but *ColourNames* lower.

This paper presents three main contributions. First, we developed three new techniques for helping people with ICV

identify desktop and environmental colours. Second, we evaluated these three techniques and showed that all three give people with CVD almost the same colour identification accuracy as people without CVD, and do it faster than existing colour namers. Third, we improved colour to name mappings for colour identification by adapting a previously-published colour-name dictionary to colour identification tools.

RELATED WORK

ICV: Impaired Colour Vision

Three causes of ICV have been identified in the literature: inherited ICV or Colour Vision Deficiency (CVD) [3], acquired ICV (typically as a factor of age) [5], and situationally-induced ICV (often due to lighting conditions) [8].

Inherited CVD is more common in males (8%) than females (0.5%) [4], and typically manifests as a reduction in the ability to discriminate along the red-green axis of colours [3], causing colours that only differ in their amount of red or green to be difficult to distinguish [25]. Acquired ICV has been identified in 64% of people over 65 years of age [5], and usually manifests as a reduction in discriminability along the blue-yellow axis of colours [21] as we age [14]. Acquired ICV can also be due to chemical exposure [16], disease [24], as well as other factors [30]. Situationally-induced ICV is less well-studied, but can be induced through variations in lighting, monitor settings, and eyewear colour [8]. Its manifestation is dependent upon the inducing situation, so can reduce colour discrimination along any axis (including luminance discrimination) [8].

Colour Name Dictionaries

Colour name dictionaries map numerical colour values to human-readable colour names. A commonly known colour name dictionary is the X11 colour names (`/usr/lib/X11/rgb.txt` in UNIX), which provides 752 colour-name mappings, and its related variants (CSS 3.0 and HTML 4.01 colours). Although assigning names to colours is an inherently subjective task, these dictionaries are typically created by small groups of people with little colorimetric training, so often introduce arbitrary decisions (e.g. the differences between ‘grays’ in X11 and web colours).

Some colour name dictionaries informed by colorimetric expertise exist, such as the NCS (ncscolour.co.uk), Pantone’s colour sets [6], and the Munsell colour system [20] but the colour coordinates of these systems need to be converted into digital colour representations (e.g., sRGB) before they can be used in colour namers, and these transformations are often proprietary or result in out-of-gamut colours.

Another approach to generating colour name dictionaries is to distill a dictionary from colour-name pairs gathered from many people – present a colour, and get people to name it. One example is HP’s multi-lingual Color Naming Experiment [19], which has been collecting colour names for several years. A more recent example is the XKCD Color Survey (blog.xkcd.com/2010/05/03/color-survey-results), which collected over five million named colours. Heer and Stone [11] processed this colour name set to allow colour-based editing and other image applications (more below).

There have also been attempts to automatically decompose colour spaces [15, 22, 1] into named regions, with applications in automatic image description [17, 18]. However this approach rarely generates the level of detail necessary to be helpful for colour namers (the names are either too simplistic or provide information not generally needed by people with ICV (e.g., describing the lightness of a colour, which usually presents no difficulties for people with ICV).

Existing Colour Identification Tools

Several tools have been developed for helping people with ICV identify colours. The Color Grab utility for Android (play.google.com/store/apps/details?id=com.loomatix.colorgrab) is a real time, colour namer that provides a general colour category (e.g., yellow) and a more specific name (e.g., lemon). We use Color Grab in the mobile evaluation of our techniques. The Colorblind Vision (Free) app (play.google.com/store/apps/details?id=com.givewaygames.colorblind_ads) has an ‘Extract Color’ feature that allows colour highlighting (similar to ColourPopper) for a user-specified colour by suppressing the saturation of all other colours. However, as people with inherited CVD have reduced discrimination along the red-green axis, they often perceive pinks/magentas and cyans/greens as grey. As a result, this feature does not help identify these colours, because they already appear grey to the CVD user. For this reason, we opted to not include this in our evaluations below. Chroma [27] is a Google Glass application for helping people with inherited CVD that features a colour highlighting mode that repaints all pixels of a user-selected colour to white, similar to the highlighting functionality of ColourPopper. However, by painting all the pixels white, the underlying subtleties (lightness, intensity, and hue variations) of the colour are lost. Colour visualization techniques (similar to ColourMeters) have also been proposed [23, 13, 12], however each of these is designed specifically for people with inherited red-green CVD. Our techniques are designed to help with general ICV – even monochromatic vision – and do not require specific information about the user’s type of ICV.

THREE NEW COLOUR IDENTIFICATION TECHNIQUES

Aiming to address the limitations with existing colour naming tools, we developed three new techniques for helping people with ICV identify colours – ColourNames, ColourMeters, and ColourPopper. We describe these in detail in this section, beginning with a description of our adaptation of Heer & Stone’s recently-published colour name dictionary [11] to use within two our tools. We demonstrate each technique using the image shown in Figure 2, top.

Colour Name Dictionary

Both ColourNames and ColourPopper rely on a colour name dictionary to identify colours that will be meaningful to the user. As identified above, esoteric colour names are probably not helpful for people with ICV (e.g., most people would have difficulty knowing what colours ‘peru’ and ‘papaya whip’ represent; a simple term such as ‘pink’ or ‘orange’ would likely suffice). Anecdotal evidence from some of our participants with CVD would suggest the same.

Figure 2. Demonstration image for our colour identification techniques (top). CVD simulation showing loss of red-green contrast (bottom).

We used the colour name dictionary generated from the XKCD Color Survey data by Heer and Stone [11]. This colour name dictionary is based on five million colour+name pairs (the largest collected to date). We used the software provided at <http://vis.stanford.edu/papers/color-naming-models> to find the most common human colour name for every RGB565 colour (for a total of 65536 possible colours). This resulted in a set of 33 unique colour names, with the eleven English basic colour terms (white, black, red, brown, orange, yellow, green, blue, purple, pink, grey) comprising 83.3% of the entire RGB565 colour space. Upon further inspection of the colour names produced by the colour name dictionary, several were identified as simple modifiers (e.g., ‘navy’ modifying ‘blue’). To help reduce the complexity of names produced by the colour name dictionary, we identified all of these cases and mapped the more complex name to their simplified forms according to Table 1. In addition to this, we also included ‘teal’ as a basic colour term as this colour (representing the blue-green set of colours) is often confused with grey by people with inherited CVD. These modifications increased the proportion of the colour space occupied by the eleven basic English colour terms (plus teal) to 94.7% of the entire RGB565 colour space.

lightpink → pink	peach (light orange) → orange
lightblue → blue	navyblue (deep blue) → blue
lightgreen → green	limegreen (bright green) → green
darkgreen → green	maroon (dark red) → red
darkteal → teal	cyan (light teal) → teal
darkpurple → purple	off white (white) → white

Table 1. Mapping used to reduce modified colour names to basic colour names (our interpretations of the modified names appear in bold).

ColourNames: Grid of Names

This technique was designed to increase colour identification speed by using visual search to replace physically scanning with the cursor or the mobile camera crosshair in existing colour namers. As physical search fully contains visual search (the eyes scan along with the cursor to read the colour names that appear), removal of the physical component of this search should increase colour identification speed.

ColourNames decomposes the incoming image (i.e., a desktop screenshot or mobile camera frame) into a tiled arrangement of small rectangles. The average RGB colour for each rectangle is calculated and converted to RGB565. The RGB565 colour is used to lookup its corresponding colour name from our colour name dictionary, and this name is drawn to the screen within its source rectangle. To provide room for more rectangles (more colour names), colour names are truncated to the first four characters. This technique is illustrated in Figure 3. The grid of rectangles can also be shown to help users target specific colours or regions.

Figure 3. ColourNames demonstration. Magnification may be necessary to see the names here, but are clearly readable in the implementation.

ColourMeters: Grid of Meters

Although ColourNames should allow faster colour identification than colour namers for people with ICV, ColourNames users still need to read and process each written colour name which might incur a high cognitive load. In addition, the names are English names, so English reading skills are required to use this tool – reducing its utility for those who do not speak English or are too young to read.

To eliminate the time required to read English colour names, we developed a second colour identification technique that uses the same rectangular grid as ColourNames, but presents a simple visualization of the average RGB value instead. This visualization takes the form of a meter or gauge; the angle of the meter represents the hue of the average RGB value, the meter's length represents the average RGB's chroma.

To determine the angle and length of the meter, the average RGB value is converted to CIE $L^*u^*v^*$ angular coordinates (LCH: Luminance, Chroma, Hue) [29]. Hue is the dominant wavelength of the colour and is represented in degrees, having values between 0° and 360° . Beginning at 0° (pinkish-red), the hue value increases through red, orange, yellow, green, blue, purple, and pink before wrapping around. Although we could map hue value directly to meter angle, this approach causes difficulties because the user will have difficulty distinguishing between meters that are 180° different (e.g., a meter pointing at blue (270°) will look identical to a meter pointing at yellow (90°) without a frame of reference). To overcome this difficulty, we divided the hue value by two to get a value between 0° and 180° . By flattening the hue angle in this fashion, we eliminated the ambiguity from using the full 360° of hue values, as the only two angles that are equivalent in this flattened case are 0° and 360° , which are already identical colours. We decided to make 0° horizontal and pointing to the right, with 180° also horizontal but pointing to the left. The meter rises from 0° to 90° , and falls from 90° to 180° .

To determine the length of the meter, we scaled the chroma of the average RGB value to the height of one grid rectangle. Due to the preponderance of low chroma colours (e.g., greys, tans) in the real world, we opted to scale the chroma by two and clamp it to the height of the rectangle to help identification of low chroma colours. Our ColourMeters technique is illustrated in Figure 4 (with no grid visible).

Figure 4. ColourMeters demonstration. Magnification may be necessary to see the meters here, but are clearly visible in the implementation.

ColourPopper: User-Selected Highlighting

By replacing textual colour names with a simple visualization, ColourMeters should increase colour identification speed. However, ColourMeters will likely require training before it can be used. To help overcome this, we noticed that the clustering of meters in ColourMeters would occasionally allow a 'popout' effect in which two indistinguishable colours (for someone with ICV) were different enough to have substantially different meters. This would allow the user to find the unique colour very quickly because its pattern of meters would 'pop out'. Taking this visualization technique forward, we designed our third colour identification technique – ColourPopper – to take full advantage of this popout effect.

By its very nature, popout allows particular data points to 'pop out' from the rest of the data allowing rapid and easy identification in visualizations [28]. To use this in ColourPopper, the user requests that a particular colour in an image or video frame be popped-out, and ColourPopper emphasizes all pixels with that particular colour name by suppressing the brightness and chroma of all remaining pixels. This technique provides the particular benefit of eliminating the scanning (either physical or visual) of all previous techniques, but at the cost of requiring the user to specify their desired colour.

ColourPopper Mechanism

To highlight a particular colour in a scene, the user selects a popout colour (using the buttons shown in Figure 5). Ten popout colours are provided by our tool – each corresponding to a single English human colour term: red, orange, brown, yellow, green, teal, blue, purple, pink, and grey. These align closely with the eleven basic colour terms identified by Berlin and Kay [2], with the specific addition of 'teal', and the removal of 'black' and 'white'. Teal was added because this colour often presents challenges for people with inherited CVD, and it occupies a reasonably large region in many colour space decompositions [11]. Black and white were removed because they comprise $< 1\%$ of the RGB565 colour space, so we decided that the added interaction time resulting from adding buttons for white and black was not worth the relatively small addition to colour identification.

To identify which RGB values map to these ten colour names, we modified the colour name dictionary described above by mapping those colours names that are not listed above (tan, olive, lavender, beige, magenta, salmon, mustard, mauve, yellowgreen) to the colour that is most perceptually similar. We determined perceptual similarity by determining the centroid of all RGB values belonging to a single colour term and then comparing the Euclidean distance between all centroids in perceptually-uniform CIE $L^*u^*v^*$ colour space.

To cause a colour to pop out, all pixels that map to that particular colour's English name remain unchanged, while all remaining pixels have their luminance and chroma reduced by scaling each by 0.1. Luminance and chroma scaling is performed in the angular representation of CIE $L^*u^*v^*$ colour space, but could similarly be done in HSB or other angular colour spaces. To convert from RGB to $L^*u^*v^*$, we used the sRGB gamma function and primaries and a D65 white-point. We opted to not scale up the luminance and chroma of the highlighted colour, as this can lead to the colour being pushed out of the gamut of the display, which can adversely change the colour drawn to the screen due to gamut clipping.

Although the colour modifications performed by the highlighting effect could be calculated on demand, this would lead to unnecessary recalculation because the modifications are entirely deterministic. As such, we used a look-up-table (LUT) to reduce the number of calculations and to improve the runtime performance of the technique by loading the LUT onto the graphics processing unit (GPU) where fragment shaders parallelize the colour replacement process.

One LUT is required for each colour term identified above. To generate each LUT, we created every possible pixel colour and modified it according to the above algorithm (leave unchanged if it belongs to the desired colour term, otherwise suppress luminance and chroma). Each resulting pixel is then written to a 1024x64 pixel image that serves as the LUT for the desired colour term. When a highlight colour is specified by the user, ColourPopper loads the corresponding LUT as a texture into the GPU and fragment shaders are used to recolor each frame. ColourPopper results for 'green' with our sample image are shown in Figure 5.

Figure 5. ColourPopper demonstration highlighting 'green'.

DESKTOP IMPLEMENTATION EVALUATION

We conducted an in-lab user study to compare our proposed techniques to existing colour namer tools. Our study focused on the problem of identifying the 'odd one out' – identifying a single element from a larger set by colour identification.

Participants

We recruited 22 unpaid participants from a local university (mean=26.8 years, SD=7.3, 18 male). Eleven of these participants were previously diagnosed with inherited CVD and eleven served as non-CVD controls. We used the HRR Pseudoisochromatic Plate Test [9] to assess the colour vision of each participant, and found that four participants had mixed protan and deutan CVD, and seven had protan CVD.¹

Stimuli & Task

To evaluate each colour identification technique, a 10x7 grid of coloured circles on a black background was presented to the participant (Figure 6). Sixty-nine of these circles were one colour (of varying luminance), and the remaining (randomly-selected) circle was another colour. The participant's task was to click on the circle that was the different colour. A rest screen between trials listed the two colour names for the next trial, which were also available during the trial.

Figure 6. Field of coloured circles presented to the user. Task was to identify the specified colour (in this case, yellow) by clicking on it.

To properly evaluate each of our techniques, it was important that the colours presented are difficult for people with CVD to differentiate, but are still easily distinguishable for people with typical colour vision (to reflect the real world situation of a person with CVD trying to identify an object from a set of distractors by colour alone). Additionally, we wanted the different colours to have clearly identifiable names (e.g., 'green') to simplify the task for all participants.

To choose our evaluation colours, we selected colours from the X11 (red, dark red, dark orange [simplified to orange], yellow, green, blue, purple, pink, saddle brown [brown]) and W3C (green [dark green]) colour sets, as well as a mid-luminance grey (0x777777). By choosing colours from these colour sets rather than our own dictionary, we sought to reduce artificially favouring our techniques.

To select which pairs (target & distractor) of colours would be presented to the participants, we found the colour confusion line (line of indistinguishable colours) that intersects each colour listed above in CIE $L^*u^*v^*$ perceptually-uniform colour space for the two dominant types of inherited CVD (protan & deutan). The minimum Euclidean distances from the (u^*,v^*) coordinates for every other colour

¹We recognize that this does not fit the expected pattern of 3/4 deutan, 1/4 protan [3] and are investigating this further.

to each line were then calculated. This resulted in two tables of distances (one protan, one deutan) that showed which pairs of colours were close to the same colour confusion line. By arbitrarily choosing a threshold maximum distance of 11.0 u^*v^* units, we identified five pairs of colours that should present difficulties for people with protan CVD (yellow+green, blue+purple, red+brown, grey+pink, darkRed+brown), and six pairs for people with deuteranopic CVD (grey+pink, darkRed+brown, red+orange, orange+green, darkRed+darkGreen, darkGreen+brown). Two pairs were shared between each set (grey+pink, darkRed+brown), leaving nine unique pairs of colours. We averaged the original luminance of each colour to reduce the chance of discriminating between the colours based on luminance differences, and generated luminance noise variations for each colour in each pair to further reduce any luminance contrasts. Each pair of colours is shown in Figure 7 along with protan and deutan simulations of the colour pairs.

Figure 7. All pairs of colours used in the study with CVD simulations.

Colour Identification Techniques

For each presentation of coloured circles, participants had either a control (no assistance) or one of four colour identification techniques available to use:

- **Control:** This technique reflects the typical unassisted task of identifying the unique colour in a set of distractors.
- **ColourNamer:** This technique represents existing colour naming tools. To ensure the performance difference between this technique and our techniques was not due to differences in colour name dictionary, we used our dictionary to provide a human-readable English colour term for the pixel underneath the cursor. The colour name was provided to the right of the cursor, and moved with the cursor.

- **ColourNames:** This technique was used as described earlier, but with one modification. The base implementation of ColourNames described above is quite overwhelming – for the coloured circles shown in Figure 6, the default implementation provides 8162 colour names. Given the substantial load this would place on participants, we opted to use a modified version of ColourNames that identifies the location of each circle, and provides a single colour name for that circle. Although this modification may be highly optimized to the coloured circle task used in this evaluation, it allows a ‘best case’ evaluation of ColourNames.
- **ColourMeters:** This technique was used as described earlier, but with a similar modification as ColourNames – meters were only provided for the coloured circles.
- **ColourPopper:** This technique was used as described earlier. Popout colour selection was made via a horizontal row of buttons across the bottom of the screen (see Figure 5). The popout colour was reset to ‘none’ after each trial to force the participant to make a selection for every trial.

Procedure, Apparatus & Design

Participants were first given the HRR Plate Test, and were then introduced to the task. Participants with typical colour vision completed a single Control session, but participants with inherited CVD completed a session using each technique described above in counterbalanced order. A single session presented the participant with 22 coloured circle screens (trials) – two for each of the nine pairs of colours identified above (each colour in a pair was the target once), plus two protan and two deutan training screens at the beginning.

For each trial, we recorded the completion time, and whether the selected colour was the target colour. Once all 22 trials were completed for a given colour identification technique (Control, ColourNamer, ColourNames, ColourMeters, ColourPopper), participants completed the standard six responses of the NASA Task Load Index (TLX) [10] for the technique just completed. The entire study took about 30 minutes to complete for participants with CVD, and about 10 minutes for participants with typical colour vision.

The study was conducted under controlled lighting on a 1920x1080 LCD BenQ GL2450H monitor colour calibrated using a Spyder4Express, driven by a Windows 7 machine. The techniques and coloured circles presentation software was custom-built in Java using the `Processing.org` libraries.

The study used a one-way factorial design with a single factor (technique) with five levels (Control, Namer, Names, Meters, Popper). As CVD participants were presented with both protan and deutan pairs of colours, we selected results from the colour set that aligned with the type of CVD of the participant (as diagnosed by the HRR plates). We used both sets for participants with mixed protan and deutan CVD.

Dependent measures were mean completion time for the five CVD techniques and the non-CVD Control, mean accuracy for the same six conditions, and the CVD participant responses to the six TLX categories for each CVD technique.

Results

Accuracy

The nonCVD Control data serves as a baseline against which the performance of participants with CVD can be compared. As such, we conducted a one-way ANOVA across the six conditions identified above (NonCVD Control, CVD Control, CVD Namer, CVD Names, CVD Meters, CVD Popper). This identified a significant main effect of Technique ($F_5=132.09$, $p<.001$). Accuracy results are summarized in Table 2.

Technique	Mean Accuracy (s.e.)	Mean Completion Time (s.e.)
NonCVD Control	100.00% (0.00)	1.58 (0.16)
CVD Control	54.24% (8.20)	13.73 (4.90)
CVD Namer	90.00% (8.09)	15.67 (2.52)
CVD Names	99.09% (0.91)	7.97 (1.32)
CVD Meters	94.55% (4.55)	5.66 (0.76)
CVD Popper	98.59% (0.99)	5.19 (0.65)

Table 2. Mean accuracy and mean completion times $\pm$ s.e. for the non-CVD control and for CVD participants in the control condition, with the colour namer, and each of our three techniques.

As we are interested in the performance of all techniques, our post-hoc analysis comprised full pairwise t -tests, which resulted in 15 comparisons. We applied Bonferroni correction to get an adjusted alpha of (.05/15=.0033). We found that CVD Control had significantly lower accuracy than the Non-CVD Control and all colour identification techniques, and that the NonCVD Control, Meters, and Popper were significantly more accurate than Namer (all $p<.05$, adjusted). Importantly, there were no significant differences between any of our techniques and the NonCVD Controls.

These results are valuable for three reasons. First, they confirm the underlying premise of this research – that people with CVD have difficulty identifying colours. Second, they show that two of our techniques (Names and Popper) resulted in higher colour identification accuracy than the colour namer. Third, it suggests (through lack of significant differences) that our three techniques allow people with CVD to identify colours as accurately as people with typical colour vision.

Completion Time

As with Accuracy, we conducted a one-way ANOVA across the same six conditions. This identified a significant main effect of Technique ($F_5=5.28$, $p<.001$). Completion time results are summarized in Table 2.

We conducted another round of Bonferroni-corrected pairwise t -tests to determine where the completion time differences lie between techniques. The NonCVD Controls were faster than all other techniques and the Namer took significantly longer than Meters and Popper (all $p<.05$, adjusted).

These results are important for three reasons. First, they unfortunately show that our techniques do not enable participants with CVD to identify colours as quickly as people with typical colour vision, so more work is needed. Second, they show that two of our techniques (Meters and Popper) resulted in faster colour identification than the colour namer. Third, we see that CVD participants are willing to spend time to achieve higher accuracy (compare CVD Control and Namer

completion times and accuracies in Table 2), suggesting that accuracy in colour identification is valuable.

Taking the accuracy and completion time results together, ColourPopper appears to be the only one of our tools that is both highly accurate (98.6%) and fast (5.2s).

Task Load Index

We performed one-way ANOVAs on each of the six measures of the NASA TLX [10] provided by CVD participants for each of the four techniques (plus the CVD Control condition) and followed this with post-hoc, Bonferroni-corrected t -tests when main effects were significant. All post-hoc results reported were significant at the adjusted .05 level (.05/10=.005). Results are summarized in Figure 8.

Figure 8. Mean TLX responses $\pm$ s.e. for CVD participants in the control and with each colour identifier.

Performance and Effort both had significant main effects of Technique ($F_4=8.79$, $p<.001$; $F_4=4.41$, $p<.01$). For Performance, post-hoc tests showed that our three techniques had higher perceived performance than the Control condition (all $p<.05$, adjusted). For Effort, post-hoc tests showed that Popper had lower perceived effort than both the Control and Namer conditions (both $p<.05$, adjusted).

These results suggest that our colour identification techniques help improve perceived performance over not having any tool (which is positive). In addition, Popper also has lower perceived effort than no tool, as well as the colour namer. Coupling these strong results with the overall pattern shown in Figure 8 (Popper lowest in every category), supports the accuracy and completion time results presented above – ColourPopper appears to be the strongest of our techniques.

Summary

Taken together the data shows that all colour identification techniques help people with CVD identify colours more accurately than with no assistance, with two of our techniques (Names and Popper) achieving almost perfect accuracy. The timing results show that this accuracy does not necessarily come at a cost, with Popper taking less time than all other techniques, although still not as quickly as people with typical colour perception. The TLX results show that our techniques help reduce the perceived effort of colour identification while improving perceived performance, again with special notice of Popper's strong scores across all of the TLX results.

MOBILE TOOLS

Given the relative success of our techniques in the desktop evaluation just presented, we implemented our techniques on a mobile platform and evaluated how well they supported people with CVD identify colours printed on paper samples.

Each tool (MobileNames, MobileMeters, MobilePopper) was implemented on a Samsung SM-T210 (Galaxy Tab 3), with a 1024x600 LED screen running Android version 4.1.2. Each system captured video frames from the built-in camera, and processed the image to either overlay colour information (MobileNames and MobileMeters) or manipulate the pixel colours via the ColourPopper LUTs described above. After processing, each frame was drawn to the screen to allow real time interactive colour identification.

MobileNames

Our mobile implementation of ColourNames utilized OpenCV libraries to overlay colour name information on each camera frame. This implementation was almost identical to the original ColourNames technique, except we opted to make the grid that identifies each individual colour naming rectangle visible. We found that the lines helped pilot testing participants properly align an individual naming cell with a target for which they wanted colour information.

MobileMeters

Our mobile implementation of ColourMeters also used OpenCV to overlay the meters as described for the original ColourMeters technique, and also displayed the individual meter cells. In addition to helping participants align the cell with a target, we also found that the grid helped reduce confusion because it provided an easily-accessible frame of reference for reading the angle of the meter. Without the grid, it was easy to get confused as the tablet was accidentally rotated during use (e.g., the meters appear to be pointing up (yellow), but in reality are pointing to the right (red/pink) and the tablet has been rotated counter-clockwise 90°).

MobilePopper

Our mobile implementation of ColourPopper used OpenGL shaders to swap every pixel in the incoming camera video frame using the LUTs described in the ColourPopper section above. As the mobile screen was not large enough to clearly present all of the available LUTs as a row of buttons along the bottom of the screen, we opted to use a pop-up menu listing the available LUTs to allow the user to make this choice.

MOBILE IMPLEMENTATION EVALUATION

To evaluate the mobile versions of our techniques, we conducted an in-lab evaluation in which the CVD participants from the desktop evaluation used each mobile tool to identify coloured targets printed on plain paper.

Tools

Participants used the three Mobile tools just described (MobileNames, MobileMeters, and MobilePoppers), plus no tool (we call this condition 'Eyes'), and a commercially-available free Android colour namer tool (Color Grab v2.6.1 – described above). Each participant used each tool in counter-balanced order for each of nine stimuli.

Stimuli & Task

To provide carefully-controlled colours, we replaced the black background with a white background in the 18 colour pair stimulation screens from the Desktop Evaluation and printed them on white paper. As there were two for each pair (e.g., one blue in 69 purple, and one purple in 69 blue), we picked one representative from each pair that maximized salience for a co-author with typical colour vision, while minimizing salience for a co-author with CVD.

Sheets were shown to participants one at a time in randomized order, and the participant used each tool in counterbalanced order to see if they could identify the target colour. Participants were instructed to identify the target using each of the techniques with the aim of getting an overall impression of that technique's effectiveness for that colour pair. After each coloured sheet, participants ranked each of the five techniques according to how well it helped with colour identification for that colour pair (five being the lowest rank, one=highest).

Results

Figure 9 contains the mean rankings for each technique. We carried out a one-way ANOVA on these results and found a main effect of technique ($F_4=7.90$, $p<.001$). We carried out Bonferroni-corrected post-hoc t -tests to explore this main effect. Five techniques gives ten pairwise comparisons, giving an adjusted alpha of $(0.05/10=0.005)$.

Figure 9. Mean rank $\pm$ s.e. for Eyes, Color Grab, and our Mobile tools.

We found that Mobile Names was ranked significantly worse (lower rank, higher number) than all other conditions except Color Grab, and Color Grab was ranked significantly worse than Eyes and Mobile Popper (all $p<.05$, adjusted).

Although less formal than the desktop evaluation, the findings from this study help refine some of our previous results. Once again, ColourPopper came out strong, with ColourMeters close behind. However, this study resulted in two surprises. First, ColourNames fared much worse in this study than would be expected from the desktop accuracy results. Many participants commented that ColourNames (with grid visible) was so visually 'busy' that it crowded out the actual image – a potential explanation for ColourNames' poor ranking. Second, Eyes fared much better in this study than in the desktop study for CVD participants. Our hypothesis is that despite our attempts at the contrary, the printed stimuli were in some cases actually distinguishable for our participants. In these cases, Eyes worked well, and the introduction of any of the mobile tools between the user and the stimuli likely resulted in the tools being rated poorly in these circumstance.

DISCUSSION

Summary & Explanation of Results

We found four main results:

1. ColourNames and ColourPopper allowed CVD participants to identify colours as accurately as their nonCVD counterparts, and more accurately than the colour namer.
2. ColourMeters and ColourPopper allowed CVD participants to identify colours more quickly than with the colour namer, but not as fast as nonCVD participants.
3. CVD participants perceived that their performance was higher with ColourNames, ColourMeters, and ColourPopper versus no tool, and that ColourPopper reduced their effort compared to no tool and the existing colour namer.
4. When tested on mobile versions of our techniques, CVD participants ranked ColourNames lowest, but ColourMeters and ColourPopper (and Eyes) highest.

The main reason for these results (ColourPopper is stronger than ColourMeters, which is stronger than ColourNames) is the progressive nature of their development; ColourNames built on colour namers, ColourMeters built on ColourNames, and ColourPopper built on ColourMeters. Overall, ColourMeters and ColourPopper appear to be the best candidates for future colour identification technology for ICV.

Strengths & Weaknesses of Each Technique

ColourNames is a simple extension of existing colour namers, that provided high accuracy and faster colour identification times than our desktop colour namer. This technique is arguably the easiest of our techniques to learn (little to no extension from colour namers), however ColourNames came out much worse in the mobile evaluation. One potential reason for this was that we turned the rectangular grids on in MobileNames, however MobileMeters also had the grid, but was not apparently penalized. Another possible explanation is that the grid actually offered little value in the MobileNames condition (in contrast to our pilot study findings), whereas the grid was valuable for providing a frame of reference in the MobileMeters condition. As such, participants may have penalized MobileNames for its unnecessarily cluttered screen.

ColourMeters had strong completion time and mobile ranking results, but had lower colour identification accuracy than our other tools (94.5% versus ~99% for ColourNames and ColourPopper). Upon closer inspection, we found that this lower score was attributable to a single CVD participant who scored a relatively low 50% accuracy. This may have happened due to confusion over how the technique works, highlighting the need for proper ColourMeters training. We did not remove outliers in the analysis presented above, but removing this single participant's data improves ColourMeter's accuracy to that of ColourNames (99.1%), suggesting that with adequate training, ColourMeters is a valuable technique for helping improve colour identification.

Of all our techniques, ColourPopper was the fastest, had the lowest perceived load, had nearly 100% accuracy, and was highest ranked, but this technique has two major limitations.

First, it required the designers (us) to determine the number of colour names ColourPopper supports, and we also had to decide which RGB colours map to which names. Fortunately, our colour name dictionary based on Heer & Stone's work [11] helped substantially with this, but there may be other use cases where our choices are not optimal. How to design ColourPopper to provide a dynamic number of colour highlighting options will be one focus in our future work.

Extensions & Future Work

The second limitation of ColourPopper is its required interaction for choosing a highlight colour. In our desktop implementation, users select the colour from a row of buttons along the bottom of the screen, and use a pop-up menu in the mobile version, but there are many more options which may prove much faster. Perhaps tracking menus [7] or contextual pie menus can provide some speed gains, but might prove cumbersome on touch-based mobile interfaces. Another option is simple voice input of just stating the name you want highlighted. This might work particularly well with ColourPopper on wearable transparent displays. We plan to explore reducing the interaction time of ColourPopper in the future.

In terms of wearable transparent displays, one of the central goals for future extensions of this work is moving our techniques to wearables. Both ColourPopper and ColourMeters offer promise for wearable platforms, which will allow our colour identification techniques to be used in a less cumbersome manner than our current mobile implementations. This extension will require revisiting our techniques for use in a wearable context, as well as evaluating our techniques in terms of real world colour identification (e.g., reading colour-coded subway maps, estimating fruit ripeness).

In spite of the slightly lower accuracy performance of ColourMeters (already discussed above), it offers potential value of a different nature than ColourPopper. First, it sometimes provides the popout effect of ColourPopper through texture patterns of its tiled meter visualizations. Second, unlike ColourPopper, ColourMeters does not require a colour name dictionary. This frees it from the limitations imposed by identifying colours by name in a particular language. ColourMeters offers the greatest promise for cross-cultural (and illiterate and preliterate) improvements in colour identification for people with ICV. Third, ColourMeters attempts to visually present raw colour information to the user. We contend that this might enable sub-sensory substitution when persistently used, in which over time, the user begins to 'see' colours (as mediated by the ColourMeters visualizations) and ceases to see the visualizations themselves. This would allow people with impaired colour vision to overcome their ICV entirely, resulting in a technologically-based 'cure' for ICV.

CONCLUSION

Colour identification helps in many day-to-day tasks such as preparing food, getting dressed, and being creative. However, for the 5-10% of the population with Impaired Colour Vision (ICV), colour identification is often frustrating and can lead to mistakes with potentially severe consequences (e.g., undercooking meat, misreading a wiring diagram). Colour naming

tools have been developed to improve colour identification, but these tools are typically too slow for many common tasks and lack precision in the colour names they provide.

To address these problems, we developed three new colour identification techniques (ColourNames, ColourMeters, and ColourPopper) and evaluated them using desktop and mobile colour identification tasks with people with ICV. We found that ColourPopper offered the best performance overall, with ColourMeters close behind; both achieved nearly 100% colour identification accuracy in the best time. With the extensions we identify above, these two techniques can be even better, potentially becoming ‘invisible aids’ that allow people with ICV to experience the full range of colours.

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