“So That’s What You See!” Building Understanding with Personalized Simulations of Colour Vision Deficiency

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ABSTRACT
Colour vision deficiencies (CVD) affect the everyday lives of a large number of people, but it is difficult for others – even friends and family members – to understand the experience of having CVD. Simulation tools can help provide this experience; however, current simulations are based on general models that have several limitations, and therefore cannot accurately reflect the perceptual capabilities of most individuals with reduced colour vision. To address this problem, we have developed a new simulation approach that is based on a specific empirical model of the actual colour perception abilities of a person with CVD. The resulting simulation is therefore a more exact representation of what a particular person with CVD actually sees. We tested the new approach in two ways. First, we compared its accuracy with that of the existing models, and found that the personalized simulations were significantly more accurate than the old method. Second, we asked pairs of participants (one with CVD, and one close friend or family member without CVD) to discuss images of everyday scenes that had been simulated with the CVD person’s particular model. We found that the personalized simulations provided new insights into the details of the CVD person’s experience. The personalized-simulation approach shows great promise for improving understanding of CVD (and potentially other conditions) for people with ordinary perceptual abilities.

Categories and Subject Descriptors: K.4.2 [Social Issues]: Assistive technologies

Keywords: Colour vision deficiency, colour vision simulation

1. INTRODUCTION
Colour vision deficiencies (CVD), also called ‘colour blindness,’ are conditions in which a person perceives fewer colours than other people. CVD can arise from genetic factors (e.g., eight percent of men have reduced sensitivity to the red-green colour axis), or can be acquired through factors such as age (e.g., cataracts or yellowing of the lens), exposure to chemicals (e.g., solvents such as styrene), or brain injury (e.g., stroke or trauma).

Colour vision deficiencies cause many different problems, ranging from minor annoyances (e.g., being unable to differentiate between visited and unvisited website links) to difficulties that compromise safety (e.g., when alert messages do not stand out from the background). Although CVD has many implications for professional activities, our focus in this paper is on the profound effects that it has on everyday life. Some of these effects are well known, such as the stereotype of a man with red-green CVD who can’t match the colour of his socks, but there are many other commonplace activities where reduced colour perception dramatically changes experience and ability. For example, a person with CVD may have difficulty buying or picking fruit (since we use colour to judge ripeness), cooking meat (since the difference between ‘rare’ and ‘well done’ is primarily a colour difference), communicating with others about things in the world (“Quick – hand me the green one!”), and sharing the aesthetic experience of rainbows, flowers, fireworks, or paintings.

These problems are not life-threatening, and people with CVD develop coping strategies to successfully get around most of the problems. However, as with many other disabilities and impairments (e.g. low visual acuity, hearing or memory loss, reduced mobility, or chronic medical conditions), there is a non-trivial degree of frustration in dealing with a world that is organized for the ergonomist’s ‘95th percentile’.

Part of this frustration arises from the difficulty that people with CVD have in communicating their perceptual experience to family, friends, and co-workers. Most CVDs are much more complex than the stereotypical ‘inability to tell red from green,’ and it is difficult for those with ordinary colour vision to imagine what life is like for the person with CVD.

One technique that can help to improve this understanding is simulation – that is, altering images using a model of CVD in order to show a person with ordinary colour vision what the image looks like to someone with a colour vision deficiency. Simulation has been successfully used in other domains, such as aphasia [9], to help convey the experience of a condition to other people.
Digital methods for simulations of CVD also exist (and have existed for many years, e.g., [16][12][3]), but existing techniques suffer from three main shortcomings when used as tools for conveying understanding of a person’s colour experience.

First, publically-available systems (e.g., Vischeck [5]) only simulate dichromatic CVD (a severe form where one type of retinal cone cell is missing), but a majority of cases of genetically-caused CVD (75%) involve anomalous trichromacy – a less severe form of the condition in which all three photoreceptors are retained, but one has a shifted colour sensitivity. Dichromatic simulations are therefore too extreme for most cases of CVD. Simulations of anomalous trichromacy do exist, but require information about how much the affected cone is shifted – a value that is not available from existing colour vision tests. Second, current systems need to know the specific type of CVD the user has, but individuals rarely know the type of their condition. Third, existing methods only simulate one type of CVD at a time, but there are cases (especially in older adults) where an individual has a combination of genetic and acquired colour vision deficiencies.

These limitations mean that although current simulations can provide a rough indication of the kinds of problems faced by people with CVD, the specific experience of a particular individual is still difficult to understand. The specificity of the simulation is actually very important, since it is the specific experience of a particular individual that the person without CVD wishes to understand. Approximations can demonstrate general problems, but can never achieve the goal of showing exactly how the world looks to a spouse, a child, a parent, or a close friend.

To address this problem, we have developed a CVD-simulation method that can provide a much more accurate and specific view of how a particular individual sees colour. Instead of using a standard model of CVD as the basis for the simulation, our method builds an individualized model of a person’s colour perception from empirical data [8][7]; this model exactly captures the type and severity of the person’s colour vision deficiency, including conditions such as anomalous trichromacy and multiple simultaneous deficiencies. Using the exact type and severity of CVD for an individual, we then alter the outputs of images to show exactly what a particular person with CVD can see.

We tested our new simulation method in two ways. First, we quantitatively evaluated the approach’s accuracy by comparing the existing dichromatic model of CVD to our personalized model. Using each model, we performed CVD simulation of the calibration procedure used in [7] and had people without CVD run the calibration. This essentially induced CVD in people with ordinary colour vision and allowed us to measure their resulting colour differentiation abilities. Our tests showed that the personalized simulation measurements were significantly closer to CVD participants’ colour differentiation ability measurements than the existing dichromatic simulation measurements – calibration measurements were only two ‘just-noticeable steps’ away in a perceptually uniform colour space [11].

Second, we investigated our method’s ability to help people share understanding of CVD conditions. We asked pairs of people (each pair having one CVD person and one non-CVD spouse, family member, or close friend) to view and discuss pictures of everyday scenes that had been simulated using the CVD participant’s individualized model. We found that even for pairs that had known each other for years, the simulations provided the non-CVD participants with a variety of new insights into the other person’s experience with colour.

Our work makes four main contributions: first, we propose the use of personalized simulations of CVD to increase understanding of CVD for people without CVD; second, we develop a personalized CVD simulation method that is based on empirical measurements of an individual’s colour differentiation abilities; third, we show that personalized CVD simulations produce substantially more accurate representations of CVD colour perception than existing models of CVD; and fourth, we show that personalized simulations can help improve understanding of CVD for people without CVD. Personalized simulation works well in the CVD domain, and shows promise for helping to share the experiences of other types of extraordinary users as well.

2. BACKGROUND
Here we summarize different types of CVD, existing simulation systems, and the standard method for dichromatic simulation.

2.1 Types of CVD
CVD can be caused by a number of internal and external factors. Internal factors are intrinsic to the user (e.g., genetic causes or acquired conditions). External factors are environmental or situational issues outside the user (e.g., lighting levels, or wearing tinted glasses). Due to the transient nature of externally-induced CVDs, we will only focus on internal causes of CVD here.

Genetic CVD. The human X chromosome contains the genetic information that determines the presence and sensitivity of the long and medium wavelength sensitive cones in the retina [1]. Due to variations in this chromosome, some individuals do not have one of these cone types (dichromacy - more specifically, protanopia for missing long-wavelength cones and deuteranopia for missing medium-wavelength cones), or have a variant form of one of these cone types that exhibits a shifted peak wavelength sensitivity (anomalous trichromacy – protanomalous for long-wavelength, and deuteranomalous for medium-wavelength) [2][25]. Men have only a single X chromosome, so their rate of genetic CVD is much higher (8% in Caucasians) than in women (~0.5%), who have two X chromosomes [4]. Short-wavelength cone genetic CVD (tritanopia and tritanomalous) is much rarer because this cone type is encoded on a non-sex-linked chromosome. Other rare types of genetic CVD occur in individuals who are missing two cones (cone monochromacy) or three cones (rod monochromacy) [1].

Acquired CVD involves damage to the vision system from events such as accident, disease, or exposure to harmful chemicals. These often result in colour perception that is similar to tritanomaly and tritanopia, because the number of short-wavelength cones is relatively small compared to the number of long and medium sensitive cones, and these are therefore more susceptible to retinal damage [13]. Exposure to ultraviolet light has been linked to yellowing of the lens with age as well as to the development of cataracts. Both conditions result in yellow-tinged colour vision; in one study almost 64% of British participants over the age of 65 showed some signs of this yellowing [6]. Many other acquired CVDs (such as those caused by retinopathy) exist, and can even be caused by depression or by antidepressants or Viagra [27].

All types of CVD cause similar problems for our purposes – they make it difficult for people to differentiate among colours that can be distinguished by most other people. This leads to difficulties in any situation that requires colour differentiation to accomplish some task, such as buying fruit, cooking meat, identifying children’s toys, getting dressed, navigating, enjoying the visual arts, and decorating [4][20][21].
2.2 Types of CVD Simulations
The earliest digital simulation of CVD, by Meyer and Greenburg in 1988 [16], describes an approach for translating colours within a colour space in order to model dichromatic colour vision. This work was extended by colour science researchers to provide an algorithm for simulating dichromacy [3][23][24]. These simulations show non-CVD individuals what images look like for people with any of the three types of dichromatic vision (protanopia, deuteranopia, or tritanopia).

More recently, simulations of anomalous trichromacy have been developed [12][14]. These simulations require both the type of anomalous trichromacy and additional information about the severity of the condition. This is typically expressed in the amount of peak sensitivity shift of the anomalous cone (expressed in nanometres). However, this type of information is not readily available from existing colour-vision tests.

2.3 Dichromatic CVD Simulation Details
To simulate the appearance of an image for someone with CVD, the colour of each pixel in the image is replaced by the colour perceived by the person with CVD. As people with CVD perceive fewer colours than people without CVD, this process of mapping original colours to replacement colours is typically compressive – different original colours will map to the same replacement colours, e.g., people with protanopia perceive particular shades of pink, grey, and turquoise all as a single grey. To identify a replacement colour, both the set of colours that are perceived identically, and the colour this set maps to need to be identified.

To find the set of colours that are perceived identically for people with dichromacy, CVD color confusion lines are utilized. In the 1976 CIE L*a*b* perceptually-uniform colour space [26], every colour has a sphere around it that defines a discrimination boundary for that colour. In people with CVD – colours inside the sphere are not differentiable from the original colour and colours outside the sphere are differentiable [22]. When measuring the discrimination spheres for people with dichromacy, it was found that the sphere had been elongated in one dimension to form an ellipsoid [15] that exceeds the L*a*b* gamut, and the direction of elongation was unique to the type of dichromacy. The line defined by the elongation (the major axis of the ellipsoid) is a color confusion line – the line or set of colours that are perceived identically by someone with dichromacy [22]. Confusion lines for each type of dichromacy are shown in Figure 2.

Confusion lines allow the identification of original image colours that are indistinguishable for someone with dichromacy, but what colour does someone with dichromacy actually perceive? This is akin to knowing that a man with inherited CVD confuses red and green, but not knowing what he actually sees. To answer this question, a special set of colours that are perceived identically by people with and without dichromacy has been identified using measurements from people with unilateral dichromacy – a condition in which a person has dichromacy in one eye but ordinary colour vision in the other eye. People with unilateral dichromacy have identified that spectral colours of 475nm (blue) and 575nm (yellow) are identically perceived by people without CVD and those with protanopia and deuteranopia. People with tritanopia perceive spectral colours of 485 nm (blue-green) and 660nm (red) the same as people without CVD [3]. Each pair of identically-perceived spectral colours define two half-planes in L*a*b* colour space. Each half-plane is defined by the spectral colour and the achromatic axis (grey scale colours from black to white) [16][3]. These half-planes are shown in Figure 3 (protanopic and deuteranopic on the left, tritanopic on the right), and are represented by the white line in each image in Figure 2.

To simulate how an image appears to someone with dichromacy, the colour of each pixel in an image is converted into L*a*b* colour space, shifted along its respective colour confusion line to the half-plane for the dichromacy being simulated, and then converted back to RGB. The resulting RGB colour is used to paint the corresponding output pixel in the simulation image.

3. PERSONALIZED CVD SIMULATION
Three shortcomings of existing dichromatic simulations were identified above:
1. Dichromatic simulations are too extreme for most types of CVD.
2. People with CVD usually do not know the type and severity of their CVD.
3. People can have multiple CVDs.

To address these three shortcomings, our method utilizes empirical measurements of each user’s colour differentiation abilities to determine the types and severities of the individual’s CVDs. Once the types and severities are known, a two-stage reduced-severity dichromatic simulation is employed to simulate the individual’s colour vision. By measuring the types and severities of CVDs, the second shortcoming is addressed; a reduced-severity simulation helps address the first shortcoming; a two-stage simulation allows red-green and blue-yellow discrimination difficulties to be incorporated into the simulation.

We also identified that the dichromatic simulation technique described above assumes that everyone without CVD has identical colour perception abilities, but recent research has identified variations in colour perception abilities among the non-CVD population [18]. To address this, we consider both the CVD and non-CVD individual during simulation. To accomplish this, our method measures the colour vision abilities of the person with CVD and the colour vision abilities of the non-CVD person who...
will be viewing the simulation. To gather this information, we use the ICD calibration procedure \[7\]1. The calibration procedure presents a gapped circle of a particular colour on a grey background (Figure 4). If the user can see the colour, they respond by indicating the orientation of the gap in the circle. If they cannot see the circle, they press the space bar. The sequence of colours is carefully chosen from the three confusion lines that intersect the neutral (grey) point in the isoluminant plane (L*=50.0) shown in Figure 2. Three confusion lines intersecting the neutral grey point give six lines of colours to present to the user, one in each direction out from the neutral grey. By presenting colours that progressively move away from the neutral point (similarly to the colour vision test presented in \[17\]), we are able to identify the discrimination limit for each line – the point at which the user is able to differentiate between the neutral grey and the confusion line colour. Because individuals with CVD have difficulty differentiating colours along the confusion line that aligns with their type of CVD, the discrimination points for people with CVD are generally farther away from the neutral grey point than the discrimination points for people without CVD.

To perform the partial dichromatic simulation, we must determine the amount to shift along each confusion line. This information is derived from comparing the two discrimination ellipses described above. To perform a simulation, the discrimination ellipses are used to inform a ‘partial’ dichromatic simulation – meaning that instead of shifting colours all the way along a confusion line to its corresponding point on the dichromatic half-plane (as in dichromatic simulation), we only shift colours a fixed distance toward these half-planes along the confusion line. This results in a partial dichromatic simulation, which aligns well with the colour vision experience of anomalous trichromacy; a small shift represents a minor degree of anomalous trichromacy, and a larger shift represents severe anomalous trichromacy.

To perform the partial dichromatic simulation, we must determine the amount to shift along each confusion line. This information is derived from comparing the two discrimination ellipses described above. First, the angle of the major axis of the discrimination ellipse for the individual with CVD is compared to the angle of the confusion lines for the neutral grey point. The confusion line angle that is closest to the major-axis angle is chosen as the ‘primary’ CVD. The confusion line angle that is closest to the minor-axis angle is then chosen as the ‘secondary’ CVD. Due to the nearly parallel nature of protan and deutan confusion lines, the primary and secondary CVD can never be protan and deutan (or vice versa), resulting in the configurations shown in Table 1.

Once the primary and secondary CVDs are identified, the amount of shift along each confusion line is determined. Due to the impossibility of protan and deutan co-occurring, we simplify this step to identifying a ‘red-green’ shift amount (either protan or deutan), and a ‘blue-yellow’ shift amount (tritan). To find the primary CVD shift amount, the absolute difference between the major axis half-length and the average of the major and minor axes’ half-lengths for the non-CVD ellipse is calculated. Similarly, the secondary CVD shift amount is the absolute difference between the CVD minor-axis half-length and the same non-CVD average. The non-CVD average axis half-length is used because the discrimination ellipses for people with ordinary colour vision are generally circular, resulting in arbitrary major axis angles. To compare axis lengths, they must be rotationally aligned, so averaging the half-lengths represents the non-CVD discrimination ellipse as a circle, thereby making it rotationally invariant and simplifying the shift amount calculations.

For each pixel in an input image, the simulation colour for that pixel is determined using existing dichromatic simulation techniques for the primary CVD. The length of the L*u*v* colour space vector from the original colour to the dichromatic colour is found and compared to the primary CVD shift amount. If the primary shift amount is greater than the vector length, then the dichromatic simulation colour is used. If the primary shift amount is less than this vector length, however, the colour along this vector that is the ‘primary shift’ distance from the original colour is used. We call the colour that results from this primary CVD simulation step the ‘primary replacement colour’.

To simulate the secondary CVD effects on colour vision, the secondary CVD dichromatic simulation colour for the primary replacement colour is found using existing dichromatic simulation techniques. The length of the L*u*v* vector from the primary replacement colour to this dichromatic colour is found and compared to the secondary CVD shift amount. If the secondary shift amount is greater than this vector length, then the pixel in the output simulation is painted the primary replacement colour. If the secondary shift amount is less than this vector length, then the colour that is ‘secondary shift amount’ distance along this vector
from the primary replacement colour is used to paint the output simulation pixel.

4. EVALUATION
We assessed the personalized simulation approach in a user study with five pairs of participants, where each pair consisted of one person with CVD (4 males – 2 mild deutan, 1 medium deutan, 1 strong protan; 1 female – unclassified red-green) and one without (3 males, 2 females). Each participant performed the HRR colour vision plate test [10], then performed calibration tests to build a personalized model. The non-CVD participant then carried out another calibration, but this time the colours were altered using their partner’s CVD simulation. The results from this calibration were used to evaluate the accuracy of the simulation. After calibration was finished, both participants engaged in a qualitative exploration of original and simulated versions of 16 images.

4.1 Simulation Accuracy
To see whether our personalized simulation more accurately simulates the CVD user’s colour vision than the existing dichromatic simulation, we compared the discrimination limits generated by each simulation to the CVD participant’s limits. We calculated the average absolute difference for each comparison. As shown in Figure 6, the personalized simulation had a significantly lower average absolute difference (paired, two-tailed t-test, p<.01). We illustrate this difference in Figure 7 by showing the discrimination ellipses for the three models: the CVD person’s model, the personalized simulation with the non-CVD user, and dichromatic simulation with the non-CVD user.

![Figure 6. Mean absolute difference between simulated model (non-CVD user) and actual model (CVD participant).](image)

![Figure 7. Original CVD discrimination ellipses (red) for three deutan participants, their non-CVD simulation discrimination ellipses (blue), dichromatic simulation ellipses (green).](image)

4.2 Qualitative Evaluation
To evaluate whether personalized simulations of CVD aid the understanding of CVD for people with ordinary colour vision, we selected 16 images from the internet depicting situations that often pose difficulties for individuals with CVD (Figure 8). Specific difficulties are described below. Once the calibrations were completed, we simulated the appearance of each image with the CVD user’s model, and presented the images (original and simulated side by side). The participants explored the sixteen image-pairs together, discussing differences and similarities. In some cases, the experimenter would pose questions about some aspect of the image in order to follow up on comments made by the participants. This part of the study was videotaped for later analysis. The study was complete when participants were finished exploring the sixteen image pairs.

To present the qualitative results from the exploration, we grouped the images into four categories (Outdoors, Food, Safety, Play), and discuss each category below. Images and categories were based on personal experience with CVD (the first author has medium-severity protanopic CVD), as well as surveys reported in previous literature [4][21].

![Figure 8. Images used in the exploration phase of the study.](image)

![Figure 9. Example image and personalized simulation (right).](image)

4.2.1 Outdoors
The colour differences contained within natural scenes often present a challenge to individuals with CVD. This challenge can range from purely aesthetic differences (e.g., the colours of a rainbow), to more practical implications (e.g., picking apples).

Participants responded strongly to the image of outdoor scenes. When examining the apple-tree image, one CVD participant remarked “Those are apples on the ground?! I thought they were just rocks”; most CVD participants commented on the difficulty of picking apples in real life. Participants without CVD noticed that the foliage appeared much less vibrant in the CVD simulation, and also commented on the severe reduction in contrast between the red apples and green leaves. One non-CVD person commented “Those look the same to you, but they are substantially different to me.”

The rainbow and Christmas tree images also provided dramatic revelations about CVD colour perception. The simulation of the rainbow was often reduced to a band of blue and a band of yellow; when a non-CVD person remarked on this, the CVD participant exclaimed “That's how they have always looked to me!” Similarly, non-CVD participants regularly remarked on how the Christmas tree (and foliage in general) looked under-watered...
and unhealthy in the CVD-simulated images. One non-CVD participant said to her partner “Now I understand why you think evergreen trees are ugly!” and another remarked “All foliage is rotten in your world?”

4.2.2 Food

Colour is an important indicator for many types of food: the ripeness of fruit (e.g., bananas become more yellow as they ripen), how cooked meat is (e.g., rare versus medium steak), and whether something is spoiled or about to spoil (e.g., tomatoes going bad).

When presented with this set of images, CVD participants immediately recalled their own difficulties with colour-dependent foods, and several remarked that the two images looked the same. This prompted several responses from the non-CVD participants. The ‘greenness’ of unripe bananas often disappeared in the simulated image, prompting one non-CVD participant to observe “I wouldn’t eat these (pointing at two bananas), but in this one (pointing to the simulation), they are the same!” When discussing the tomatoes, one non-CVD participant remarked “It’s a wonder you can find any tomatoes at all – they’re all green!” Difficulties with tomato colour were also discussed by a CVD participant who said that one tomato was a “strange colour,” to which his non-CVD partner replied, “No, it’s an almost-ripe tomato.” Another non-CVD participant remarked that some of the simulated image tomatoes looked either “not yet ripe – or spoiling.” Regarding the peppers, several non-CVD participants remarked on the “strange” colour of the orange peppers in the simulated image, with one commenting that “[they] now look completely unappetizing!”

The most powerful responses in this set of images were to the meat image. Many non-CVD participant responses expressed shock and disbelief that their CVD partner could not see the pink in the meat or the blood in the juices. This elicited responses such as “I’m not letting you barbecue anymore!” and “No wonder you don’t ever want to cook meat!”

4.2.3 Safety

In addition to food characteristics, colour helps us when detecting illness (e.g., rashes), as well when we navigate the world around us (e.g., traffic signs). Trouble differentiating colours in these circumstances can have clear implications for personal safety.

Participants who viewed these images responded differently to the traffic images (stop sign and traffic light) than to the skin images (rash and sunburn). Traffic images elicited anecdotal evidence of how individuals with CVD successfully navigate the driving world by relying on redundant encodings (e.g., the position of traffic lights and the shape of stop signs) or other drivers (e.g., watching other cars or asking for help from a passenger), and by driving more defensively. The traffic images elicited several comments from non-CVD participants (e.g., “That’s why you call the green light white!”), even though none of the non-CVD participants remarked on feeling unsafe when driving with their CVD partners. This suggests that the discussion around the traffic images helped non-CVD participants gain understanding of the coping strategies used by people with CVD.

When examining the rash and sunburn image, individuals with CVD would closely examine the original image, stating that they could see something discoloured on the skin, but were unsure of what it was. One CVD participant remarked that neither image (rash or sunburn) would “indicate any cause for concern.” This prompted recollections from non-CVD participants regarding their CVD partner getting severe sunburns in the past (“...and now I know why!” one said). Similarly, a non-CVD participant said that the sunburned girl “just looks embarrassed to you” (referring to his CVD friend).

4.2.4 Play

One participant with CVD commented that his mother figured out he had CVD when he “kept bringing home elephants coloured pink.” This highlights the difficulty people with CVD have with children’s activities and toys, because of their reliance on colour. This series of images helped non-CVD participants get a clearer understanding of their CVD partner’s difficulties. The crayon image was examined closely by all participants. Many commented on the overall muted state of the crayons in the CVD simulation, but noticed that yellows and blues were often retained (an important realization, as people with protan and deutan CVD largely retain their ability to distinguish yellows and blues). Many non-CVD participants also commented on how the clear colour differences in the original image were reduced to subtle variations in brightness in the simulated image; one CVD participant agreed, stating “I have to worry about specific shades and tones, because that’s all that is different.” The coloured candy image had non-CVD participants playing the ‘can I sort them?’ game with their CVD partners. These discussions again brought up comments about large colour differences being reduced to subtle variations in similar shades, and one non-CVD participant commented on her partner's ability to pick out tiny variations in brightness or intensity to identify different colours. She further commented that she would likely miss these subtleties because to her the colours are “just different.” When presented with the image of the blocks, one non-CVD participant exclaimed “Now I understand why you hate yellow,” to which her partner replied “It’s too bright!”

4.2.5 Other observations and survey responses

Most participants greatly enjoyed the exploration sessions, and discussed a wide range of colour-related topics. We observed that most of the CVD participants remarked at least once on the similarity of the original and simulated images, providing additional evidence of the personalized simulations’ accuracy. In addition, the CVD users seemed to find value in the simulations, even though they were designed primarily for the non-CVD users; in several cases CVD participants learned new things about how their partner saw the world, information that could help future communication with people who have ordinary colour vision.

Finally, both before and after the exploration session, we asked non-CVD participants to complete a short questionnaire asking how well they felt they understood the CVD participant’s condition. The responses after the session were almost universally higher (mean of 0.9 higher on a seven-point scale), indicating that the personalized simulations did help provide new understanding of the everyday experience of CVD. (We note that this increase may be partially due to the effects of simulation more generally, since some pairs may not have used other simulation tools).

5. DISCUSSION

Our study showed three main findings:

• Personalized colour-perception models (that were originally designed for recolouring tools) can be used as the basis for simulations of a particular person’s CVD;

• These personalized simulations accurately simulate a person’s colour vision deficiency for another (non-CVD) person, and are substantially more accurate than the standard dichromatic model;

• Using the personalized simulation to explore images of everyday scenes led to new insights and understanding for CVD/non-CVD pairs of participants;
In the next sections we provide explanations for these results, and then discuss three main issues that arise from our experience with personalized simulations: improvements to the current technique, further applications of the approach within the CVD domain, and applications to other domains of assistive technology.

5.1 Explanations of Study Results

We measured accuracy by comparing each CVD users’ colour-perception model with the simulation-induced model for their partner. As shown above (Figure 7), the discrimination ellipses for the two models were very similar for all pairs of participants – and much more similar than for the standard dichromatic model.

The reason for this improvement follows directly from the basic premise of this work – that an empirical model of an individual’s actual colour perception provides a much better foundation for a simulation tool than a generic model of CVD. The standard dichromatic models do not work well for most people with CVD because the dichromatic discrimination ellipses are much larger than those corresponding to anomalous trichromacy (which is much more prevalent, but much harder to model [14]). As a result, the standard models produce incorrect simulations that do not accurately convey a particular person’s CVD experience.

The success of the personalized simulations in the exploration part of the study is more difficult to assess, since we did not ask people to use the standard CVD simulations during the exploration phase. However, our observations highlight two points that argue for the value of our approach. First, the fact that long-time couples and friends found new insights in the exploration phase suggests that the personalized simulation provided information that they had not found through other means (including available tools such as Vischeck [5]). Second, it was clear from our observations that participants appreciated the specificity of the simulation, and the close match to the experience of the person with CVD. CVD participants made several remarks about how the two images (e.g., Figures 1 and 9) looked the same to them, and much of the discussion between the two people involved specific details of the simulation (e.g., small differences in the colour of a tomato). These detailed explorations would not have been possible with the generic dichromatic simulation, due to its inaccuracy for most types of CVD.

5.2 Improvements to the Current Technique

There are two main possibilities for improving our current technique: extension to monochromatism and handling variations in luminance perception.

As described above in Section 2.1, individuals who have zero or one cone types have monochromatic vision. Our simulation currently handles this case by setting very large R-G and B-Y shift amounts (essentially removing all red-green and blue-yellow contrasts). However, the dominant perceived hues of the secondary CVD (blue and yellow for protan and deutan; red and blue-green for tritan) remain in the simulated image, because the primary and secondary simulation steps occur independently (except that the second step takes input from the first). To address this, we can perform the secondary CVD simulation step within a constrained colour set – the set of colours that are perceptible to the user according to the primary CVD simulation. This would allow the secondary CVD simulation step to incorporate the effects of the primary CVD, thereby reducing or eliminating the dominant perceived hues of the secondary CVD in the simulation.

A second way to improve the technique is to incorporate simulation of perceived brightness for different types of CVD. For example, in cone monochromatism, colours that maximally stimulate the single cone type appear much brighter than for non-CVD individuals. To incorporate these further personal variations, additional calibration steps that measure perceived brightness could be added to the calibration procedure, and used to inform the L*U*V* coordinates of the original input colour.

5.3 Further Application to the CVD Domain

The simplicity of the personalized approach and its success in helping participants share the experience of CVD suggest that the method could be used more broadly; here we consider four directions for wider deployment.

- **Web-based deployment.** The modeling and simulation mechanisms used in the tool and study can be repackage for a platform such as the WWW, and can be used in an unsupervised fashion (like existing tools, but with a modeling stage added to the process). In addition, a Web deployment can allow server-side performance optimizations (such as parallelization) for large complex images.

- **A community of simulations.** A web-based approach would also provide an opportunity for people to share their models more widely. A broad set of models and associated simulations would be a valuable resource for visual designers – essentially as an extended version of existing tools such as Vischeck [5]. A community of models would allow designers to test a proposed design under simulations from several different CVD participants in order to ensure visibility and usability for a wider range of real-world users.

- **Images from people’s real lives.** The images used in the study initiated considerable discussion for our participants, but there would likely be more opportunity for shared understanding if participants could produce simulations of images from their own daily lives; this would couple the specificity of the personalized approach with objects and scenes from people’s local context. The main issue in simulating arbitrary images is the number of colours in the image (computation time is proportional to this number), but quantization or resizing can be used to reduce processing time (or to provide an initial simulation while a finer-grained version is produced).

- **Real-time mobile simulation.** An extension to simulating people’s real-life images is the idea of moving the simulator to a mobile device such as a smartphone, and allowing CVD and non-CVD users to create simulations on demand in everyday use. A mobile version of the tool can be used to improve understanding, but also extends the approach to become an accommodation aid for a non-CVD person – that is, as they go through daily life, they can immediately answer the question “Will my friend with CVD be able to see that?”

5.4 Application to Other Assistive Domains

The overall approach of personalized models and simulation can also be applied more widely than just in the domain of CVD. First, the idea of simulation from modeling is itself a generalizable concept – the personalized models of CVD were not originally conceived as a tool for improving understanding, but rather as a tool for improving accessibility (e.g., [8][7]). As a result, models that capture perceptual or other capabilities can be used in many ways, and the example of personalized simulation shows that they can provide other benefits.

Second, the basic mechanisms for modeling and simulation described here can be applied to other areas of assistive technology. In general, the approach is applicable to any condition
where people’s perceptual capabilities can be empirically tested, and where those capabilities are based in underlying psychometric functions (so that they can be modeled accurately). Two areas where the approach could work well are hearing loss and low visual acuity. As with CVD, these conditions have many variants, and personalized models could be used both for new assistive technologies as well as for simulations that help to improve understanding of living with these conditions.

In addition, it may also be possible to extend the approach to some muscular conditions that affect motor control (e.g., Parkinsonian tremors). For example, it may be possible to empirically record and model the characteristic movements of these conditions for a particular person, and then simulate them for people without the condition (e.g., by adding movements to a mouse cursor in order to demonstrate the difficulties experienced in carrying out targeting actions). These kinds of applications would complement work already done to simulate conditions such as aphasia [9], but would add the value of providing an experience that is specific to a particular person.

6. CONCLUSIONS AND FUTURE WORK

Simulation tools can provide an understanding of what a person with CVD experiences, but current simulation methods do not provide accurate reflections of most CVD users’ perceptual abilities. We developed a new simulation approach that uses a personalized model to provide a much more accurate simulation of a particular person’s experience with CVD. The new approach was shown to be much more accurate than the standard model, and proved to be a valuable aid in helping non-CVD people to understand a CVD person’s view of the everyday world. The personalized-simulation approach provides a valuable new tool for people with CVD and those who live and work with them.

In future work, we plan to explore all three directions outlined in the discussion above. First, we will continue to refine and improve upon the current tools by extending it to cone monochromatism and variations in perception of brightness. Second, we will deploy the model much more widely, by developing a public website where people can build personalized models and view simulations of images from their own lives, and by developing a mobile application that allows non-CVD people to dynamically check any scene to see how it appears to someone with CVD. Third, we plan to extend the personalized-simulation approach to other assistive-technology domains such as hearing loss and low visual acuity.

7. REFERENCES