Dynamic Simulation of Color Blindness for Studying Color Vision Requirements in Practice

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Abstract

We report on a dynamic simulation of defective color vision. Using an RGB video camera connected to a PC or laptop, the captured and displayed RGB colors are translated by our software into modified RGB values that simulate the color appearance of a person with a color deficiency. Usually, the simulation of deficient color vision is restricted to static images and to dichromats (lacking one cone type). We are now able to also simulate color blindness in near real time video, and for both dichromats and anomalous trichromats. We discuss how these techniques were applied in a field study into color vision requirements in Dutch maritime practice and present visualization examples thereof.

Introduction

What colorblinds actually see is of great value for understanding the visual problems that they may meet in daily life [1]. Their reduced ability to discriminate between certain colors is probably best experienced when "looking through their eyes". Visualization of the effects of color blindness to color normals is a technique that does precisely this. Designers may take advantage of such visualizations to apply color schemes that are "safe" for anybody [2, 3, 4] (a principle known as *design for all)*. In many industries red and green are still used for indicating situations that are to be associated with danger and safety. Unfortunately these colors are the ones that are also most often confounded by the majority of the colorblind population [5].

Although awareness of potential problems with color coding is growing, we can still find many examples in disadvantage of color defectives. Using an algorithm for simulation of colorblindness as described by Brettel et al. [6], Pardo et al. [7] showed that the euro-coins are difficult to discriminate on the basis of color. This example is not a dramatic one, but demonstrates the usefulness of color blindness simulation in relation to practical issues.

In occupations where normal color vision is strictly required there is no need to debate on practical problems associated with color discrimination. However, when a certain degree of color deficiency is allowed there is plenty of room for discussion. We were asked by the Netherlands Shipping Inspectorate to perform a field study into the color vision requirements in Dutch (civil) maritime practice, for which a mild color deficiency is tolerated. We here describe the methodology used and main results.

Methods

We used static and dynamic simulation of color blindness to answer two main questions. First, when a certain degree of color blindness is allowed, what does it mean for exercising one's profession? Second, from the viewpoint of the work to be carried out, what level of color discrimination should be required? Both questions are addressed in this paper.

Simulation of defective color vision

Here we present the general aspects relevant for a broad understanding. A more detailed explanation of the simulation and its scientific background are presented elsewhere [3,8]. The simulation incorporates a model for deficient color vision, including both dichromats and anomalous trichromats. Whereas normal color vision is mediated by the relative excitations of three cone classes (L,M,S), our model for deficient color vision assumes that the spectral sensitivity of one cone type is shifted along the wavelength axis. In case of a *protanomal* the sensitivity of the L-cone is shifted towards that of the M-cone, as illustrated in Fig.1. In case of a *deuteranomal* the spectral sensitivity of the M-cone is shifted towards that of the L-cone. The degree with which the cone type's sensitivity curve is shifted can be indicated by a value between 0 (no shift) to 1 (complete shift) and corresponds to a specific degree of color blindness. A zero value corresponds to normal trichromatic color vision whereas a value of 1 corresponds to a dichromat.

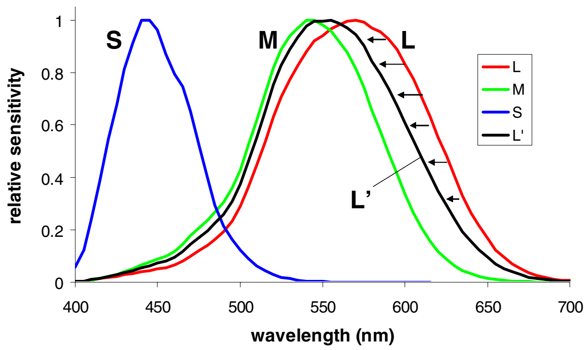

Figure 1. *Relative spectral sensitivities of the L,M,S cone types involved in normal color vision [9]. The black curve is the hypothesized (shifted) sensitivity of the protanomal L' cone for an intermediate value of the shift.*

The cone excitations associated with normal color vision, here denoted by L_c, M_c, S_c, are computed by integrating the product of a spectral power distribution (light source or reflected from an object) and the cone sensitivity in question over the relevant wavelength region. The consequences of a shifted spectral sensitivity are captured by replacing the L_c,M_c,S_c cone excitations by modified values, denoted by L_c',M_c',S_c', as follows:

$$\begin{pmatrix} L_c' \\ M_c' \\ S_c' \end{pmatrix} = D \begin{pmatrix} L_c \\ M_c \\ S_c \end{pmatrix} \tag{1}$$

in which the 3x3 matrix D depends on the type and degree of color blindness. Note the different meanings of the L,M,S symbols used in eq.(1) and Fig. 1. In Fig. 1 they denote spectral sensitivity functions (action spectra), in eq.(1) they denote cone excitations. In case of a protan, eq.(1) reads

$$\begin{pmatrix} L_c' \\ M_c' \\ S_c' \end{pmatrix} = \begin{pmatrix} 1-d & d & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} L_c \\ M_c \\ S_c \end{pmatrix} \tag{2}$$

And likewise, for deutans it becomes

$$\begin{pmatrix} L_c' \\ M_c' \\ S_c' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ d & 1-d & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} L_c \\ M_c \\ S_c \end{pmatrix} \tag{3}$$

For tritans we arrive at

$$\begin{bmatrix} L_c' \\ M_c' \\ S_c' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ d/2 & d/2 & 1-d \end{bmatrix} \begin{bmatrix} L_c \\ M_c \\ S_c \end{bmatrix} \tag{4}$$

The parameter d in the equations is referred to as the *deficiency coefficient* that determines the degree of anomaly. It represents the fraction of the light absorption that is taken over by another cone (M for protanomaly and L for deuteranomaly). For tritanomaly the assumption is made that the L and M cones take over from the S cone in equal quantities. Note that neutral excitation of the cones ($L_c=M_c=S_c$) results in a neutral simulated color ($L_c'=M_c'=S_c'$).

Dynamic simulation

The dynamic version of the color blindness simulation involves the continuous replacement of input RGB values from a video stream (originating from a video camera or a video file) by appropriate output R'G'B' values. This process was implemented by creating a look-up table that contains for each possible RGB-combination (2^{24} combinations for a 24-bit video system) the appropriate R'G'B' value. For each type and degree of color deficiency this look-up table has to be created once (assuming the display color profile to be constant) and loaded into memory. Before actual display of the video the look-up table is either created on the fly or is read from disk. The software allows the processed video to be exported and saved so that it can be viewed with a standard video player.

Display calibration

We use an Eizo ColorEdge CG18 LCD display in combination with a GretagMacbeth Eye-One calibrator for maintaining accurate color control. Software (developed by Eizo) allows the display to be measured by the calibrator but also to be adjusted at a specific profile. So, this combination of display and calibrator ensures that the monitor can be kept in the same colorimetric condition. In our experiments the monitor was adjusted to comply with the sRGB standard, i.e. a maximum white luminance of 80 cd/m^2, a white point of 6500 K, and gamma 2.2 for each of the three primary channels [10].

Procedure

For our investigation we first had to determine the proper value for the deficiency coefficient d in our simulator to match the degree of color blindness tolerated in Dutch (civil) maritime practice. The latter is determined by specified diagnoses on the Ishihara, HRR (Hardy Rand and Rittler) and TMC (Tokyo Medical College) color vision tests as stated in Dutch regulations [10,11]. On the HRR test, a diagnosis "mild" is tolerated, and likewise "second degree" on the TMC test. We assumed that identical diagnoses should be obtained when color normals view the *simulated* color vision tests on display, when using the proper value for the deficiency coefficient d.

With a Canon 300D camera we took digital stills of the test plates of Ishihara, HRR and TMC. These tests were placed in a MacBeth SpectraLight II viewing booth under D_{65} illumination. A number of test colors of the Ishihara test were measured with a Photo Research PR 650 spectrophotometer and plotted in CIE x,y chromaticity space. Also, the x,y chromaticities of these colors as reproduced on the LCD were plotted, closely resembling the measured ones. This proved that the color management in our set-up was satisfactory.

Five naïve subjects (2 male and 3 female, age 28 to 43) with normal color vision (as confirmed with Ishihara and HRR) viewed test plates presented on LCD that were processed by our color deficiency software. Prior to these sessions, the two authors inspected the simulated color vision tests while playing with the value of the deficiency coefficient d. This led to an estimated setting for d in the experiment with the naïve subjects. Both the protanomalous and the deuteranomalous simulations were tested. An example of a simulated test plate is shown in Fig. 2.

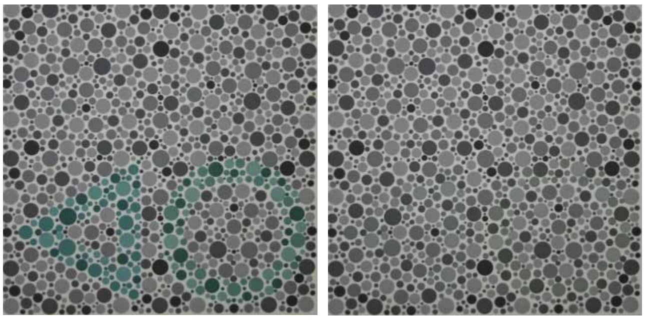

Figure 2. *Plate 7 in the HRR color vision test showing a triangle and a circle in the bottom. Left: original. Right: simulated color deficiency (protanomalous) corresponding to the maximum degree of deficiency tolerated in Dutch (civil) maritime practice.*

Results

Administering simulated color vision tests

Each of the five subjects took two simulated color vision tests (HRR and TMC) for two types of simulated color deficiency (protanomalous and deuteranomalous), leading to a total of 20 test diagnoses. For the simulated HRR, the diagnosed deficiency type was correct 7 times out of 10, and 3 times unclassified (i.e. no preference for protan or deutan). The diagnosed degree of color deficiency was correct in all 10 cases. For the simulated TMC, the diagnosed deficiency type was correct 5 times out of 10, 4 times unclassified and 1 time incorrect. The diagnosed degree of color deficiency was correct 5 times out of 10, 1 time too mild, and 4 times in between (i.e. close to correct). Considering that we did not need to distinguish between protans and deutans we concluded that with the setting of the deficiency coefficient d we were very

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close to the degree of deficiency that was tolerated in Dutch maritime practice.

Visualization examples

Using the abovementioned setting for the deficiency coefficient *d* in our simulator, we visualized the workplace and followed personnel in their daily routines aboard ships. This was done with both the static and the dynamic version of the simulator[1]. In Fig. 3 an example with color coded electricity wires is given, showing that the discrimination between the colored wires has become difficult, if not impossible, for a color deficient person.

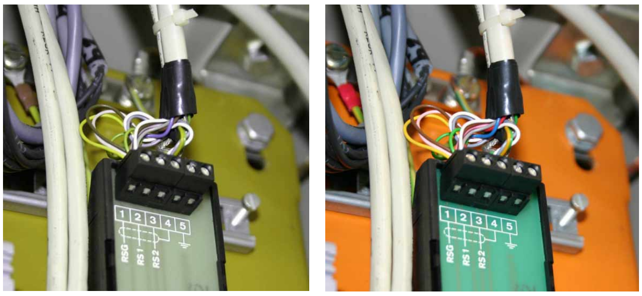

Figure 3. *Electricity wires: original (top) and simulated color blindness (bottom) for a protanomal. The degree of color deficiency that is simulated corresponds to the maximum degree that was still allowed in Dutch maritime practice.*

A second example (Fig. 4) shows a series of simulated anomalies, using a photograph of a situation that we encountered in our investigation. It shows a red and a green button side by side, without any additional coding. Note the change in color discrimination between the two buttons when varying the value of the deficiency coefficient in our simulation.

Discussion

The visualization of color deficiency, and the dynamic version in particular, has proven to be a very powerful tool for investigating color vision requirements in practice. Compared to static visualizations, the clear advantage of video is that the role of color for performing a job (in its full context) is much better understood. Color perception can be very important, but is only a single aspect of our visual performance, and sometimes less important than other aspects.

The question remains whether the simulated colors of the color blind are exactly those that they perceive. We assume that color blinds perceive neutral colors (white) as neutral. Also, the choice of the (tritan) line through the white point that is used as projection line for the colors on protanope and deuteranope confusion lines is somewhat arbitrary; and this is where our approach differs from that of Brettel et al. [6]. However, for our purpose the most important goal of the simulation is to show the reduced potential to discriminate between colors. The display of differences in color (or rather, the lack thereof) is more important in this respect than the display of absolute (perceived) colors.

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[1] Here we can only show static examples

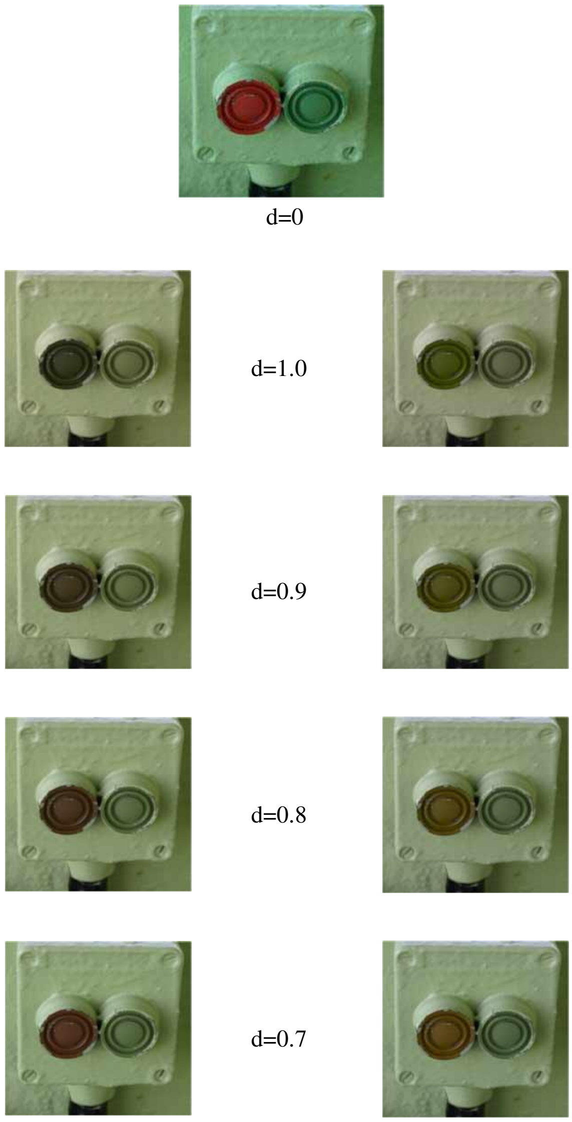

Figure 4. *Red and green button aboard a ship, shown for different settings of the deficiency coefficient d. Top: original. Left: protanomal. Right: deuteranomal. A setting of d=1 corresponds to dichromatic color vision, d=0 to normal trichromatic vision.*

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Author Biography

Marcel Lucassen received an M.S. degree in Technical Physics from Twente University (The Netherlands) in 1988 and a Ph.D. in Biophysics (Quantitative studies of color constancy) from Utrecht University in 1993. From 1993-1999 he worked at the Colorimetry department of Akzo Nobel Coatings. Since 1999 he has worked at TNO Human Factors where he headed the Vision and Imaging group from 2002-2005. His interests lie in both basic and applied vision research, and color vision in particular. He is an associate editor for Color Research and Application.

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