Algorithm for Colorblindness Detection Sets Generation

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Abstract. Currently there are numerous methods for detecting colorblindness. They differ in many aspects, e.g. the quality and accuracy of diagnosis, the spectrum of colors used during test or the ability of being reproduced on a mass scale. However, there is one thing that those methods do have in common – they are based on predefined, limited sets of color elements.

This paper presents the algorithm for generation of colorblindness detection sets – so called *quodlibets* – pairs of colors that are easily distinguishable by a person with normal color vision, but are hard (or impossible) to tell apart by a person with certain color vision disorder within defined timeframe. The discussed algorithm allow to generate many different *quodlibets*, which allow not only to detect certain types of colorblindness but also to estimate the strength of a color vision impairment.

Keywords: Colorblindness · Color vision disorders · Computer-aided diagnostic systems

1 Introduction

It is estimated that about 10 % of the whole human population is affected with some kind of color vision disorder, which is defined as the inability (or reduced ability) to distinguish between certain colors or shades under normal lighting condition [5]. There are several types of color vision disorder, differing from total color blindness (monochromacy), through dichromacy (where one out of three types of retinal cones are missing or strongly underdeveloped), up to reduced visible color spectrum – anomalous trichromacy, where the aforementioned types of retinal cones are underdeveloped or not working properly [12].

Colorblindness can be of genetic or acquired nature. In the first case, the majority of colorblindness types is caused by a faulty gene carried on the X chromosome (which results in higher percentage of colorblind males, since they have only one X chromosome), with an exception of tritan-type defects, which are encoded on chromosome 7 (which is gender-independent). In the second case, color vision disorders may be a result (or a symptom) of a disease, trauma (either to the optic nerve or brain) or exposure to certain chemicals (e.g. drugs) [10]. Acquired color vision disorders may be permanent or temporal.

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Genetic types of colorblindness may be classified not only by the severity of color vision disorder, but also by the type of cone missing or not working properly. This classification is presented in Fig. 1. Table 1 presents the classification of acquired color vision disorders and their similarity to the genetic ones.

Due to the limitation of this paper and relative similarity of types between genetic and acquired types of color vision disorders, only the terms used for genetic types will be used from now on. The paper will also focus on dichromats and anomalous trichromats, as monochromacy is extremely rare and relatively easier to detect other kinds of color vision disorders.

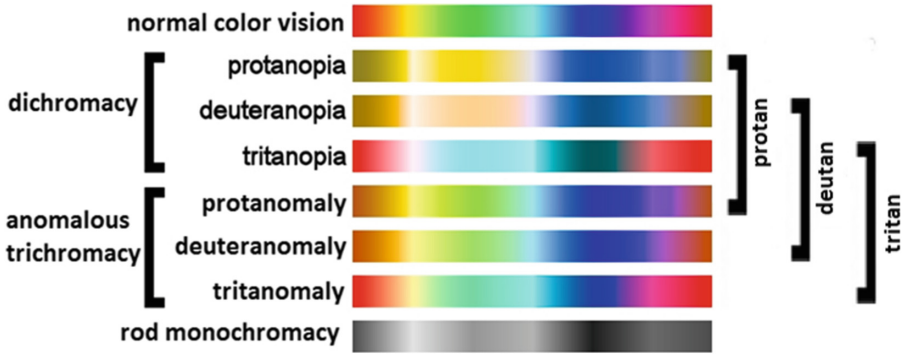

Fig. 1. Different approach to classification of genetic color vision disorders (Color figure online) (source: own work based on data from [3])

Table 1. The classification of acquired color vision disorders (source: [1])

Color vision disorder	Characteristics
Type 1	Similar to protan vision disorders
Type 2	Similar to deutan color vision disorders, less sensitive to shortwave light
Type 3a	Similar to tritan color vision disorders although with sensitivity shifted to shortwave light
Type 3b	Similar to tritan color vision disorders

2 Overview of Currently Used Colorblindness Detection Methods

Currently there are numerous methods for detecting color vision disorders. Those methods can be divided into four main groups:

- **arrangement,** in which the examinee has either to select a number of samples with color matching (or close to) to the one given by the examiner or to arrange the

samples in a certain order (e.g. from the lightest to the darkest). Example: Farnsworth D-15 pane.
- **nominative**, where the examinee usually has to read and name the pattern which is noticeable for people with normal color vison, but difficult to see (in certain timeframe) or even unnoticeable by persons with certain color vision disorder. Example: Ishihara's pseudoisochromatic plates.
- **spectral,** which are based on the fact that certain color can be obtained by mixing two other colors, e.g. yellow light can be obtained by mixing green and red light in a certain ratio.
- **lamp,** which focus only on checking the examinee's ability to distinguish only certain signal colors (e.g. used in navy or aviation), not to determine the type of potential color vision disorder

While analyzing the colorblindness detection methods, one should keep in mind that some of them allow not only the detection of color vision impairment, but also the classification of certain type, while others focus only on determining whether the testee has the ability to distinguish certain colors. Moreover, those diagnostic methods do differ on many factors, the most important being:

- **sensitivity,** which measures the proportion of people who are correctly identified as having the condition (in discussed case – people with color vision disorders) to the whole tested group. Sensitivity is often referred to as true positive rate;
- **specificity,** which measures the proportion of people who are correctly identified as not having the condition (in discussed case – people with normal color vision) to the whole tested group;
- **difficulty level** – some methods require certain knowledge or abilities of examinee (therefore are not suitable for testing color vision in children) or examiner;
- **examination cost** – including equipment cost (purchase cost, cost per use and top accuracy period), staff cost, etc.
- **time cost** – including examination time as well as time needed for analysis of the results.

Table 2 present the short overview on most popular color vision diagnostic methods, concerning sensitivity, specificity and main limitations.

As it can be noticed in Table 2, none of the methods can serve as ultimate diagnostic tool, due to different limitations. However, there is one more limitation to be considered: each of the discussed methods use certain, predefined set of colors. This means that only a small percentage of all colors which are perceivable by human eye (about 10 million) is used. In some cases this may be an additional risk of getting false diagnosis, as examinee e.g. can just learn the correct order of pseudoisochromatic plates. This problem will be discussed further in next chapter.

Table 2. Short overview on most popular color vision diagnostic methods (source: [1–5, 12])

Type	Method	Sensitivity	Specificity	Main limitations
Nominative	Ishihara plates	50-96	89-100	Cannot detect tritan color vision disorders, minimal age: 6 years
	AOHRR plates, 4th ed.	83-100	33-96	Min. age 3 years
Arrangement	FM-100	100	83	Time consuming data analysis, not suitable for screening
	D-15	30-60	100	Time consuming data analysis, not suitable for screening
Spectral	Nagel anomalosope	100	100	Cannot detect tritan color vision disorders, complicated diagnostic process, expensive equipment
Lamp	FALANT	25	100	Checks only the ability to distinguish certain colors

3 Diagnostic Sets of Colors – An Overview

Each diagnostic method uses different set of colors for testing purposes. The number of those colors can be greatly reduced – e.g. lamp methods usually use up to five different colors (however, one should keep in mind, that this method just check if the examinee is able to distinguish between certain navigational lights). Moreover, the finite number of colors may be the result of the research: for example Shinobu Ishihara used pastels to create the first set of his pseudoisochromatic plates, therefore using only the available colors. Figure 2 presents the palette of colors used for generating standard Ishihara plates and FM-100 color pane superimposed on sRGB color space (triangle) and CIE 1931 color space.

It should be emphasized that despite the development of technology, creating a computer version of "analog" colorblindness detection method is not a trivial task, mainly due to the problem of converting printed colors into on-screen representation (effectively conversion from CMYK to RGB). This process is influenced not only by the potential conversion errors, but also by errors due to hardware – e.g. scanners and quality of the diagnostic equipment (as the pigments wear off with time).

All of those factors confirm that there is a need of developing new, computer based algorithm for generating sets of colors for diagnostic purposed, which will be hardware-independent.

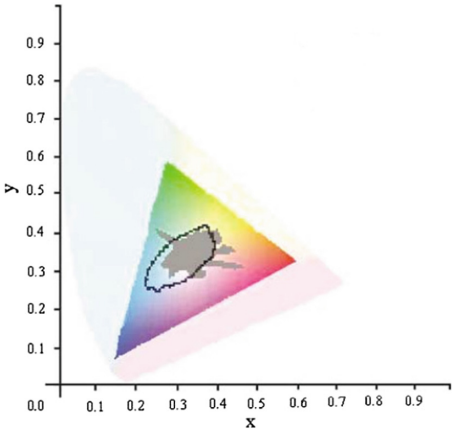

Fig. 2. Palette of colors used for generating standard Ishihara plates (gray area) and FM-100 color pane (black outline) superimposed on sRGB color space (triangle) and CIE 1931 color space (Color figure online) (source: [9])

4 The Algorithm

In order to generate sets of colors which allow detecting different types of color-blindness, the following algorithm is proposed. Algorithm generates pairs of colors, which are easily distinguishable by people with normal color vision and are hard (or impossible) to tell apart by people with certain color vision disorder within a defined timeframe. Those pairs are called quodlibets, from Latin *quod libet*, meaning *whatever you like*, as a colorblind person should not be able to tell the colors apart. Algorithm is used only for generating those color pairs, which should be used in some diagnostic method (e.g. arrangement method).

4.1 Confusion Lines

Confusion lines, also referred to as confusion axes, are intersecting lines (for each type of dichromacy) going through CIE 1931 color space. Colors placed on those lines are hard (or in case of severe color vision disorders – impossible) to distinguish by people with certain type of dichromacy [10]. Each type of dichromacy has a main confusion axis, which divides the color space into two halves, each with dominant hue (e.g. in case of protan defects, due to the red cone missing, one half is populated with colors with dominant green factor, while the other – with dominant blue factor).

It should be noticed, that sources differ on the coordinates of intersection point for each type of axes. Table 3 presents different coordinates as stated by Stiles and Wyszecki, as well as Pokorny and Smith. Figure 3 illustrates confusion axes within the CIE 1931 color space.

Table 3. x and *y* coordinates (in CIE 1931 chromacity diagram) of intersection points for each type of confusion axes (source: [8, 11])

	Wyszecki & Stiles		Pokorny and Smith	
Type of color vision disorder	x	y	x	y
Protan	0.747	0.253	0.7635	0.2365
Deutan	1.080	−0.800	1.400	−0.400
Tritan	0.171	0	0.1748	0

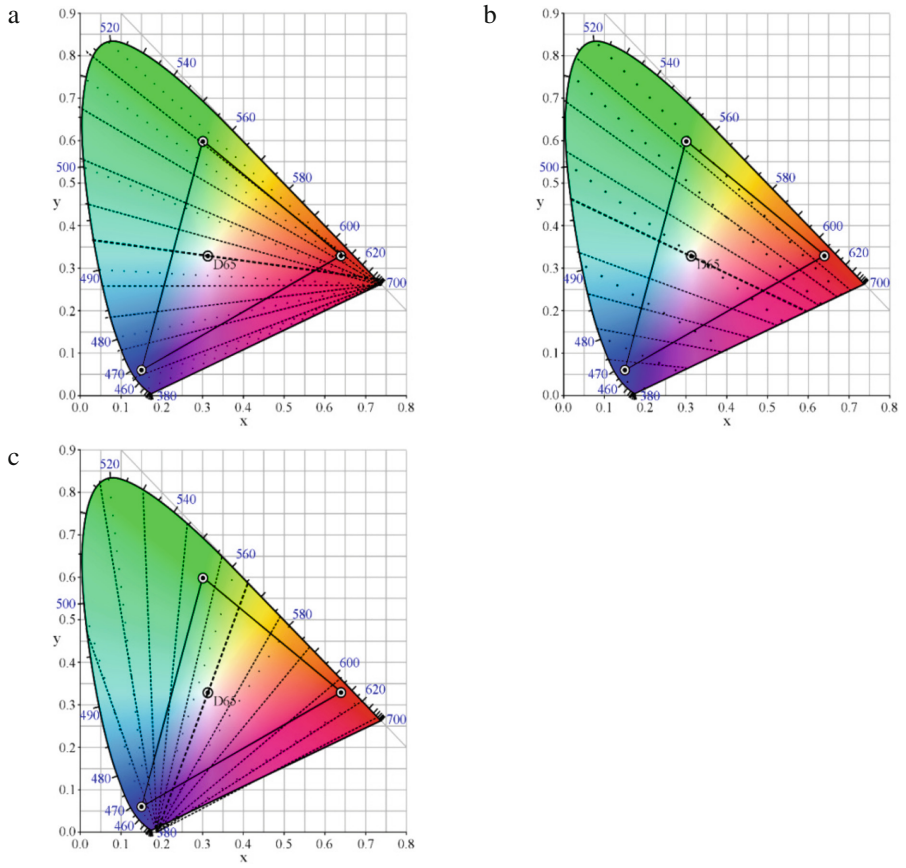

Fig. 3. CIE 1931 chromacity diagram with confusion lines for (a) protan, (b) deutan, (c) tritan color vision disorders. Confusion axes according to Wyszecki&Stiles are marked with dashed lines, according to Pokorny&Smith – with dotted lines. Main confusion line (according to Wyszecki&Stiles) is bolded. RGB color space and D65 illuminant are also marked. (Color figure online) (source: own work adapted from: [8, 11])

Confusion axes are also based on observations by Wright (Fig. 4a) and MacAdams (Fig. 4b), who designated the areas of visually equal color zones – in other words colors within those areas are perceived as the same by a person with normal color vision. However, it should be emphasized, that colors placed on a confusion axis should be distinguishable by such person.

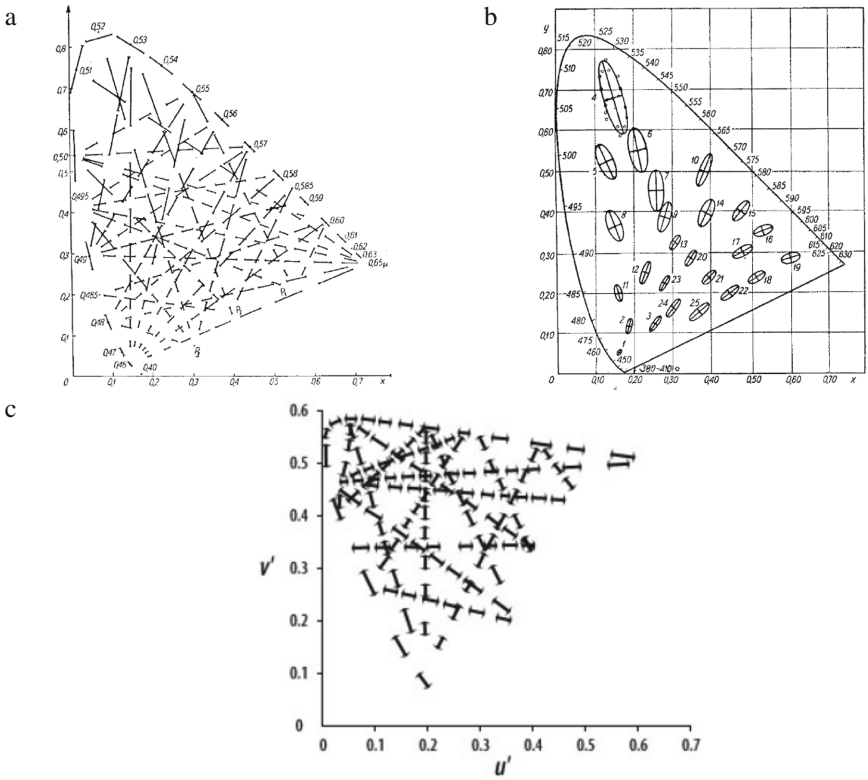

Fig. 4. (a) Perceptually equal colors in CIE 1931 chromacity diagram according to Wright (magnified 3 times) [13], (b) MacAdams ellipses (magnified 10 times) [13], (c) perceptually equal colors from (a) transferred to CIE LUV [13]

Confusion axes are usually shown on CIE 1931 chromacity diagram, which is not perceptually equal – in other words the distance between two colors does not collate with the difference in their perception. This fact can be observed by comparing Fig. 4a (showing visually equivalent color stimuli in CIE 1931 chromacity diagram) and Fig. 4c (which shows the same color stimuli in CIE LUV). The 1976 CIELUV color space is one attempt at providing a perceptually uniform color space. In this color space, the distance between two points is based on how different the two colors are in luminance, chroma, and hue.

By transferring confusion lines to CIE LUV (Fig. 5), an interesting observation can be made: the main confusion axis for protan disorders is perpendicular to main

confusion line for tritan disorders. Additionally, by placing lines orthogonal to each confusion line (going through the illuminant point), it is possible to illustrate so called residual hues, which are perceived by dichromats in almost the same way as by persons with normal color vision [9].

The orthogonality of confusion lines and residual hues lines is more clearly visible upon transfer to color circle in CIE LUV space escribed around the point corresponding to D65 illuminant (Fig. 6).

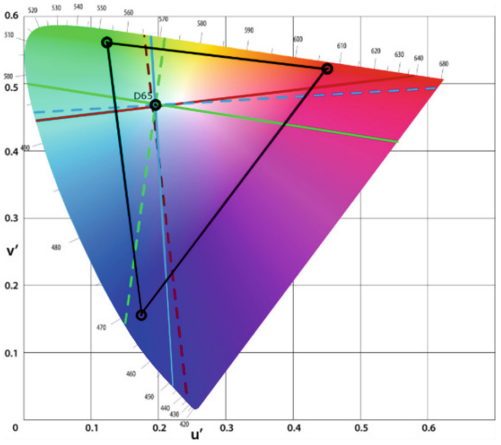

Fig. 5. Main confusion axes (solid lines) and corresponding residual hue axes (dashed lines). for protan (purple), for deutan (green) and for tritan (blue) in CIE LUV. sRGB color space and D65 illuminant also marked (Color figure online) (source: own work adapted from [9])

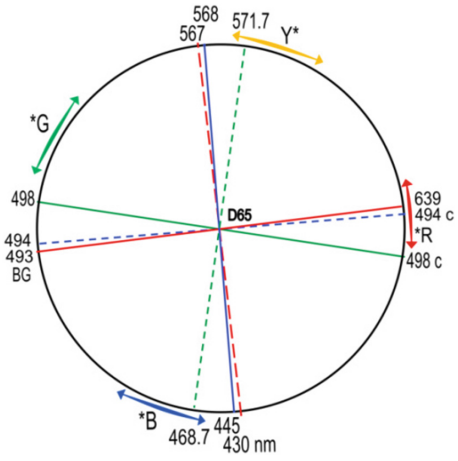

Fig. 6. Main confusion axes (solid lines) and corresponding residual hue axes (dashed lines) for protans (purple), deutans (green) and tritan (blue), transferred to color circle in CIE LUV space escribed around the point corresponding to D65 illuminant. (Color figure online) (source: [9])

4.2 Just Noticeable Difference

While discussing color perception, one should keep in mind that human eye has limited perception. This fact was illustrated in Fig. 4a–c. Just Noticeable Difference (JND) is a variable experimental parameter to determine the threshold T above which the observer (with normal color vision) reaches a desired level of confidence that two observed colors are different.

The color difference between two colors in CIE LUV can be computed as [7]:

$$\Delta E = \sqrt{(L_2 - L_1)^2 + (u_2 - u_1)^2 + (v_2 - v_1)^2} \tag{1.1}$$

The color difference follows this dependence [7]:

- $0 < \Delta E < 1$ – the observer (with standard color vision) is not able to notice the difference between colors
- $1 < \Delta E < 2$ – an experienced observer is able to notice the difference between colors
- $2 < \Delta E < 3.5$ – an inexperienced observer is able to notice the difference between colors
- $3.5 < \Delta E < 5$ – a significant difference between colors
- $5 < \Delta E$ – observer sees two completely different colors.

4.3 Algorithm Assumptions

Algorithm for generation of colorblindness detection sets is based on the following assumptions:

- There should be separate color set for detecting each type of dichromacy and each type of trichromacy
- Each set should consist of pairs of colors which are at least possible to be told apart by an inexperienced observer with normal color vision – $JND \in (1 < \Delta E < 2)$
- Developed pairs should be complementary in corresponding types of color vision disorders: e.g. people with protanomaly should be able to distinguish colors, which are perceived wrongly by people with protanopia.
- Each pair for detecting trichromacy should have a JND lower than pair for detecting dichromacy. Therefore quodlibets with $JND \in (1 < \Delta E < 1.5)$ will be used for detecting anomalous trichromacy while pairs with $JND \in (1.5 < \Delta E)$ will be used for detecting dichromacy.
- Differences in confusion axes definition should be taken into account while generating quodlibets.
- Pairs should be generated relatively randomly, so that testee cannot influence the results of examination by e.g. memorizing the order of elements used.

4.4 Algorithm

The algorithm consists of following steps:

1. A color vision disorder type (protan, deutan, tritan) is selected (e.g. by examiner);
2. Examiner selects if the quodlibets should be generated for testing dichromacy or anomalous trichromacy;
3. Examiner selects number of quodlibets to be generated;
4. A point on confusion axis corresponding to the selected color vision disorder is chosen randomly (confusion axis with coordinates by Wyszecki&Stiles is being used) in CIE LUV. This point A(u,v) represents the first color of a quodlibet;
5. Vector B(± a, ± b) is chosen randomly from the area defined by JND (based on point A) for the generated type of quodlibet. The considered area should also be placed within sRGB color space in order to be properly displayed on standard computer screen.
6. Second color is chosen by offsetting point A(u,v) by a vector B(± a, ± b). The color represented by point B(u ± a, v ± b) is the second color of a quodlibet;
7. The quodlibet is saved and scenario repeats from step 4 until sufficient number of color pairs is generated).

5 Example Quodlibets for Dichromats

Example quodlibets for each type of color vision disorders are presented in Table 4, with color values presented in RGB format. Additionally, to illustrate the potential difficulties of distinguishing colors in each quodlibets by a person with certain color

Table 4. Example quodlibets (source: own work)

	Normal color vision		Color vision disorder - simulation	
Type of color vision disorder	**Color 1**	**Color 2**	**Color 1**	**Color 2**
Protanopia	#344C51	#704E53		
Deuteranopia	#4CBCAB	#FA86BC		
Tritanopia	#DD607B	#DB6D00		

vision disorder, Vischeck simulation software was used. It should be noticed that due to its nature, colorblindness concerns subjective perceptions, so any kind of simulation should be perceived as illustrative only.

6 Conclusions and Future Work

The proposed algorithm allows in theory to generate almost any combination of color pairs which can be used for colorblindness detection. However, it should be noticed that colorblindness is a very individual vision disorder and the ability to distinguish between two colors may be different even among people who are e.g. deutans (suffering from deuteranopia). Therefore the quality of generated quodlibets should be verified experimentally.

The quodlibets generated by described algorithm may be used in any diagnostic method which allows user to compare with each other two color elements, e.g. arrangement method. Experimental results of implementing quodlibets into diagnostic process may be found in paper [6]. The results of those experiments seem promising, although still require some more research to be done.

There are several issues to be solved in the near future:

- What is the optimal value of JND to distinguish dichromat from anomalous trichromat?
- May this algorithm be used for generating control group (distinguishable by anyone) for quodlibets?

The described algorithm can serve as an basis and relatively cheap alternative to currently used colorblindness tests. Limiting generated color pairs to sRGB color spaces allows using quodlibets in any context, e.g. as a replacement of original colors in computer implementation of certain colorblindness detection method.

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