A new approach to image enhancement for the visually impaired

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Abstract

This works aims at enhancing images by using the colour appearance model CIECAM02 for the visually impaired to view digital displays to complement the existing image processing approaches with a reference to normal visions. Specifically, by studying the images perceived by low-vision users, the colour ranges of these perceived views are compared with those viewed by normal vision and then characterized and represented using CIECAM02 correlates, which include lightness, colourfulness, and hue. For low-vision users, the extents of these attributes are therefore obtained. Subsequently, for any input image, these CIECAM02 attributes are subsequently enhanced through histogram equalizer technique within their respective ranges for low-vision users. In comparison with the approach of RGB histogram equalizer, the preliminary result has shown that the proposed method appears to be better to enhance the contents depicted in an image. The evaluation experiment was carried out using an array of low-vision simulator glasses to be worn by a group of subjects with normal vision. The next stage of the work remains to invite real low-vision users to evaluate the proposed work.

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Introduction

According to the report published by WHO on *Vision 2020: The Right To Sight* [1], there are about 314 million people living with a certain degree of visual impairment in the world. Of these, 153 million people are visually impaired by causes other than uncorrected refractive errors, such as aging. Hence, to maintain those people's normal quality of life, a number of visual aids could be beneficial.

Visual impairment

Visual impairment or low vision refers to sight loss that cannot be fully corrected using glasses or contact lenses, and affects as many as 3% of the population in the UK [2]. Two elements of vision are measured when determining a person's visual impairment - their visual acuity and their visual field. The former refers to the central vision used to look at objects in detail, such as reading a book or watching television. So when a visual acuity score is given as 2/20, it indicates the person in concern can only read at 2 metres away what a person with typical eyesight can read at 20 metres away. Visual field refers to the area that a person can perceive while he/she is looking straight ahead, which is tested using techniques that measure a person's responses to light stimuli in various parts of their potential visual field. Some people with visual impairment may have poor visual acuity (i.e., 3/60-6/60) but have a full field of view. Others might have relatively good visual acuity (up to 6/18) but a significantly reduced visual field. To illustrate, Figure 1 epitomises the perceived images by a number of low-vision conditions, including Scotoma, Cataract, Diabetic, Hemianopia and Tunnel vision (images are extracted from the webpage of Vision Rehabilitation Services LLC [3]).

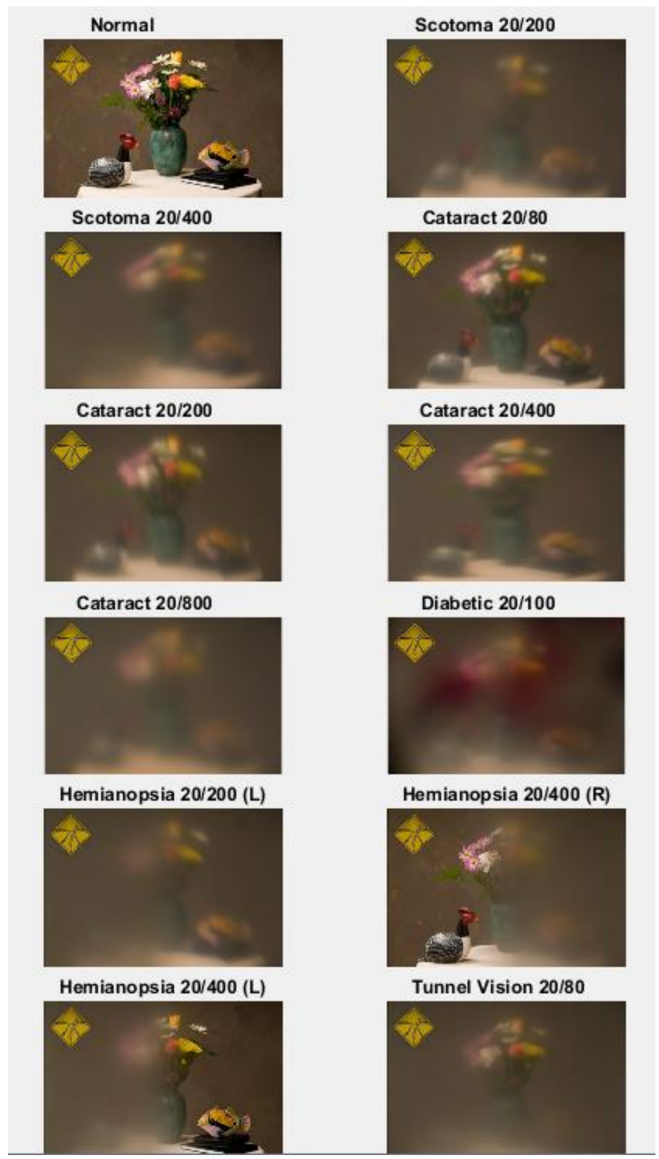

Figure 1. The perceived images by a number of vision conditions, the top-left being the original image [3].

The most common causes of visual impairment in adults include: a) age-related macular degeneration (AMD), where the central part of the back of the eye stops working properly; b) cataracts where cloudy patches can form within the lenses of the eyes; c) glaucoma where fluid builds up inside the eye; d) damage to the optic nerve, and e) diabetic retinopathy where blood vessels that supply the eye become damaged from a build-up of glucose. Although a number of treatments are available to restore vision for some conditions, such as operations for cataracts suffers, loss of vision caused by AMD, glaucoma or diabetic retinopathy usually cannot be reversed.

Image enhancement for the visually impaired

Due to increasingly ubiquitous computer technology, more and more quotidian activities (e.g., shopping, reading newspapers or banking) are currently conducted using digital devices, such as televisions, computers, or mobile phones. As a direct result, a number of strategies have been developed to support those with visual impairments to interact with these devices. For example, with regard to viewing televisions, Fresnel positive lens [4] remains available to give a television screen an extra layer, whereas telescopic aids [5], brightness contrast, and audio description [6] can be readily achieved through a television's control panel.

Since these pieces of state of the art equipment (e.g. televisions and mobile phones) are digitally enhanced (i.e., programmable), a plethora of research work has been carried out towards the development of image processing techniques to improve certain desired features for viewing [7]. As early as in the 1980s, this research began to explore improving technologies for those with visual impairments, when pioneer work on image enhancement was proposed by Peli et al. [8, 9]. Following this line of research, a number of image filters then flourished, including band pass filters [10], adaptive thresholding [11], frequency-based (e.g, Fourier transform, Wavelet transform) [12], generic [13] adaptive, and unsharp masking [14]. In addition, the synergy of these approaches is also fostered. For example, in [15], superimposed images are rendered for a television with enhanced brightness/lightness contrast as well as sharpened edges. Evidently, there are more complex factors at play for many types of low vision, which cannot be alleviated simply by way of image enhancement. In [16], an investigation is conducted to study, compare and ascertain the effectiveness of a range of generic image enhancement filters with regard to the improvement of the perceived visibility of coloured digital nature images. They conclude that there is no one-size-fits-all filter that can improve all sorts of images (e.g., indoor, out-door, sports) for the visually impaired. On the other hand, similar to many other studies, their research reiterates the procedures by processing images firstly with a number of known algorithms, then to invite people with a certain degrees of visual impairment to classify the preference of filtered images. Although with many advantages, it is unlikely for this type of approach to exhaust all the existing techniques and may compromise the development of new techniques.

More importantly, since these algorithms rests on a host of assumptions, they sometimes may not resonate with low-vision users. In light of this, and with such large quantities of image processing techniques being developed, and the fact that some of these filters are already being incorporated into video magnifying devices for the visually-impaired [17], in our work, we have taken a different approach. Firstly, we quantify the extent of the loss for several common conditions of low vision in perceiving coloured images, in terms of perceptual attribute correlates, i.e., lightness, colourfulness, and hue by way of their perceived appearance, using CIE colour appearance model CIECAM02. Then, within the visible ranges of these colour attributes, the histogram equalization technique is applied to maximize their visual scope.

Stemming from Hunt's early colour vision model [18-19], and employing a simplified theory of colour vision for chromatic adaptation together with a uniformed colour space, CIECAM02 can predict the change of colour appearance as accurately as an average observer under a number of given viewing conditions. In particular, the way that the model describes a colour is reminiscent of subjective psychophysical terms, i.e., hue, colourfulness, chroma, brightness and lightness.

The remainder of the paper is then structured as follows. Methodology details the methodologies applied in this work, which is then followed by the analysis of images. Finally, the paper is concluded in section of Discussion and Conclution with a brief summation of the ideas explored in this research, and a number of recommendations for potential future work.

Methodology

Image representations using CIECAM02 colour appearance model

To begin with, CIECAM02 takes into account of measured physical parameters of viewing conditions, including tristimulus values (X, Y, and Z) of a stimulus, its background, its surround, the adapting stimulus, the luminance level, and other factors such as cognitive discounting of the illuminant. The output of the colour appearance model predicts mathematical correlates of perceptual attributes. Table 1 summarises the input and output parameters of CIECAM02.

Table 1. The input and output information for CIECAM02.

Input	Output
X, Y, Z: (Relative tristimulus values) X_W, Y_W, Z_W: (Relative tristimulus values for white) L_A: (Luminance of the adapting field (cd/m*m) = 1/5 of adapted D65) Y_b: (Relative luminance of the background) c, Nc, F = 0.41, 0.8, 0.2: (Surround parameters for luminous colours (i.e., monitor)).	Lightness (J) Colourfulness (M) Chroma (C) Hue angle (h) Brightness (Q) **Saturation (S)**

With regard to the representation of the colour appearance of an image, in this investigation, an image originally expressed in RGB colour space is converted into the perceptual colour attributes of lightness (J), colourfulness (M) and hue (H), which are calculated using Eqs. (1) to (4) respectively.

$$J = 100(\frac{A}{A_w})^{cz} \tag{1}$$

$$C = t^{0.9}(\frac{J}{100})^{0.5}(1.64 - 0.29^{n})^{0.73} \tag{2}$$

$$M = CF_L^{1/4} \tag{3}$$

$$h = tan^{-1}(\frac{b}{a}) \tag{4}$$

where

$$A = \left[2R'_a + G'_a + \tfrac{1}{20}B'_a - 0.305\right]N_{bb} \tag{5}$$

$$t = \frac{50(a^2+b^2)^{\frac{1}{2}}100e\left(\frac{10}{13}\right)N_cN_{cb}}{R'_a+G'_a+\frac{21}{20}B'_a} \tag{6}$$

$$a = R'_a - \frac{12G'_a}{11} + \frac{B'_a}{11} \tag{7}$$

$$b = \tfrac{1}{9}(R'_a + G'_a - 2B'_a) \tag{8}$$

and R'_a, G'_a, B'_a indicate the post-adaptation cone responses with detailed calculations specified in [19] whereas A_W refers to the A value for reference white. Constants N_{bb}, N_{cb} are calculated as

$$N_{bb} = N_{cb} = 0.725\left(\tfrac{1}{n}\right)^{0.2} \tag{9}$$

where n $= Y_b/Y_w$, with Y_b *and* Y_W representing the Y value for both background and reference white respectively.

Results

After the acquirement of the images perceived by those low-vision conditions, data analysis takes place. Towards this end, the acquirement of lightness, colourfulness and hue values proceeds first by the application of colour appearance model CIECAM02. Then for each colour attribute, computational analysis is undertaken in the form of histograms. In this way, comparion with normal vision in terms of viewing range can be achieved. Figure 2 presents the histogram comparison results between the 5 types of low vision together with the normal vision for the image of colour checker shown in Figure 3, whereas Figure 4 demonstrates the similar result for the images displayed in Figure 1, showing the diagrams of perceived Lightness, Colourfulness and Hue values (y axis) calculated by CIECAM02 plotted with those obtained from the normal vision image (x-axis).

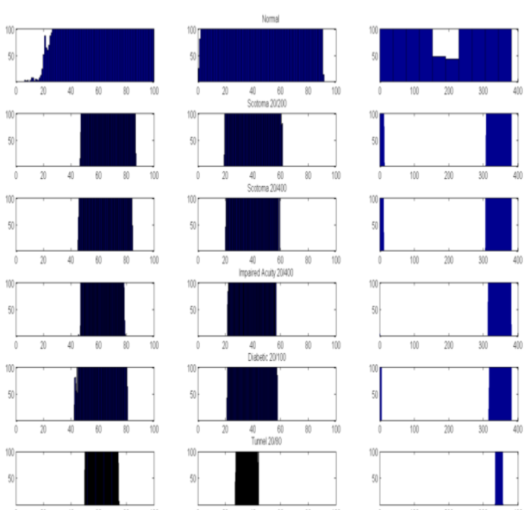

Figure 2. The histograms of lightness, colourfulness, and hue values calculated using CIECAM02 from 5 types of low vision and the normal vision. From top: normal, Scotoma 20/200, Scotoma 20/400, Impaired acurity, Diabetic, Tunnel vision.

Figure 3. The colour checker applied in Figure 2.

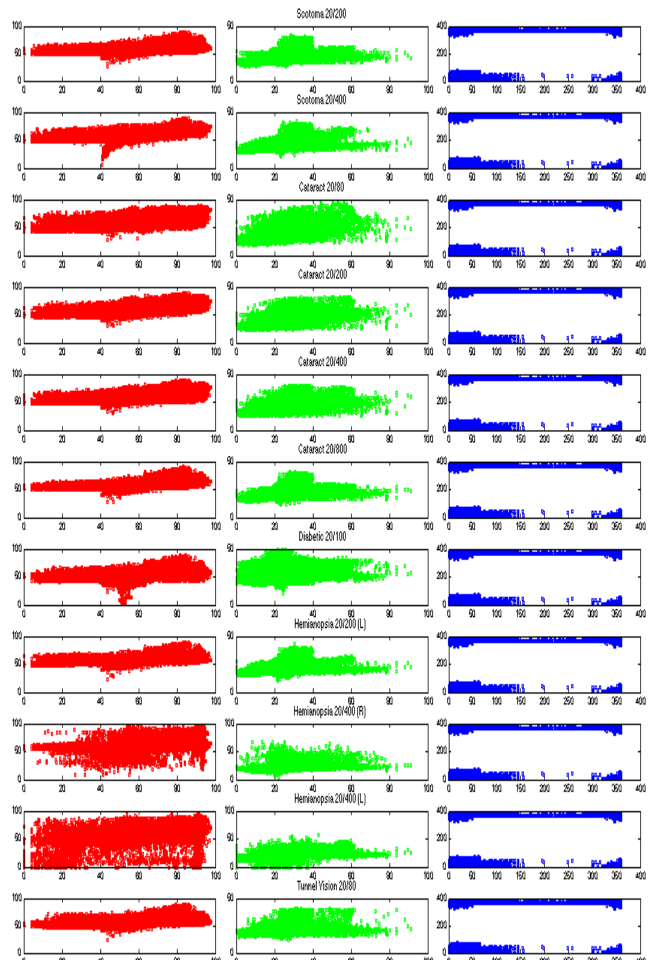

Figure 4. The perceived Lightness(left), Colourfulness(middle) and Hue(right) values (y axis) calculated by CIECAM02 plotted with those obtained from the normal vision image (x-axis).

As expected, the above figures clearly indicate that the normal vision (top graph in Figures 2) covers nearly all the viewing ranges in terms of lightness (e.g., with range of 0-100), colourfulness (e.g., 0-90), and hue (e.g., 0-400), whereas the results for what can be perceived with a visual impairment, are confined to limited regions. For example, with regard to lightness, whilst normal vision extends over the region of nearly 0-100%, the low-vision conditions stay in the regions of 45% - 90%, with tunnel vision (the bottom graph in Figures 2 and 4) being the most affected. In other words, no matter what lightness level a picture entails, a person with tunnel vision can only perceive brightness between 55-75%, indicating a heavy loss of the sensitivity of brightness contrast. In addition, people with low vision perceive limited colourfulness contrast, ranging from 20 to 60 whereas the normal vision range lies between 0 and 90. Again, the tunnel vision (the bottom graph) recognises the least range, between 30-45 (or 33% to 50%) with a difference (contrast) of only 15.

Additionally, Figure 5 displays the hue-colourfulness plot for the above 5 types of low-vision (blue 'o') together with the normal vision (red '+') when viewing the colour checker. The hue circle remains Red (R), Yellow (Y), Green (G) and Blue (B) whereas the distance to the centre of the cross-point between the lines of R-G and Y-B refers to the colourfulness values.

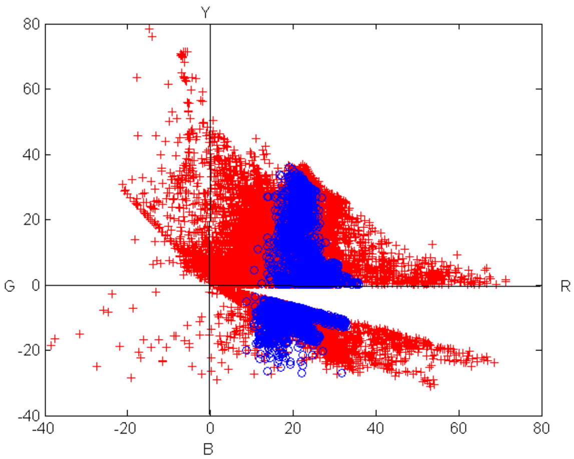

Figure 5. The hue-colourfulness plot for the above 5 types of low-vision (blue o) together with the normal vision (red +) for viewing the colour checker. The hue circle remains Red (R), Yellow (Y), Green (G) and Blue (B) whereas the distance to the centre refers to the colourfulness values.

Significantly, the majority of those with a visual impairment have lost the perception of almost all of the hues, with everything appearing to be purplish in colour to them in comparison with normal vision. Specifically, for those with tunnel vision, everything appears to be of medium lightness (lightness=60%) and purplish in colour with little colourfulness (colourfulness being 30-45) as further evidenced in Figure 5. The extent of hues in the original image perceived by those with normal vision, is represented using red crosses (+) and covers most of the hue-colourfulness region whereas blue circles (o) representing the hues perceived by the visually impaired cover less than a quarter of it, with all hues tend to be reddish colour.

Extrapolating from the above figures, it is clear to envisage that in order for the visually impaired to get the most detailed possible perception of a picture, image enhancement by increasing hue contrast makes little sense. Therefore, it appears most beneficial to maximise the contrast for both lightness and colourfulness within the limits identified above. Towards this end, the approach of histogram equalisation is applied for both attributes of lightness and colourfulness.

In a nutshell, histogram equalisation is a method used to increase the global contrast when the usable data of an image is represented by their close contrast values. Through this adjustment, the attribute in concern can be better distributed on the histogram, allowing the regions of lower local contrast to gain a higher one. In other words, for an image f with the total number of pixels being n and an attribute scope being L, e.g., $L = 45\ (= 90 - 45)$ for the attribute of lightnes in our case, the histogram equalised image g can be defined in Eq. (13) [12].

$$g_{i,j} = (L-1)\sum_{n=0}^{f_{i,j}} p_n \tag{13}$$

where i, j indicate the image pixel coordinate position; and p refers to the probability of an occurrence of a pixel with the attribute at level k as formulated in Eq. (14). In addition, i, j indicate the image pixel coordinate position.

$$p_f(k) = p(f = k) = \frac{n_k}{n} \tag{14}$$

This is equivalent to transforming the pixel attribute (e.g., lightness) value of k, of f by the function in Eq. (15).

$$T(k) = (L-1)\sum_{n=0}^{k} p_n \tag{15}$$

In this study, under the illuminant D65 (equivalent to average daylight), for the visually impaired, the perceivable ranges of lightness and colourfulness are between 45 to 90 and 20 to 60 respectively. Therefore, equalisation of both lightness and colourfulness takes place in those ranges using Eqs. (13) to (15).

In summary, to enhance an image, the conversion from RGB space to XYZ is firstly conducted. Then, CIECAM02 is applied to calculate lightness and colourfulness. Next, the equalisation of lightness and colourfulness is performed according to Eqs. (13) to (15). Finally, these attributes of lightness, colourfulness and hue are transformed back to XYZ from reversed CIECAM02 model, then to RGB space in order to display the image using reversed matrix of Eq. (12). Figures 6 to 8 portray the results of three examples of this process applied to an image (CIECAM02 LMH Equaliser, top), as well as showing the results of the current common approach of equalisation using RGB values (RGB equaliser, middle), as well as the original image (bottom).

Figure 6. Example 1: image enhancement based on the proposed CIECAM equalisation (top), together with RGB equaliser (middle) and the original image (bottom).

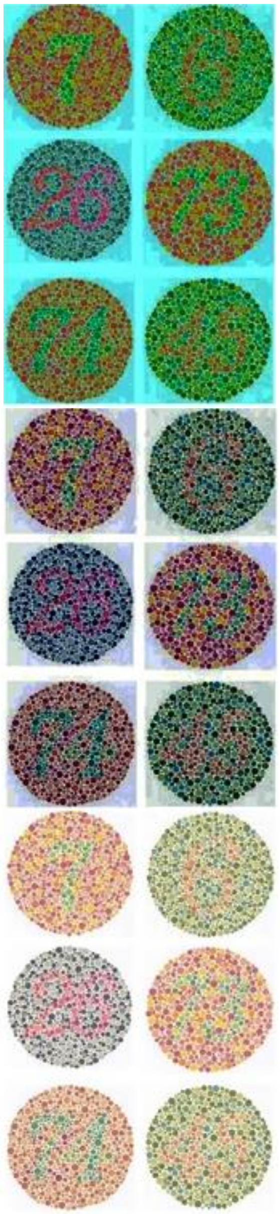

Figure 7. Example 2: image enhancement based on the proposed CIECAM equalisation (top), together with RGB equaliser (middle) and the original image (bottom).

Figure 8. Example 3: image enhancement based on the proposed CIECAM equalisation (top), together with RGB equaliser (middle) and the original image (bottom).

To evaluate the processed images, six subjects with normal vision participate in the experiment by wearing low-vision simulation glasses. Each subject votes the most identifiable or clearest image among the three. The results are given in Table 3, which indicates that the majority of subjects prefer the image enhanced using the approach developed in this paper, i.e., the CIECAM02 LMH Equaliser. For example, all 6 subjects prefer the image processed using the LMH Equaliser when wearing glasses simulating the visual conditions of Diabetic Retinopathy, Scotoma 20/400 and Impaired Acuity. Similarly, for the other visual impairment conditions (e.g., Tunnel Vision and Scotoma 20/200), the majority of subjects also prefers the images processed using the LMH Equaliser.

Table 2. The evaluation results by the number of subjects who have evaluated the above enhanced images by wearing low-vision simulator glasses.

Vision	**CIECAM02 LMH Equaliser**	**RGB Equaliser**	**Original**
Tunnel vision	**3**	2	1
Diabetic Retinopathy	**6**	0	0
Scotoma 20/400	**6**	0	0
Scotoma 20/200	**4**	1	1
Impaired Acuity 20/400	**6**	0	0

Importantly, the findings in this research corroborate a number of accounts from other researchers' work, addressed in [17]. Specifically, the majority of people with visual impairment experience visual acuity loss as demonstrated in Figure 1, and therefore the magnification facility appears to be the desideratum for them in order to obtain improved resolution. In particular, image enhancement coupled with magnification can maximise the benefit of viewing experience.

Conclusion and discussion

This research investigates the extents of what a person with low-vision can perceive in comparison with normal vision. In summary, it was found that the perceived lightness for those with a visual impairment ranges from 45% to 90% and the perceived colourfulness from 20 to 60. All hues appear reddish colour to the visually impaired. Based on these data and findings, this research developed an algorithm that is to maximise the perception of those with visual impairments. Built on the CIECAM02 model, this algorithm is developed to equalise the existing perception range of lightness and colourfulness for the visually impaired to maximise their viewing contrast. Subsequently, subjects in the experiment give very positive feedback that images enhanced in this way provide a clearer view in comparison with an existing popular approach.

Since it is only a preliminary investigation, several other phenomena need further attention. For example, in Figure 9 (in the box) (also shown in Figure 4, 2nd row, the tail), some colours with similar lightness values are perceived differently by the visually impaired, especially to those with Scotoma 20/400. The bottom graph of Figure 9 magnifies the tail circled on the left. From these magnified regions, it can be seen that these colours maintain low colourfulness (19-23, near neutral grey colour) and are close to red. However, the reasons why those colours are perceived differently remain unanswered. One could speculate that they are perceived randomly or factored by any surroundings. Future work will explore the reasons behind this type of perception.

This research aims to analyse, from a normal vision point of view, the perceived view ranges by the visually impaired, and therefore in turn to enhance their view as close as possible to that by a normal vision. Hence, CIECAM02 is applied. It is understood that CIECAM02 has been developed for normal vision and in the future will be extended to cover impaired vision.

Acknowledgement

This work in part is funded by EU WIDTH project (2011-2014) under Marie Curie People Scheme (Grant number of PIRSES-GA-2010-269124). This financial support is gratefully acknowledged.

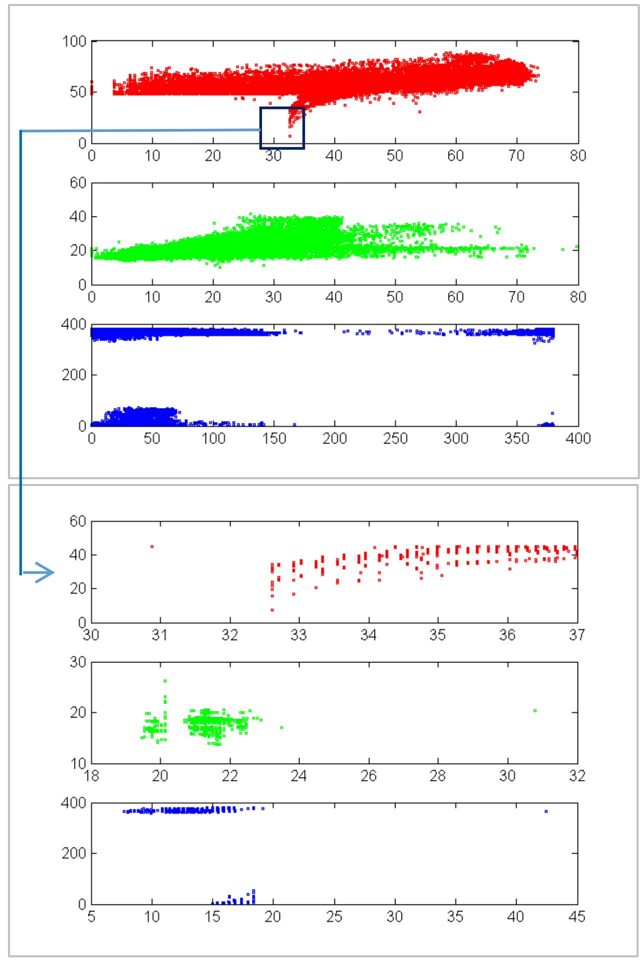

Figure 8. The colours with the same lightness values (in the box) are perceived differently by the low-vision (Scotoma 20/400) people with different lightness values.

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