Optimal and Acceptable White-Point Settings of a Display

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Abstract

This study demonstrates that the preferred white-point for optimised colour rendering depends on image content. In general, people want to compensate for the average colour of the image, i.e. they choose a white-point that shifts the average colour towards a more neutral colour. The range of white-points that people tolerate was found to be extremely large. The region that was acceptable to 75% of the participants was about 0.04 wide along the daylight curve and about 0.02 perpendicular to the daylight curve (in terms of $\Delta u'v'$). The results suggest that, if one has to choose between the most common white-point settings of a TV, a white-point of 6500 K or 8700 K will be reasonable, whereas a white-point of 11000 K will be less optimal.

Introduction

The colours that can be shown on an RGB-display are determined by the chromaticity coordinates of the red, green and blue primaries and the white-point. The European Broadcasting Union (EBU) has developed a standard for the primaries and white-point of an RGB-display [1]. According to their recommendation, the chromaticity of each primary must lie within an area around the standardised value, with a width of about 0.01 units on the CIE 1976 u'v' chromaticity scale. The white-point must correspond to illuminant D65. Since most image material is recorded according to this standard, only displays that follow the standard are able to reproduce coloured image material accurately.

Not all display technologies are able to meet the EBU colour reproduction standard with respect to the chromaticity of their primaries and white-point. For mobile LCDs, for example, the colour gamut defined by the primaries is substantially smaller than the EBU colour gamut and the combination of the spectral distributions of colour filters and backlight does not always yield the D65 white-point. By properly balancing the contribution of the red, green and blue primaries, the position of the white-point may be shifted towards D65, but at the expense of maximal brightness. Hence, it is important to know which range of primaries and white-points are still acceptable to human observers. Langendijk and Heynderickx[2] measured the tolerance range for the three primaries on a display with a white-point of 6500 K. In this study, the tolerance range for the white-point will be measured on a display with EBU primaries. In addition, the optimal white-point will be measured, i.e. the white-point that is judged to give the best colour rendering.

The white-point recommended by the EBU does not always yield the optimal image quality. For instance, Jun et al.[3] studied the influence of white-point setting on perceived image quality for European and Chinese people. Three white-point settings were compared: (x,y) = (0.303, 0.314), (0.289, 0.299) and (0.270, 0.280), which corresponds to a correlated colour temperature (CCT) of about 7200 K, 8700 K and 12000 K, respectively. It was found that the preferred white-point depended on image content. In general, most participants preferred a white-point of 8700 K.

In this paper two experiments are presented. In the first experiment, the most preferable white-point was determined. Participants were asked to select from a list of images with different (simulated) white-point settings the image that they preferred most with respect to colour rendering. In the second experiment, the range of acceptable white-points was determined. Participants selected the image for which the colour rendering was just acceptable, i.e. the image should still look natural. The results of these experiments can be used to choose a (variable) white-point setting for a display in order to optimise image quality or to improve technological properties of the display, such as lifetime, power consumption or maximum luminance output.

Experiment 1: Optimal White-Point

Participants

Ten employees of Philips Research Eindhoven with a European cultural background participated. Their age ranged from 20 to 45 years. About half of the participants worked in a display-related field. All subjects had good colour vision, which was tested with the Ishihara test.

Images

Ten original images with a resolution of 720 x 567 pixels were used in the experiment. The images are presented in figure 1. The first five images were chosen because they contained a significant amount of neutral colours, whereas the other five images were chosen because their average colour was clearly different from D65.

Display

The images were displayed on a high-end 30-inch calibrated CRT (Sony Triniton). The colour points of the red, green and blue primaries of the display were close to the EBU colour points. The white-point was set to D65 (x = 0.313, y = 0.329) and did not change noticeably with the grey level. The display had a maximum luminance of about 100 cd/m^2 and a gamma of 2.3.

Simulation of Change in White-Point

The white-point was changed along and perpendicular to the daylight curve. The change in white-point was simulated by manipulating each pixel of the image with the following procedure:

- Scale the RGB values to [0,1] and apply a gamma correction of 2.3.
- Transform RGB to XYZ, using the red, green and blue chromaticity coordinates of the display and the new white-point.
- Transform XYZ back to RGB, using the red, green, blue and white chromaticity coordinates of the display
- Clip RGB values larger than one and smaller than zero.
- Apply an inverse gamma correction of 1/2.3.

Protocol

Participants were seated at a distance of 2.25 m from the screen. The ambient lighting was adjusted to 20 lux, measured perpendicular to the screen in the direction of the observer. At the beginning of the experiment, participants were made familiar with the procedure. They were asked to step trough a list of images by pressing the + or - button on the screen of a laptop. They were told that the colour rendering of successive images changed in a consistent way. When they selected the first or the last image of the list, the - or + button changed colour to indicate that they had reached the boundary.

The task of the participant was to select the image that they preferred most with respect to colour rendering. In the first part of the experiment, the white-point of the images was changed along the daylight curve. The shift in white-point was expressed as the geometrical distance between the chromaticity coordinates (CIE 1931) of the new white-point and D65 (Δxy). The colour difference Δxy between successive images varied between -0.10 (towards lower colour temperature) and 0.14 (towards higher colour temperature) with steps of 0.01. For each of the 10 original images a list of images was made and presented once to the participant. When the participant had finished the first part, the data were analysed and the optimal white-point along the daylight curve was determined per image.

In the second part of the experiment, the white-point was changed perpendicular to the daylight curve along three axes, each crossing the daylight curve at a different point (see dotted lines in figure 2). One of these points corresponded to the optimal white-point, as determined in the first part of the experiment for that participant. The other two points were located along the daylight curve at a distance of $\Delta xy = \pm 0.02$. This resulted in three lists of images per original image. The colour difference Δxy between successive images in the list varied between -0.05 and 0.05 with steps of 0.005.

Experiment 2: Acceptable White-Point

Participants

Twenty employees of Philips Research Eindhoven with a European cultural background participated. Ten of them also participated in experiment 1.

Figure 1. Images used in experiment 1 (all) and experiment 2 (first five).

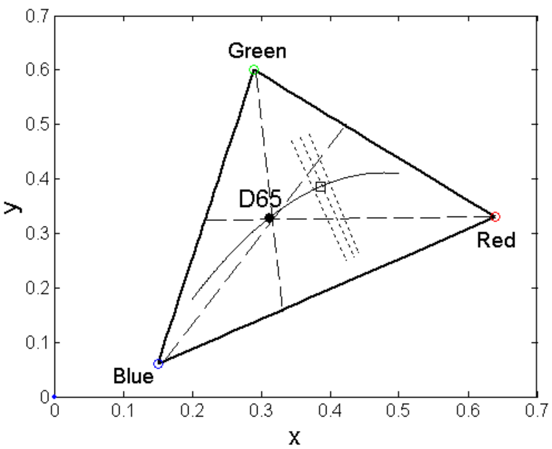

Figure 2. Chromaticity coordinates (CIE 1931, xy-colour space) of the red, green and blue primaries of the display. The curved black line corresponds to the daylight curve and the dotted lines intersect this curve perpendicularly. The dashed lines correspond to the primary axes along which the white-point was varied in experiment 2.

Images

The first five images of figure 1 were used. The procedure to simulate a change in white-point was similar to that of experiment 1.

Procedure

The task of the participants was to step through the list of images and select the image for which the colour rendering was just acceptable. This means that the colours of the image should still look 'natural'. The white-point was changed along the daylight curve or along one of the three primary axes (see figure 2): the line through D65 and the red primary (the red axis), the line through D65 and the green primary (the green axis), and the line through D65 and the blue primary (the blue axis). The first image of the list was always the original image and the colour difference Δxy of the successive images in the list varied in only one direction, i.e. towards higher colour temperatures (positive direction) or towards lower colour temperatures (negative direction) for changes along the daylight curve and towards the primary (positive direction) or away from the primary (negative direction) for changes along the primary axes.

The distance Δxy between successive images varied from 0 to 0.20 with steps of 0.005 for changes along the daylight curve, from 0 to 0.05 with steps of 0.005 and from 0.05 to 0.10 with steps of 0.01 for changes along the red and green axis, and, from 0 to 0.10 in steps of 0.01 and from 0.10 to 0.20 in steps of 0.02 for changes along the blue axis. The resulting forty lists of images (i.e. 5 original images x 4 axis x 2 directions) were presented twice.

Results

Experiment 1: Optimal White-Point

In the first part of experiment 1, the preferred white-point along the daylight curve was determined for each original image. Figure 3a presents the colour difference Δxy between D65 and the preferred white-point along the daylight curve per original image. The colour difference averaged across images and participants was -0.026, i.e. the preferred white-point was shifted towards higher colour temperature. A statistical analysis (ANOVA) with 'image content' as a fixed factor and 'participant' as a random factor revealed a significant effect of image content on the preferred white-point ($p < 0.01$).

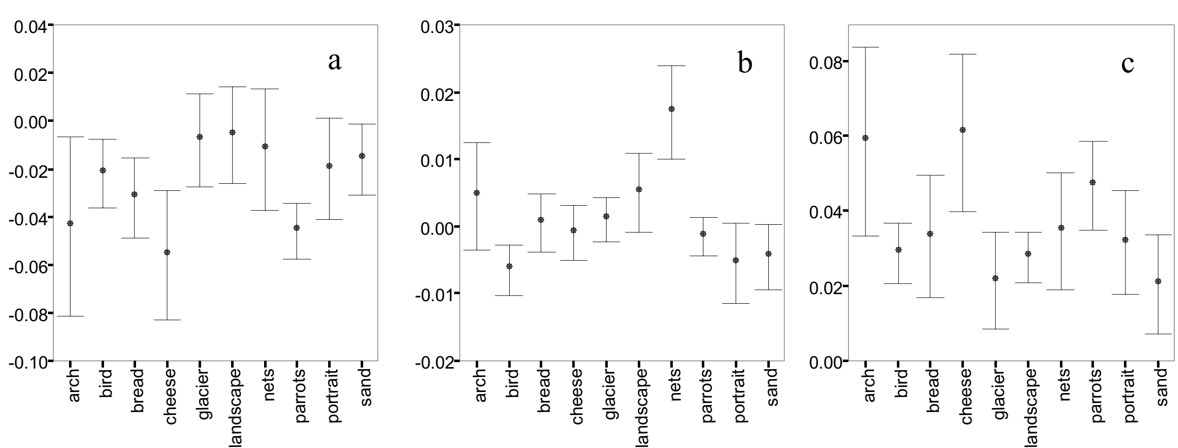

Figure 3. The colour difference Δxy between (a) the preferred white-point along the daylight curve and D65, (b) the optimal white-point and the daylight curve, and, (c) the optimal white-point and D65.

In the second part of the experiment, the preferred white-point perpendicular to the daylight curve was determined. This was done by varying the white-point along three lines, each crossing the daylight curve around the preferred setting per image and per participant. The average across the three responses represents an estimation of the most 'optimal white-point' for a particular image and a particular participant. Figure 3b presents the colour difference •xy between the daylight curve and the optimal white-point per image. The deviation from the daylight curve was on average 0.001, i.e. located slightly below the daylight curve. A statistical analysis showed that there was a significant effect of image content on the deviation from the daylight curve ($p<0.001$). Another way to analyse the data is to calculate the colour difference between D65 and the optimal white-point as measured in the second part of the experiment (see figure 3c). The colour difference averaged across images and participants was 0.036. Again, the effect of image content was significant ($p<0.001$). The magnitude of the white-point shift was largest for the images 'arch' and 'cheese' and smallest for the images 'glacier' and 'sand'.

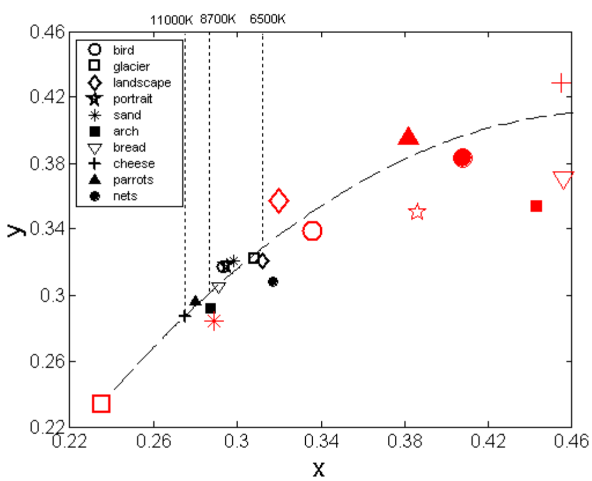

Figure 4. Optimal white-point for each image (small data points) and chromaticity coordinates of the average pixel of an image (large data points).

As the shift in optimal white-point was largest for images with a dominant colour and smallest for rather neutral images, an analysis was performed to test whether the dependency of optimal white-point on image content could be explained in terms of the average colour of the images. Figure 4 shows the optimal white-point per image averaged across participants and the colour of the image averaged across all pixels. It can be seen that for most images the optimal white-point is not located around D65. The average optimal white-point was $(x_{opt}, y_{opt}) = (0.295, 0.309)$. Moreover, the location of the optimal white-point seems to be opposite to the location of the average colour point of the image. For example, the average colour of the image 'cheese' corresponds to a high colour temperature while the optimal white-point of this image is shifted towards lower colour temperature. We calculated per image the colour difference between its optimal white-point and the overall average (x_{opt}, y_{opt}) and the colour difference between the average colour and (x_{opt}, y_{opt}). The colour differences were significantly correlated ($r = 0.73$, $p = 0.015$). This implies that the shift of the optimal white point of an image is correlated to the deviation of its average colour.

Experiment 2: Acceptable White-Point

Figure 5 shows the mean of the white-point that was judged to be just acceptable per image, per axis and per direction. Positive values correspond to the acceptability range along the positive direction of the axes (towards the primary or towards higher colour temperature) and negative values correspond to the acceptability range along the negative direction of the axes (away from the primary or towards lower colour temperature). A statistical test revealed a significant effect of image content, axis, direction and participant ($p<0.001$). The figure shows that the difference between images is rather small and that participants are most tolerant for changes along the daylight curve and the blue axis.

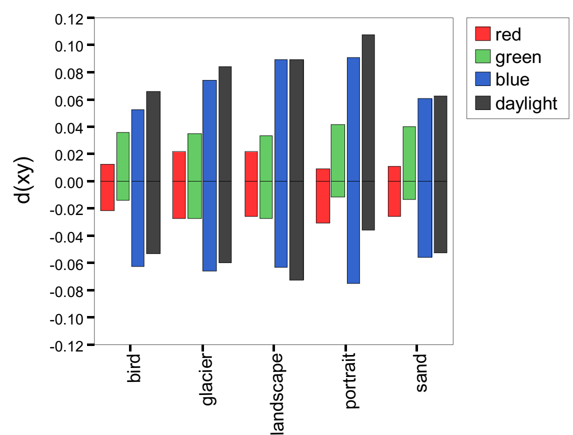

Figure 5. The range of acceptable white-points (expressed as Δxy) in the positive and negative direction of the red, green and blue axis and along the daylight curve. The data were averaged across participants.

In figure 6 the results are averaged across all images. The figure shows the range of white-points that was acceptable to 50% of the participants and the range that was acceptable to 75% of the participants. In addition, the daylight curve and the black body curve are plotted and the three white-point settings that are usually available on a TV display. The results are presented both in the xy and u'v'-colour space.

Discussion

In this study the optimal and acceptable white-point settings of a display were investigated. In the first experiment, participants were asked to select the image that they preferred most with respect to colour rendering. The experiment showed that the average optimal white-point did not correspond to $(x_{D65}, y_{D65}) = (0.313, 0.329)$ but to $(x_{opt}, y_{opt}) = (0.295, 0.309)$. This difference is about five times the visibility threshold of colour differences [4]. Hence, shifting the white-point from D65 to (x_{opt}, y_{opt}) is expected to be clearly seen by all viewers.

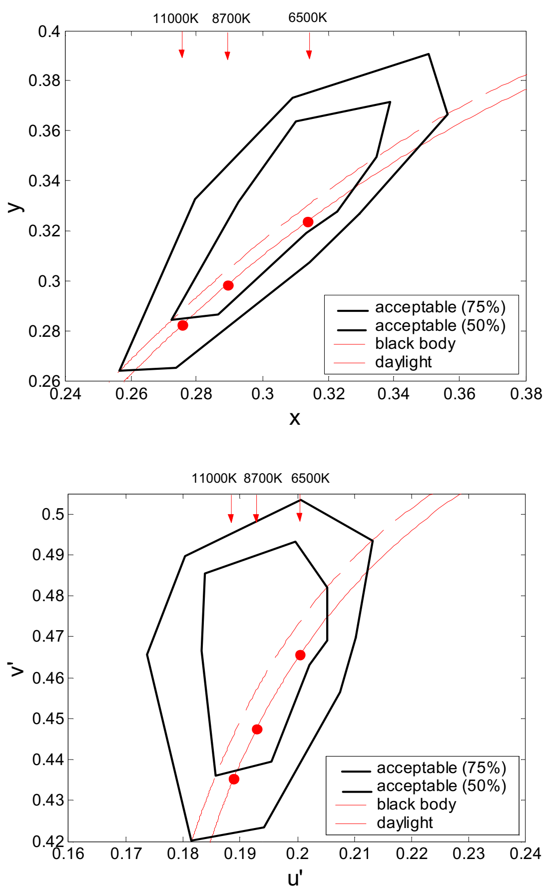

Figure 6. Range of acceptable white-points (50% and 75%), expressed in the xy- colour space (upper) and the u'v'- colour space (lower).

The average optimal white-point (x_{opt}, y_{opt}) corresponded to a CCT of about 8000 K. Most TVs have the possibility to choose between three different white-point settings, viz. a white-point with a CCT of 6500 K, 8700 K and 11000 K (see figure 6). The optimal white-point was located closest to 6500 K for four of the ten images, closest to 8700 K for five of the images and closest to 11000 K for only one image.

We found that the difference in optimal white-point between images can be explained in terms of the average colour of the image. The optimal white-point was shifted towards a higher colour temperature with respect to the average optimal white-point for images with a yellowish content (e.g. image 'cheese') and towards lower colour temperature for images with a bluish content (e.g. image 'glacier'). Hence, participants preferred to change the white-point such that the average colour of the image shifts towards more neutral colours.

This finding is contradictory to what one would expect when the effect of image content is caused by chromatic adaptation. It is known that the human eye can adapt to about 60% of the presented colour in only a few seconds.[5] Therefore, it is possible that the participants adapted (partially) to the average colour of the image that was shown. For instance, if participants adapted to an image with a yellowish content, the colour that would be perceived as neutral would shift towards yellow. Hence, neutral colours would be perceived as bluish. In order to perceive neutral colours on the display as being neutral, the white-point should shift towards yellow, i.e. *towards* the average colour of the image. This is, however, opposite to the results. Therefore, the effect of image content on preferred white-point is not the result of chromatic adaptation.

In the second experiment, participants were instructed to select the image for which the colour rendering was just acceptable. The tolerance for variations of the white-point was measured along the lines through D65 and the three primaries and along the daylight curve. Figure 6 showed that people were most tolerable of white-point changes along the daylight curve. The region that was acceptable to 75% of the participants was about 0.04 wide along the daylight curve and about 0.02 perpendicular to the daylight curve (in terms of $\Delta u'v'$). It is interesting to notice that the points with a colour temperature of 6500 K and 8700 K fall within this region, but a white-point of 11000 K is just not acceptable to 25% of the participants.

References

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Biography

Ingrid M.L.C. Vogels obtained a M.Sc. in physics in 1993 and a Ph.D. in Physics in 1997, both at the University of Utrecht in the Netherlands. She worked at the Instituut of Perceptie Onderzoek (IPO) for 3 years. Now, she is working at Philips Research Laboratories Eindhoven as a Senior Researcher. Her main interest includes human perception, especially visual perception and the application of image quality improvement.