19.2: The Visibility of a Local Deviation in Luminance and White-Point of a Display

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Abstract

The visibility threshold of a Gaussian deviation in the luminance or the white-point of a display has been determined. In the most critical situation, i.e. for homogeneous and moving images, the threshold corresponds to a ΔE^*_{uv} of about 1 in the case of a local luminance variation and a ΔE^*_{uv} of about 2.5 in the case of a local variation in the white-point.

1. Introduction

In principle, each display technology suffers to some extent from a non-uniformity in luminance and/or chromaticity. For instance, CPTs (Cathode Picture Tubes) can have a luminance decrease of about 50% from the center towards the corners of the screen. For LCDs (Liquid Crystal Displays) and CDTs (Cathode Data Tubes) the luminance usually decreases by about 20%. There are many factors that give rise to luminance and chromaticity non-uniformities across a display. Luminance variations can be caused, for instance, by variations in the glass thickness of a CRT or by inhomogeneities of the LCD back-light. Chromaticity variations can occur by temporal deformations of the shadow mask in a CRT or by variations in the thickness of the LC layer in an LCD.

An interesting question, especially for manufactures of displays, is whether these non-uniformities are visible or not. There is already quite some literature about the sensitivity to luminance and chromaticity differences. Visibility thresholds or just noticeable differences (jnd) of luminance and chromaticity are often expressed in terms of ΔE^*_{uv} or ΔE^*_{ab}. Song and Luo [1], for instance, reported that a luminance or chromaticity difference of $\Delta E^*_{ab} = 2$ between two natural images is just perceptible. In practice, a visibility threshold of $\Delta E^* = 1$ is often adopted. When the chromaticity difference between two regions is negligible, a ΔE^* of 1 corresponds to a luminance difference of about 3% at high luminance values and about 7% at low luminance values. This is in good agreement with, for instance, the results of Lubin and Pica [2], who found that a step-wise luminance difference of about 1% is visible.

When the luminance varies more gradually within a stimulus, thresholds are usually larger. In a previous study [3], we measured the visibility of a gaussian luminance variation over the whole screen, using natural and homogeneous images, with and without presenting the undistorted image as a reference. Thresholds, expressed as $\Delta L/L_{max}$, varied between 5% and 30%, depending on the shape of the luminance profile, the image content and the presence or absence of a reference. In terms of ΔE^*_{uv} the threshold varied between 2 and 12. In another study [4] we measured the visibility of a linear increase in hue or saturation from the edges towards the center using natural images. When the undistorted and distorted images were presented simultaneously, the visibility threshold for hue and saturation, calculated as the maximum difference between the undistorted and distorted image, corresponded to a ΔE^*_{uv} of about 1.

Apart from the sensitivity to a luminance or chromaticity variation on a global scale, i.e. the width of the profile is approximately equal to the width of the stimulus, researchers have also measured the sensitivity to variations on a local scale, i.e. the width of the profile is much smaller than the width of the stimulus. Many of these studies have focused on profiles with a regular pattern. The threshold for spatial luminance or chromaticity patterns has been found to depend on the shape of the pattern (e.g. sinusoidal or blocked), the spatial frequency, the number of cycles, the mean luminance and the size of the display (see [5] for an extensive overview). In the most sensitive situation the luminance threshold ($\Delta L/L_{max}$) can be as small as 0.6% [6]. The chromaticity threshold in CIE 1931 coordinates ($\Delta xy = \sqrt{(\Delta x)^2 + (\Delta y)^2}$) can be as small as 0.003 [7].

There is less information about the sensitivity to a single local luminance or chromaticity profile. Bijl et al. [8] reported that for a circular symmetric gaussian luminance profile on a homogeneous background smaller than 15 times the stimulus diameter, the visibility threshold rapidly decreases with increasing stimulus diameter. For stimuli larger than about 40 arcmin the threshold slightly increases again. It is not known whether the visibility thresholds are the same for images with a natural scene. Therefore, we measured in experiment 1 the visibility of a local deviation in *luminance* for both natural images (still and moving) and a homogeneous image. In experiment 2 we measured the visibility of a local deviation in *chromaticity* (in this case a deviation in white-point), for both natural images and a homogeneous image.

2. Experimental design

In two separate experiments, we measured (1) the visibility of a local deviation of the luminance and (2) the visibility of a local deviation in the white-point of a display. We did not present the undistorted image as a reference, as we expected thresholds to be close to $\Delta E^*_{uv} = 1$ in the case of a reference, based on the results of a previous study [4].

2.1 Luminance and chromaticity profiles

In order to vary the luminance and chromaticity non-uniformities in a controlled manner, we applied several distortions onto an image and presented the distorted images on a display that was as uniform as possible (see 2.2). The distortion was a 2-dimensional Gaussian function with a width σ_x in horizontal direction and a width σ_y in vertical direction. For convenience, we described the coordinates of the screen by $-1 \le x \le 1$ and $-9/15 \le y \le 9/15$ (the aspect ratio of the screen was 9:15). Figure 1 shows some examples of the distortion profiles used in this study.

 ISSN/0003-0966X/03/3402-0820-$1.00+.00

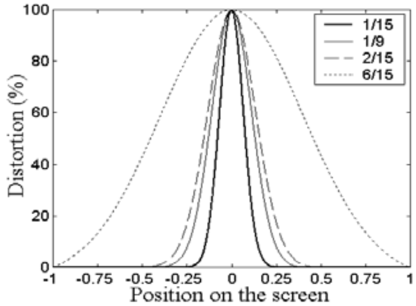

Figure 1: non-uniformity profiles for the values of σ that are used in experiments 1 and 2.

In experiment 1, the luminance of the images (L) was either increased or decreased relative to the original value (L_0). The amplitude of the distortion varied between -30% and +30%, with steps of 2.5% (in terms of $(L-L_0)/L_0$). The width (σ_x, σ_y) of the luminance profile was (1/9, 1/9) or (1/9, 1/15). The distortion was always centered in the middle of the screen.

In experiment 2, the white-point was changed in the direction perpendicular to the black body loci, either towards a more greenish color or towards a more purple/reddish color (see figure 2). The width (σ_x, σ_y) of the white-point distortion was (1/15, 1/15), (2/15, 2/15) or (2/15, 6/15). The amplitude of the distortion varied between -0.02 and + 0.02, with steps of 0.001 (in terms of Δxy). The distortion was centered either in the middle of the screen or at the position (2/3, 0).

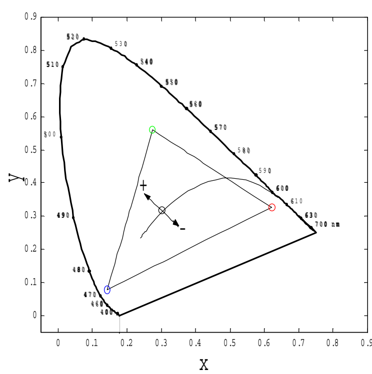

Figure 2: Chromaticity coordinates in CIE 1931 of the red, green and blue primaries and the white-point of the display. The curved line corresponds to the black body loci. The white-point was changed along the straight line through the white point.

2.2 Display

The images with the simulated non-uniformities were presented on a 30" LCD-TV. The contrast and brightness setting of the LCD-TV were adjusted such that the display had a black-level of 1.5 cd/m^2 and a maximum luminance of 370 cd/m^2. The display had a maximum luminance deviation of 15% (neglecting an area of 1 cm near the edges) over such a distance that the luminance gradient was 0.75% per cm. The maximum color deviation of the display was $\Delta xy = 0.0016$. The display was surrounded by a large black frame.

2.3 Protocol

In order to measure the visibility threshold, we used the tuning method (also called method of adjustment). In each trial, participants could increase or decrease the distortion of the image, by pressing the page-up or page-down keys, till the distortion was just *not* visible any more. Two consecutive images were always separated by a homogeneous adaptation image that was shown for 2.5 s. We decided not to use the stair-case method, as we found in a previous study on the visibility of a global luminance profile [7] that this method can lead to unstable results when there is no reference image presented.

In experiment 1, four images were used (see figure 3). Two of them were natural still images ('cedars' and 'sand'), one was a homogenous grey image of 60 cd/m^2 ('grey') and one was a panning movie with a relatively dark scene ('movie'). Each image was processed several times. The luminance profiles could have a size of (σ_x,σ_y) = (1/9, 1/9) or (1/9, 1/15), and the amplitude of the profile could be positive (increasing luminance) or negative (decreasing luminance). Each of the 12 conditions (4 images x 2 sizes x 2 amplitudes) was presented twice. In the first half of the experiment, the image with the maximum distortion was presented at the beginning of each trial. In the second half of the experiment, the trials started with the undistorted image.

In experiment 2, three images were used (see figure 3). Two of them were natural still images ('girl' and 'sand') and one was a homogenous grey image of 100 cd/m^2 ('grey'). Each image was processed several times. The white-point profile could have a size of (σ_x,σ_y) = (1/15, 1/15), (2/15, 2/15) and (2/15, 6/15), the amplitude of the profile could be positive (i.e. changing the white-point towards green) or negative (i.e. changing the white-point towards purple/red) and the profile could be centered in the middle or towards the right edge of the screen (i.e. (x,y) = (0,0) or (2/3, 0)). However, for the image 'girl', the distortion was only applied in the center, as this image was only chosen for its skin tones. Each of the 30 conditions (5 combinations of image and position x 3 sizes x 2 amplitudes) was presented once. The trials always started with the maximally distorted image .

Both experiments started with one practice trial for each original image. The viewing distance was equal to six times the height of the screen (i.e. 2.35 m) and the ambient illumination was adjusted to 20 lux, measured perpendicular to the screen in the direction of the viewer.

Figure 3: in the local luminance experiment we used the images 'cedars', ' sand', a homogeneous grey image and a movie with a panning scene; in the local white-point experiment we used the images 'sand', ' girl' and a homogeneous grey image.

2.4 Analysis

For each experiment we collected the visibility threshold per condition and per participant. The data were analyzed with an ANOVA, using the statistical package SPSS version 11.0.1. We used a significance level of $p = 0.05$ to establish that a factor or interaction was statistically significant.

The thresholds for the luminance profiles were expressed in terms of $\Delta L/L_0$ and the thresholds for the white-point profiles were expressed in units Δxy, being the geometrical distance between the new white-point at the maximum of the distortion profile and the actual white-point of the display in the x,y chromaticity coordinate space. In order to compare the results with other studies, we transformed the thresholds into ΔE^*_{uv} units. This was done by calculating on a pixel-to-pixel base the difference ΔE^*_{uv} between the pixel of the original image and the pixel of the image with a distortion equal to the average threshold. The resulting ΔE^*-profile is a function of the horizontal and vertical spatial dimensions (x,y) of the image and resembles the profile of the luminance distortion. The maximum of the $\Delta E^*(x,y)$-profile was taken as the visibility threshold.

3. Results

3.1 Experiment 1

Figure 4 shows the visibility threshold for a local luminance profile for each combination of image content, amplitude of the distortion and size of the profile. The error bars represent the 95% confidence intervals. The most striking effect in this figure is the effect of image content: thresholds are much lower for the homogeneous grey image and the movie than for the natural images. Table 1 shows the mean thresholds per image.

The data were analyzed with an ANOVA, with 'image content', 'profile', 'amplitude' and 'initial distortion' as fixed factors and 'participant' as random factor. The analysis showed that the effect of 'image content' was the only significant main effect and that all 2-way interactions with the factor 'image content' were significant. Therefore, we performed an ANOVA for each image separately. We found a significant effect of 'profile' for the images 'sand', 'grey' and 'movie'. However, the difference between the two profiles was very small, on average 1.2%, and depended on the image content. We also found that the threshold was significantly higher in the case of a positive amplitude compared to a negative amplitude for the images 'grey' and 'movie'. Finally, the effect of 'initial distortion' was only significant for the image ‘cedars’. The threshold was on average 3.5% higher when starting the trial from the original image instead of starting from the maximally distorted image.

The thresholds were transformed into ΔE_{uv}^* units, as described before. The results are given in table 1. It shows that the visibility threshold of a local luminance deviation corresponds to a ΔE_{uv}^* of 1 for the homogenous image and the movie, whereas it is about 10 times larger for the still natural images.

Table 1: Visibility threshold in terms of $\Delta L/L_0$ and ΔE^*_{uv} for a local luminance deviation for the images of experiment 1

image	cedars	sand	grey	movie
threshold $\Delta L/L_0$	27%	20%	5%	4%
threshold ΔE^*_{uv}	10.6	9.8	1.1	1.5

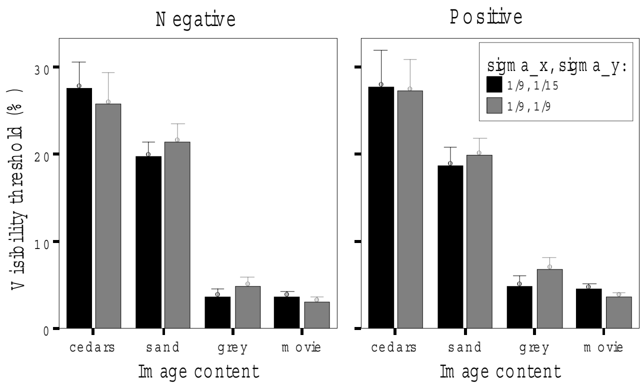

Figure 4: Visibility threshold of a local luminance profile, averaged across all participants, as a function of the size of the profile, for each image in the case of a negative profile (left) and a positive profile (right).

3.2 Experiment 2

Figure 5 shows the visibility threshold for a local variation in the white-point as a function of the size of the profile, for each combination of image content, position of the distortion and amplitude of the distortion. The figure shows again that the threshold is smallest for the grey image. Moreover, the threshold seems to decrease with increasing size of the profile. Table 2 shows the mean threshold per combination of image and position.

The data were analyzed with an ANOVA. As we did not measure the effect of the position of the distortion for each image, we cannot test the main effect of position separately. Therefore, we treated the 5 combinations of image and position as one factor, called 'image_position'. Thus, 'image_position', 'profile' and 'amplitude' were included in the ANOVA as fixed factors and 'participant' as random factor. The analysis revealed a significant main effect of 'image_position': all images were significantly different from each other and the effect of 'position' was significant only for the image 'sand'. There was also a significant effect of 'profile': thresholds were significantly lower for the white-point profile with the largest size. Finally, the interaction of 'image_position' with 'amplitude' was found to be significant. The influence of the amplitude of the distortion, i.e. changing the white point towards green or purple/red, was significant for the image 'sand' when the distortion was located near one of the edges and for the image 'girl' when the distortion was centered in the middle of the screen.

The thresholds were transformed into ΔE_{uv}^* units, as shown in table 2. The visibility threshold of a local deviation in the white-point corresponds to a ΔE_{uv}^* of 2.5 for the homogenous image, whereas it is about 2 to 3 times larger for the natural images.

Table 2: Visibility threshold in terms of $\Delta(xy)$ and ΔE^*_{uv} for a local deviation in the white-point for the images of experiment 2.

image position	girl center	sand center	sand edge	grey center	grey edge
$\Delta(xy)$*1000	8.1	4.5	5.5	2.2	3.0
ΔE^*_{uv}	6.4	5.6	7.3	2.1	2.5

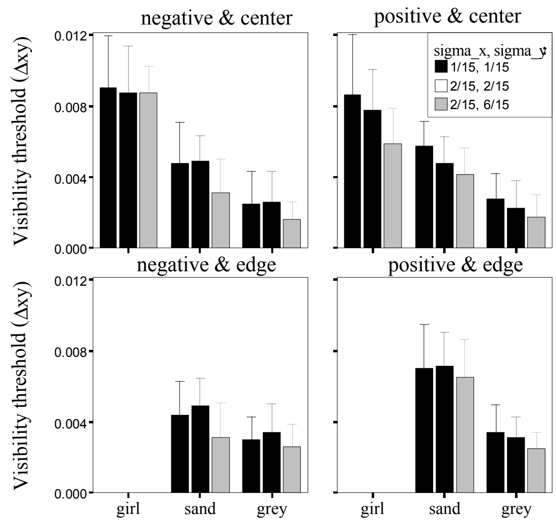

Figure 5: Visibility threshold of a local deviation in white-point, averaged across all participants, as a function of the size of the profile per image. The profile had either a negative (left) or a positive (right) amplitude and was positioned either in the center (up) or near the left or right edge of the image (down).

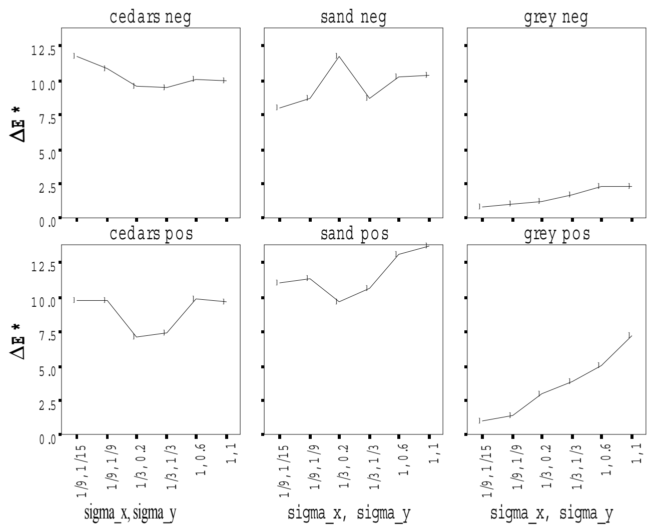

Figure 6: Visibility threshold of a luminance profile as a function of the size of the profile, for each image in the case of a negative profile and a positive profile. The 95% confidence interval was ±1.5 for the natural images and ±0.76 for the grey image.

3.3 Effect of size of distortion

In experiment 1, we found a small, but significant, difference in the visibility threshold between the two local luminance profiles for three of the four images. The profiles had the same size in horizontal direction, but differed in vertical direction. It could be that the effect of profile is related to the size of the profile (e.g. σ_x*σ_y), or to the shape of the profile (e.g. σ_x/σ_y). In a previous study [3] we measured the visibility threshold for luminance variations at a much larger scale. Since the same images were used, we can compare the results of both experiments. Figure 6 shows the visibility threshold (in terms of ΔE_{uv}*) of a luminance distortion as a function of the size of the profile.

It can be seen that the threshold increases with the size of the distortion for the image 'grey'. The increase is larger for a positive than for a negative amplitude. For the image 'sand', the threshold tends to increase with size, although there is a small increase (negative amplitude) or decrease (positive amplitude) for the intermediate sizes. For the image 'cedars', the threshold is significantly larger for the two smallest profiles. In general, the results show that the effect of 'profile' is more related to the size of the profile than to its shape. The effect of size, however, depends on the image content. The latter is caused by the fact that the artificial luminance profile is sometimes interpreted as being natural, e.g. due to a local sunshine.

4. Discussion and conclusions

When a display has a Gaussian luminance distortion with a size σ of 1/9 times half the width of the display, the distortion is visible at an amplitude of about $\Delta L/L_{max}$ = 5% for homogeneous and moving images. This corresponds well with the result of [3], where the visibility threshold of Gaussian luminance profiles was measured at a large range of sizes. The visibility threshold is much larger for still images with a natural scene, viz. 20-25%. These values correspond to a ΔE^*_{uv} of about 1 and 10, respectively. In general, the luminance distortion becomes less visible when the size of the profile is increased.

When the white-point of a display varies locally in the direction perpendicular to the black body loci with a Gaussian profile, the distortion is visible at an amplitude of about Δxy = 0.0025 in the case of a homogeneous grey image. The visibility threshold is about 0.005-0.008 for still natural images. In terms of ΔE^*_{uv} the threshold varies between 2 and 7, for the images tested. These values are very similar to those found in the case of a local luminance distortion. The white-point variation becomes slightly more visible when the size of the profile is increased.

5. References

[1] Song, T. & Luo, R. (2000). Testing color-difference formulae on complex images using a CRT monitor. *IS&T/SID Eight Color Imaging Conference*, 44-48.

[2] Lubin, J. and Pica, A.P. A non-uniform quantizer matched to human visual performance. SID Digest 22, 619.

[3] Heynderickx, I., Vogels, I., Swinkels, S., Bech, S. and Mastenbroek, E. (2003). The visibility of a global luminance profile of a display. SID 03 Digest.

[4] Heynderickx, I., Seuntiens, P., IJsselsteijn, W. and Langendijk, E. Visibility of a color gradient across the screen for stimuli presented time-sequentially and simultaneously. SID 02 Digest, p. 812 (Boston, May 2002).

[5] Olzak, L.A. and Thomas, J.P. (1986). Seeing spatial patterns. In: *Handbook of Perception and Human Performance, Volume I*, Eds. Boff, K.R., Kaufman, L. and Thomas, J.P. (John Wiley & Sons, New York, 1986), pp 7.1-7.56.

[6] Van Nes, F.L. and Bouman, M.A. (1967). Spatial modulation transfer in the human eye. *Journal of the Optical Society of America*, 57, 401-406.

[7] Van der Horst (1969). Fourier analysis and color discrimination..Journal of the Optical Society of America, 59, 1670-1676.

[8] Bijl, P., Koenderink, J.J. and Toet, A. (1989). Visibility of blobs with a gaussian luminance profile. *Vision Research*, 29 (4), 447-456.