Chromatic flicker perception in human peripheral vision under mental load

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Abstract

Results from two experiments testing flicker sensitivity are presented. Human sensitivity at different visual angles (35° , 60° and 90°), base-color points (red, green and blue), color attributes (Lightness, Chroma and hue) and frequencies (5Hz, 10Hz, 20Hz, 40Hz and 60Hz) were determined using a detection task and fitting of a psychometric curve. Results demonstrate a large effect of eccentricity on the flicker perception. For chroma and hue flicker the sensitivity decreases with the increasing eccentricity at all frequencies. The results for lightness changes show a more complex frequency dependance, with higher sensitivity at larger visual angles for frequencies lower than 15Hz. Generally, we have higher sensitivity to lightness flicker as compared to Chroma and hue flicker for all eccentricities and all frequencies. Lightness, contrary to chroma and hue, is also independent of the base color point. The second experiment demonstrated that mental load significantly impairs detection of flicker in the periphery. The color model used to create the stimuli was designed for central vision and does not account for the density of cones and rods in the far periphery and their interactions. This explains the visibility of chromatic changes even at 90° . Still, for some base points and directions of change, no flicker was detected at any frequency and amplitude for the largest visual angle.

Introduction

In recent years LEDs (Light Emitting Diodes) have become more frequently used due to several advantages of such systems over conventional lighting systems (like light bulbs). The dynamic capabilities of LEDs allow their use in many applications, which range from common indicators and road signs to personalized atmosphere creation. The main challenge in the design and control of dynamic lighting systems is the perceived attractiveness of the temporal light changes they produce. LED lamps are typically controlled in a way that produces chromaticity and brightness changes in discrete steps at discrete time intervals. When the size of these steps is too large the light change is perceived as jerky, stepped, or unsmooth. Flicker, which is defined as the rapid alternation between two colors or brightness levels, is one example of such effects, and from the perspective of perceived attractiveness, it is an especially annoying one. Under some conditions, for example for very high frequencies (above 80 Hz), flicker is not perceived. Instead, a temporal fusion, which means a steady, continuous light is perceieved [1]. Previous studies demonstrated that flicker perception is influenced not only by frequency, but by numerous other factors, which include luminance [2], chromaticity irrespective of brightness [3], size of the stimulus [4] and finally the retinal position of the stimulus [5].

In order to be able to define a distance between a pair of color stimuli defined within a color space, at which alternating light produces smooth and not flickering light, the notion of the visibility threshold was introduced. It is defined as the largest amplitude for the particular stimuli that produces smooth and not flickering light changes. Color spaces in the temporal domain are not defined yet. Spatial just noticeable differences are described by, among others, the CIE Luv and CIE Lab color spaces, which demonstrate relatively uniform color differences predictions for spatial vision [6].

Recent studies have shown and roughly defined the flicker sensitivity in the central vision; i.e. when fixated directly on the light source [7]. However, LED based lighting systems can also be extended to the peripheral vision, which comprises the region beyond the very center of the eyes' fixation to the limit of about a 100° to each side. It is known that, due to the structure of the human eye, the perception of motion and color changes at the periphery. For example, Abramov et al. [8] showed that the photopic luminosity function (the average visual sensitivity of the human eye to light of different wavelengths), as defined by heterochromatic flicker photometry, is not the same in the periphery of the retina as it is in the fovea. For that reason one particular alternating color pattern that appears to be smooth in the central vision may be perceived as flickering in the periphery, and vice versa. Thus, the results from [7] cannot be assumed in the periphery and a new study is required. The hypotheses formulated in the current research are largely based on the fidings in [7].

It is commonly known that the density of cones in the human retina decreases when moving away from the centre of the retina, and therefore color perception is impaired significantly as well. Hansen et al. [9] found that humans are able to perceive some colors at large eccentricities (more than 50°) and cone opponent channels, however sparse, are still present at these angles. Therefore, it is hypothesized that there is an effect of the eccentricity on the lightness, chroma and hue flicker visibility thresholds, but it is still perceivable at large eccentricities. Sekulovski et al. [7] demonstrated that lightness changes are more visible than changes in chroma and hue, when the color changes are expressed in the CIELab color space. The experiments in this study are designed to check if this fact is valid for peripheral vision as well. In line with previous findings it is also hypothesized that there exists a frequency for which the visibility threshold has a minimum value.

Lighting is sometimes the main object of direct attention but most frequently it facilitates other activities, which are the main tasks. Carmel et al. (2007) demonstrated that including and increasing of the perceptual load impairs flicker perception. It happens because the temporal resolution of conscious perception is determined by the attention availability. Similarly, it is hypothesized that there is an effect of mental load on the flicker sensitivity. Flicker visibility thresholds is expected to be smaller without mental load task [10].

In order to gain a better understanding of the way in which human visual system processes temporal patterns in the area of the dynamic lighting applications, two experiments were conducted, the results of which are presented in this paper.

Experiment 1: Flicker sensitivity thresholds at different eccentricities

The first experiment was designed to measure human sensitivity to chromatic flicker at different visual angles. Flicker stimuli were created by choosing pairs of color in LCh color space and alternating between them. These pairs were selected along each of the L, C, and h axes, and thresholds were expressed in ΔE_{ab}, the Euclidean distance in the CIE Lab color space. Given the results of previous research on related topics discussed above, the effects of eccentricity, frequency of the changes, base-color points and direction of change on the visibility thresholds are investigated.

Method

Equipment

As a light source, a LED luminaire was used, with three RGB LEDs at the top and three RGB LEDs at the bottom of a cylindrical diffuser. Another, flat, diffuser was mounted 20 cm in front of the lamp to reduce sharp edges that may be detected during saccadic eye movements. The light source was 23 cm wide, or 5.3° of visual angle at a distance of 2.5 meter. Maximum luminance of the LED luminaire was 405 cd/m^2. The detailed profile of the light source used is presented on Figure 1.

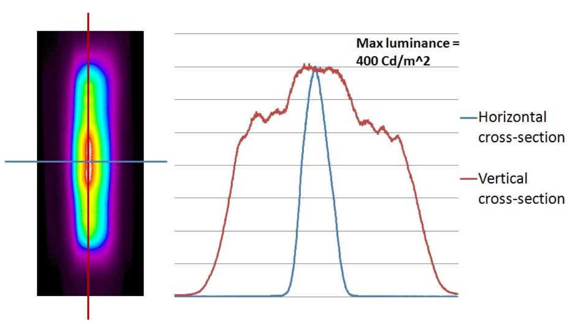

Figure 1. *False color image showing luminaire distribution with a cross section plot*

The LEDs were driven using pulse width modulation (PWM) with a driving frequency of 500 Hz and 11 bit levels. The driver accepted RGB values in the device color space of the LEDs. The target stimuli were defined in CIE LCh and transformed via XYZ to the RGB device color space using a computer program running on PC connected to the light units.

In the transformation, the D65 white point was used, being the white point of the mental task display. It was the white point of the display used for the mental task. Care was taken that the requested colors were within the device gamut of the light source.

Stimuli

The stimuli were square-wave discrete flicker, alternating between $LCh_{base} - \frac{S}{2}$ and $LCh_{base} + \frac{S}{2}$ every $\frac{1}{f}$ seconds. LCh_{base} denotes the base point in the CIELAB LCh color space and S is the amplitude of the flicker in one of the directions $d \in L, C, h$, S stands for the step size, which is equal to the amplitude of the flicker, and f is the frequency. Example stimulus for a flicker change in direction d is depicted in Figure 2.

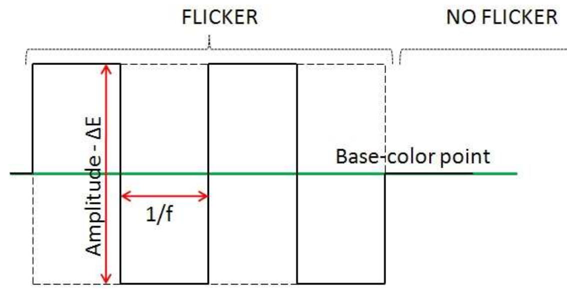

Figure 2. *Example stimulus used in the experiment*

The stimuli were varied in eccentricity (35° , 60° and 90°), frequency (5, 10, 20, 40 and 60Hz), base-color point (Red, Green and Blue), direction of change (Lightness, Chroma and hue) and amplitude expressed in ΔE. Base-color points had the following LCh values: red (60, 60 45), green (60, 60, 150), and blue (60, 60, 290). A series of pilot tests were conducted in order to produce a robust fit. Lightness flicker had amplitudes of values 1,2,4,6,10, and 60 ΔE, Chroma flicker had amplitudes of values 10, 20, 40, 60, and 80 ΔE, and hue flicker had apmlitudes of values 24, 40, 60, and 80 ΔE.

In the choice of the eccentricities various criteria were considered. 35° was chosen because it corresponds to the retinal region of highest flicker sensitivity [5]. 90° was chosen as it matches the most distant retinal region, at which human vision still functions. Finally, 60° was chosen as a middle value between 35° and 90° . The three base-color points: red, green and blue were chosen because these are the desaturated primaries for which the change within CIELab LCh allows for large amplitudes along each of the axes. The experiment consisted of three sessions, each of them at different eccentricity. The stimuli were presented in three blocks, each representing different base-color point, randomized across the subjects. Within each block the stimuli were presented in randomized pairs of flickering and non-flickering light. The duration of the flickering light was fixed at four seconds whereas non flickering light duration varied between two and four seconds. In this way participants could not predict when exactly the light was producing the flickering pattern. The total number of stimuli was 675 (225 flickering and 225 non-flickering blocks for each eccentricity).

The mental load task was a simple game created in Adobe Flash. It was displayed on a screen position 2.5 meters in front of the participants, who controlled it with a computer mouse placed on a table in front of them. Participants had to move one of four balls in such a way that it did not touch/hit the remaining three balls which moved according to general physics laws. When the player ball touched any of the other balls, the red "HIT" text appeared in the left corner of the screen. This specific mental load task was chosen because it forces the participant to fixate on the screen, but still allows for flicker detection. Moreover, it enforces two types of eye movements: saccadic and continuous ones, which are both important for flicker sensitivity.

Participants

Participants were 10 female and 20 male Philips Research employees, aged between 23 and 45, with a mean age of 29. All subjects had normal or corrected to normal vision. They didn't wear glasses (from distant angles flickering light reflected in the glasses as demonstrated pilot tests). They all had normal color vision, tested with Ishihara Test of Color Deficiency. Before the start of the experiment, participants were asked if they, or a member of their family, suffered form epileptic attacks, migraines or any other known condition for which flickering light could have negative consequences.

Procedure

In an otherwise darkened room, the LED luminaire was placed at different eccentric positions and it faced the participant. Subjects were seated at a distance of 2.5 meters from the light source. To ensure fixed position of subjects' eyes and the constant distant to the light source, their chin was placed on the chin rest mounted on the table in front of them. They were seated 2.5m from and directly facing the display with the mental load task.

Before the start of the session the participants received verbal instructions. They were instructed to fixate on the display and carry on the mental load task for the duration of the entire session. They were asked to press the space bar on the keyboard placed on the table in front of them every time they saw the flickering. A brief trial session was implemented so that participant got used to the stimuli before startig the experiment.

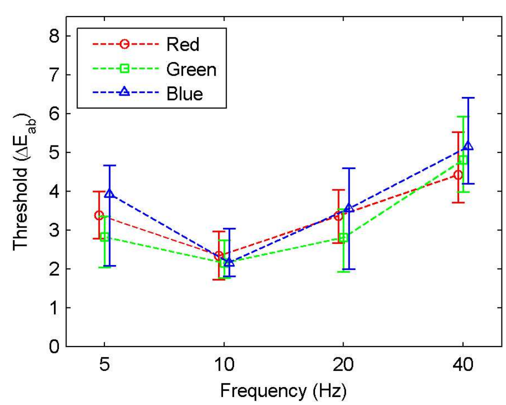

Figure 3. *Visibility thresholds for Lightness flicker at* 35°

Results

The amplitude, given in ΔE_{ab}, for which 50% of the participants detected flicker was defined as the threshold. In order to obtain the visibility thresholds, a psychometric curve was estimated by fitting a logistic curve to the values found for each set of amplitudes of every particular stimulus. The visibility threshold was then defined as the amplitude at which the psychometric curve reached 0.5. Each of the curves was resampled 1000 times using bootstrapping, in order to estimate 95% confidence intervals for the thresholds [11]. The median threshold amplitudes were analyzed using ANOVA (Analysis of Variance) with eccentricity, base-color point, direction of change and frequency as fixed factors. A number of significant effects, most important of which are discussed below, were found. In several high-angle, high-frequency cases, reliable thresholds were not found for a majority of observers. These points are absent from the plots.

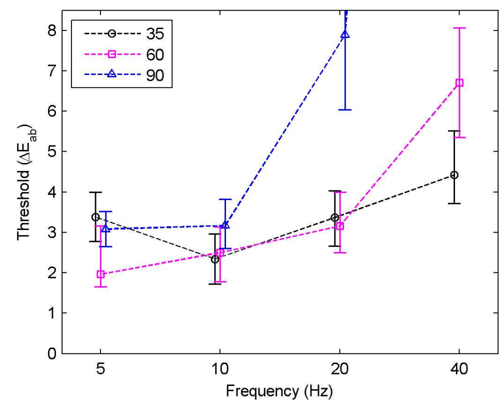

Figure 4. *Lightness flicker thresholds averaged across base-color points for the 3 eccentricities tested. For the* 90° *and 20Hz, the upper error bar reaches 13* ΔE_{ab}

Effect of eccentricity on lightness flicker

Eccentricity was found to have a significant effect on peripheral lightness flicker perception ($p<0.01$), as shown in Figure 4. A post-hoc test revealed that visibility thresholds for 90° are significantly different than both 35° and 60° . The 90° thresholds are hihger than 35° and 60° thresholds for the frequencies above 10Hz.

Effect of eccentricity on chroma and hue flicker

Eccentricity was found to have a significant effect on chroma and hue flicker perception ($p<0.01$), as illustrated on Figures 5 and 6. A post-hoc tests revealed that the all of the tested visual angles significantly differ from each other; the further into the periphery, the larger the visibility thresholds are. This is in line with what is expected based on human's retina structure and study of Hansen et al. (2009) [9].

Lower thresholds for lightness flicker compared to chroma and hue flicker

The direction of change was found ($p<0.01$) to have a significant effect. A post-hoc tests revealed that lightness visibility thresholds are significantly lower then chroma and hue flicker. This is in line with the findings of Sekulovski et al. [7] who demonstrated a similar effect for central vision.

Independence of lightness flicker and dependence of chroma and hue flicker on the chromaticity of the base-color point

No main effect of the base-color points tested ("Red", "Green", and "Blue") was found for the peripheral lightness flicker. Figue 3 illustrate the base-color point independence for

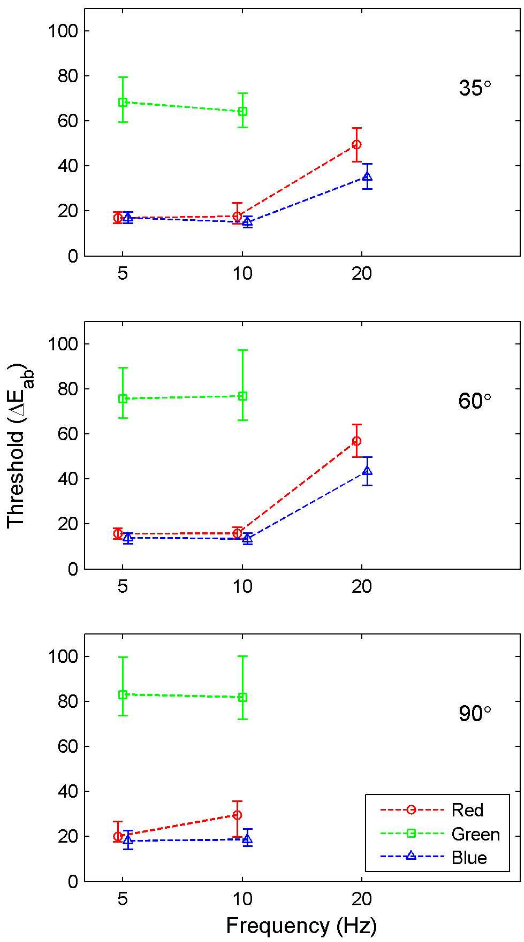

Figure 5. *Thresholds for Chroma changes expressed in ΔE_{ab} as a function of frequency and base color point for different eccentricities*

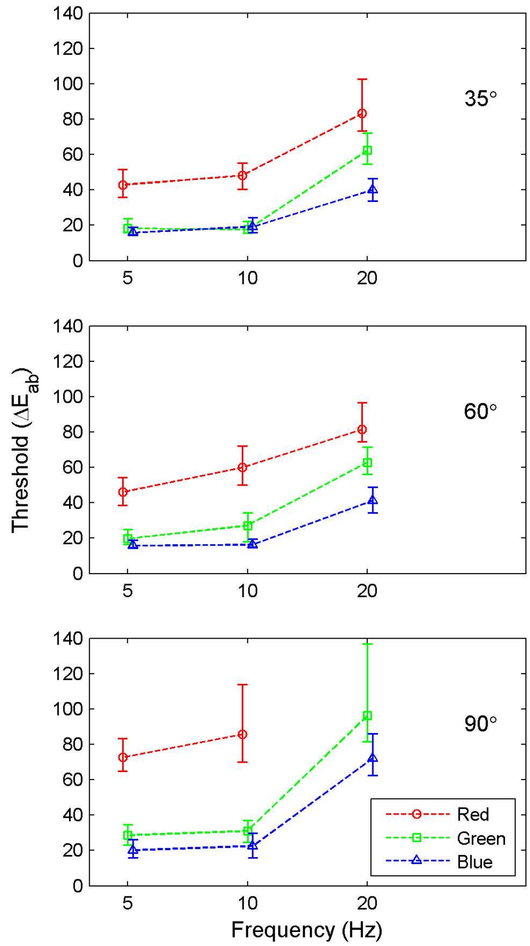

Figure 6. *Thresholds for hue changes expressed in ΔE_{ab} as a function of frequency and base color point for different eccentricities*

35°. The curves for lightness flicker are u-shaped for all of the base-color points and eccentricities tested, which shows the band pass nature of the visual system. Contrary to lightness flicker, it was found that base color point has a significant effect on hue and chroma peripheral flicker ($p<0.01$). For chroma flicker, it was found that ”Green” has higher thresholds than ”Blue” and ”Red”. In fact, visibility thresholds for ”Green” are so high for all of the eccentric angles, that they can be neglected. Furthermore, for a visual angle of 90° , no Chroma flicker was perceived around ”Green” for any amplitude and frequency. In case of hue changes, all of the base color points were found to significantly differ from one another. Post-hoc test revealed that humans are most sensitive to ”Blue” and least sensitive to ”Red” hue flicker.

Effect of frequency

Frequency was found to significantly affect peripheral flicker perception ($p<0.01$). Inspection of Figure 4 reveals that the visibility threshold to lightness flicker has a minimum value at 10Hz. This effect is more apparent for smaller eccentricities. With the

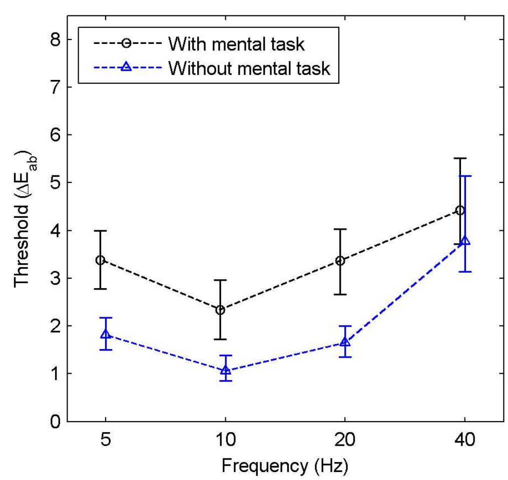

Figure 7. *Effect of mental task on Lightness flicker perception*

increase of eccentricity this effect disappears. A post-hoc test revealed that the threshold for 10Hz is significantly lower than all the other thresholds for lightness flicker.

Experiment 2 : Effect of mental load on flicker perception

One of the assumptions in the first experiment was that the introduction of an additional task changes the sensitivity to peripheral flicker. Experiment 2 was designed to test this assumption. To limit the duration of the experiment, the results for only one visual angle with and without a task were compared. Because the thresholds for 35° visual were the most accurate, this angle was selected.

Method

Participants

Seven female and thirteen male Philips Research employees, aged between 23 and 41, with a mean age of 27, participated in the experiment. They fulfilled the same conditions as in the first experiment. The two sets of participants had partial overlap.

Procedure

The same experimental setup and procedure as in the first experiment were used. It was assumed that the mental load has the same effect on flicker perception for every eccentricity. Thus, the second experiment included one session in which 35° was tested. Instead of the mental load task a fixation cross was displayed on the screen.

Results

Effect of mental load on lightness and chroma flicker

An ANOVA with mental load, frequency, base-color point, and direction of change was computed. It was found that mental load significantly impairs flicker perception at all frequencies for both Lightness and Chroma. There were not enough data point to calculate this effect for hue. Thresholds with mental load were 2.09 times higher than without mental load for 5, 10, and 20Hz, and for 40Hz this factor was 1.2. In case of chroma flicker, the performance was impaired under mental load mostly for "Green". The interaction effect of the condition and base-color point was found to have a significant effect ($p<0.01$), confirming that mental load has different effect on different base points. The mental load used in the current study was relatively low. If the mental load is increased it is expected that flicker thresholds would [10].

Conclusion

Results from two experiments were presented. They support most of the previous findings on flicker visibility thresholds and demonstrate new effects relevant to the control of dynamic, LEDs based systems. It was shown that when using CIE LCh color space, which is almost an uniform one for spatial differences, the peripheral flicker sensitivity is much higher when the change is in lightness compared to chroma or hue directions. Furthermore, the chromaticity independence of lightness flicker was also shown. Lightness flicker sensitivity peaks at 20Hz, but this effect becomes weaker when moving away into the periphery. Chroma and hue flicker gets impaired with increasing eccentricity. Lightness flicker sensitivity increases for 5Hz and 10Hz frequencies but decreases for higher frequencies when eccentricity increases. Finally, the mental load was verified to have an impairing effect on flicker perception in the periphery.

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