Smoothness and flicker perception of temporal color transitions

Dragan Sekulovski, Ingrid M. Vogels, Maurice van Beurden, Ramon Clout; Philips Research Europe; Eindhoven, The Netherlands

Abstract

We present results from two experiments designed to explore temporal properties of human color vision relevant to dynamic lighting applications. Sensitivity for smoothness perception of linear temporal transitions and flicker visibility was tested.

Stimuli in the first experiment were linear color transitions, varying in either lightness, chroma or hue, around a base color represented in CIE LCh. Results show a significantly lower smoothness threshold for lightness changes than for chroma and hue changes. Moreover, the thresholds for lightness change show independence from the chroma and hue of the base color in contrast to thresholds for chroma and hue changes. A difference between the sensitivity for chroma and hue changes was also demonstrated.

In the second experiment, the sensitivity for linear transitions is compared to flicker sensitivity for the same base colors. Results show that visibility thresholds for flicker are significantly lower than the thresholds smoothness of linear changes, demonstrating an influence of the type of change to the temporal sensitivity. The results from the flicker experiment show the same tendencies as the linear changes. The results from these experiments show a need for a model of perceived smoothness to control temporal changes in dynamic lighting systems and give the first steps towards building such a model.

Introduction

Advances in lighting, especially in Solid State Lighting, enable new uses of light. Having improved spatial and temporal resolution, more saturated primaries and lower power consumption, LED based lighting systems can be used to design more complex and attractive lighting atmospheres. One of the largest differentiators of such lighting systems are their dynamic capabilities. However, the produced dynamic lighting atmospheres need certain properties to be attractive to the users.

Perceived smoothness is one of those desirable properties. Aside from a limited set of applications, such as for disco lights and concerts, or being used as attention attractors, abrupt changes in environment lighting are hardly perceived as pleasant. Other properties of the produced lighting atmospheres that might have an influence on the attractiveness such as the hue composition or the spatial distribution, moreover, are more subjective.

The work presented in this paper studies temporal properties of human color vision relevant to dynamic lighting applications, namely thresholds for smoothness perception of linear transitions and flicker visibility. To understand the possible source of problems connected to smoothness perception, we discuss the design of modern lighting systems and applications first.

Modern lighting applications use discrete control of the light sources, with a limited number of intensity levels. Contrary to the analog systems which have a continuous change in color, in digital systems the smallest distance between two colors, both in color and time, is limited by the resolution of the system. Similar to spatial color perception, an unapropriate minimum distance between colors can introduce perceived discontinuities.

Existing dynamic lighting systems use the device color space (usually RGB) of the lights to control the temporal changes. To produce smooth light transitions, low pass filters are applied on the individual color channels. Under some conditions, especially for light effects computed from another medium (such as a video signal for Philips ambiLight^{TM}), this leads to seemingly unsolvable problems. If the parameters of the low pass filter are tuned such that the transition from low intensity to high intensity of the lights appear smooth, the transitions between chromatic colors are perceived as too slow. In the case of content dependent dynamic lighting, notably for video, this introduces a mismatch between the color of lighting and the representative color of the video frames during the transition. A video transition from a red sunset to a blue underwater scene is followed by a light transition being purple for a noticeable time. This behavior is deemed undesirable by most users.

The above mentioned problem is present in all dynamic lighting systems that control the temporal changes in a device color space. The core of the problem is that using a device color space, the properties of the human visual system, which determine the perceived qualities, are not taken into account. Previous work on the temporal properties of the human visual system shows differences in the way intensity and chromaticity changes are perceived. Namely, the human visual system processes intensity changes faster than chromaticity changes [1, 2]. Moreover, the changes in chromaticity are smoothed by the human visual system more than the changes in intensity [3, 4]. Using a device color space to control the temporal changes does not allow the use of such results.

To compute the required distances between colors that produce spatial patterns which appear smooth, the notions of visibility threshold and just noticeable difference [5] were introduced. The continuation of the work on spatial just noticeable differences led to development of, among others, the CIE Luv, CIE Lab, and CIECAM97s color spaces [6], which show a relatively good uniformity in the predicted differences, thus predicted smoothness of spatial patterns.

Unfortunately, no such spaces exist for temporal patterns. The fact that the perception of the temporal transitions depends on the frequency at which the changes are made, further complicates the representation and smoothness prediction in the temporal case. To gain better understanding of the way the human visual system processes temporal patterns in the context of dynamic lighting applications, we designed two experiments and present the results.

Previous work on temporal properties of the human visual system closest to the topic of interest of this paper comes from the area of flicker sensitivity. In [7, 8], De Lange describes flicker sensitivity at different frequencies and for different average luminance levels and types of stimuli. The results of De Lange were supported by results of Kelly [9, 10], in which he additionally studies the effects of the surround average luminance on flicker perception and spatio-temporal effects.

Using different methods, several authors report differences between sensitivities to luminance and chrominance flicker. In [4], the response of the visual system is modeled as a finite impulse response filter and differences in the properties of luminance and chrominance flicker were demonstrated. Kelly [11] uses spatio-temporal properties to show a difference between the luminance and chrominance flicker effects.

This work differs from previous work in a number of points. First, in one of the experiments presented we use discrete linear transitions, while in prior work either flicker or a fixed number of rectangular pulses were used. Second, The chromaticity changes are further subdivided in chroma and hue changes. And third, the thresholds are computed for a number of points not only with different luminance, but also chrominance coordinates.

To be able to compare the temporal sensitivity results to results from spatial visibility thresholds, the presented experiments use the CIE LCh color space and the ΔE_{ab} metric.

Based on previous studies on temporal properties of human vision described before, we form and test the validity of two main hypotheses.

- There is a difference in the sensitivity for lightness and chromaticity changes. The thresholds for lightness are lower.
- There is an effect of the base color point on the visibility thresholds for lightness, chroma and hue changes.

Smoothness thresholds for linear color transitions

The first experiment was designed to measure the sensitivity for discontinuities in linear temporal color transitions. The transitions are built in the CIE LCh color space and the threshold are expressed in ΔE_{ab}, the Euclidian distance in the CIE Lab color space.

Given the results of previous research on related topics discussed above, we investigate the effects of frequency of the changes, base color point and direction of change on the visibility threshold tested. For possible directions of change, directions parallel to the axis of the CIE LCh color space were taken.

Method

Equipment

As a light source, a LED lamp was used, with three RGB LEDs at the bottom and three RGB LEDs on the top of a diffuser. 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 space of the LEDs. The target stimuli were defined in CIE LCh and transformed via XYZ to the RGB device space of the light units using a computer program running on a PC connected to the light units.

In the transformation, the D65 white point, not the white point of the system, was used. Care was taken that the produced colors are inside the device gamut of the light source.

In order to validate that the light sources produced the expected colors and temporal patterns, three experiments were carried out. First, we tested the independence of the L, C and h axis using a colorimeter. Second, the linearity of each channel separately and all the channels together was tested using a colorimeter. Third, the temporal respones of the lights were tested using a high speed camera. The results of these experiments didn't show significant differences between the model used and the physical properties of the hardware.

Stimuli

The stimuli were discrete linear temporal transitions in a color space with a base (middle) color point LCh_{base} in a direction $d \in \{L, C, h\}$, with a total length A and a step size of S around the base color point, changing every $\frac{1}{f}$ seconds, where f is the frequency of change. The stimuli consisted of $\frac{A}{S} - 2$ number of steps with size S and additional $2p$ number of steps with step sizes $\frac{S}{2^i}$, $1 \leq i \leq p$. For the experiment, a value of $p = 6$ was used. Example stimuli for a change in direction d are depicted in Figure 1.

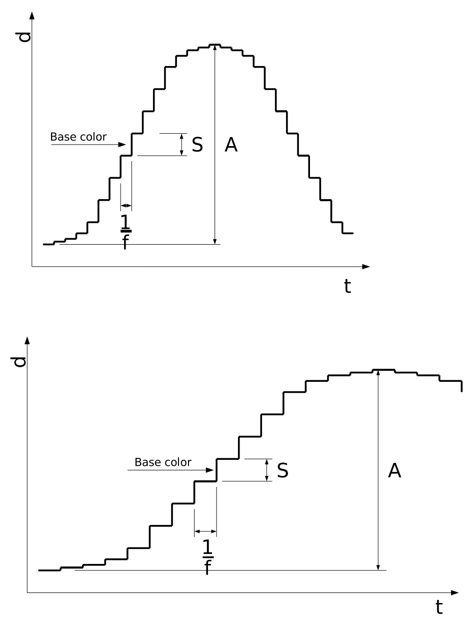

Figure 1. Base stimuli for different frequencies.

Single transitions were repeated in alternating directions to allow for easier tuning. To diminish the perceived effects of the edges of the repeated transitions, the length of the transition was at least one order of magnitude larger than than the step size and smoothing of the edges of the repeating pattern was applied, as described above.

The linear transitions were varied in frequency, base color and direction of change. During each tuning, the frequency and total length of the path were kept constant. As a result the speed and the time of a transition changes. A pilot experiment showed that for frequencies larger than 30Hz, the speed was to high to detect discontinuities for changes in chroma and hue. Therefore the frequencies used in the experiment were 5, 10 and 20Hz for all base colors and 30 and 40Hz for a subset of the base color points, as shown in Table 1.

Two criteria were taken into consideration in the choice of the base colors. First all the three primary colors are be included. Second, the available amplitude of change at those base points has to be large enough. Beside the chromatic colors, three nonchromatic color points at different luminance level were included.

The base color points used in the experiment and the tested frequencies are listed in Table 1.

For possible directions of change, directions parallel to the axis of the CIE LCh color space, lightness, chroma and hue, were selected. However, the stimuli with achromatic base color points were only varied along the lightness axis. The color space was selected and the axis were used as possible directions of change to test the independence of the axis and compare to spatial sensitivity. The length A of all transitions in direction L was $50\Delta E$, for direction C - $120\Delta E$, and for direction h - $100\Delta h$, where Δh is the angular difference in degrees between the extremes of the transitions.

As can be seen in Table 1, the total amount of stimuli was 53, presented in two parts, a training set of stimuli given in the same order for every participant and a testing set of stimuli which was randomized. The randomization was done to average over possible learning effects, tiredness and flicker adaptation [12].

Name	L	c	h	x	y	Y	Frequency (Hz)
Magenta	60	60	350	0.397	0.254	0.281	5 10 20
Red	60	60	45	0.506	0.370	0.281	5 10 20 30
Green	60	60	150	0.274	0.484	0.281	5 10 20
Blue	70	60	290	0.224	0.201	0.408	5 10 20
High L	75	0	0	0.313	0.329	0.483	5 10 20 30 40
Middle L	50	0	0	0.313	0.329	0.184	5 10 20 40
Low L	30	0	0	0.313	0.329	0.062	5 10 20 30 40

Base color points in (LCh) and (xyY) used in the experiment, with corresponding frequencies.

Participants

Nine females and thirteen male subjects participated in the experiment. Their ages ranged from 22 to 35 years. All participants had normal color vision, tested with the Ishihara's test of color deficiency. Three of the subjects had experience with viewing dynamic color patterns.

Procedure

The above describer LED lighting system was used as a light source in the experiment. The light coming from the LED shone on a wall and the participant was only able to see the reflected light. The light source itself was covered by black paper so the participants were not able to look directly into the lamp. The participants were seated on a distance of 3 meters from the wall at which the maximum luminance of the reflected light from a $D65$ stimulus was $35cd/m^2$.

Before the start of the session the participants received instructions. Participants were instructed to look at a fixation point in the middle of the light spot reflected on the wall and to judge wether the discontinuity of the color transition was visible or not. By selecting a button on a control keyboard they could

1. Increase the step size,
2. Decrease the step size, and
3. End the trial and go to the next.

Participants were asked to select the step size at which the discontinuity was just *not* visible, i.e. the transition was perceived as smooth. Preceding the experiment a training session was implemented to get used to the stimuli and the test.

Each trial started with the largest step size which was $\Delta E_{ab} = 15$ for hue and chroma changes and varied between $\Delta E_{ab} = 2$ and $\Delta E_{ab} = 7$ for lightness changes depending on frequency. The largest step size was selected as a largest step possible to keep a desired ratio between the total length and the step size or a step size that produces a clearly visible step. The step size could be increased or decreased by $\Delta E_{ab} = 0.1$ for lightness and $\Delta E_{ab} = 0.5$ for chroma and $\Delta h = 0.5$ for hue. After each hue tuning the selected step sizes for hue changes in Δh were transfered to ΔE_{ab}.

After five participants, the data showed that the starting step for all the conditions with lightness changes at frequencies of 20 Hz and 30 Hz was too low. After these five participants the starting thresholds were increased for these 2 conditions.

During the experiment the participants could chose their own break when they got tired. Because the tunings where randomized the effect of this break is averaged over all the tunings.

Results

The step size, given in ΔE_{ab}, for which the participant perceived the transition as smooth is defined as the threshold. For lightness changes at 20 and 30 Hz, the first 5 participants had a lower threshold than the other participants due to the lower starting step size. Although this effect was not significant, the data for these conditions and participants was excluded from the analysis.

For each condition the distribution of the results over the participants was tested for normality. For some conditions the data was skewed. This shows that for some participants the transition with the starting step size was already perceived as smooth and the actual threshold is larger than the starting step size. The results were skewed for lightness changes for 40Hz, and chroma and hue changes at 20 and 30Hz for all participants. The skewed results were excluded from the analysis.

The mean thresholds and 95% confidence intervals are given in Figure 2. The dashed line in the figure represents the maximum possible step size. Figure 2 includes the conditions for which the date was skewed for illustration. Note that for those conditions for which the distribution is skewed, the confidence intervals are not reliable.

The results were analyzed with an ANOVA with base color point, direction of change and frequency as fixed factors and participant as random factor. A number of significant effects, also visible in the Figure 2, were found. The effects most important for this presentation are discussed below.

Lower thresholds for lightness changes compared to chroma and hue changes The effect of direction was found to be significant ($p < 0.01$), when taking into account only those base colors and frequencies that appear for all directions. A post hoc test revealed that the thresholds for lightness changes are significantly lower than the thresholds for changes of Hue and Chroma. This results validates, in the context of this experiment, the first hypothesis. This is also in accordance with previous results on flicker sensitivity that show difference in flicker sensitivity for luminance and chrominance flicker [4]. It has to be noted, however, that previous studies use modulation thresholds to describe the

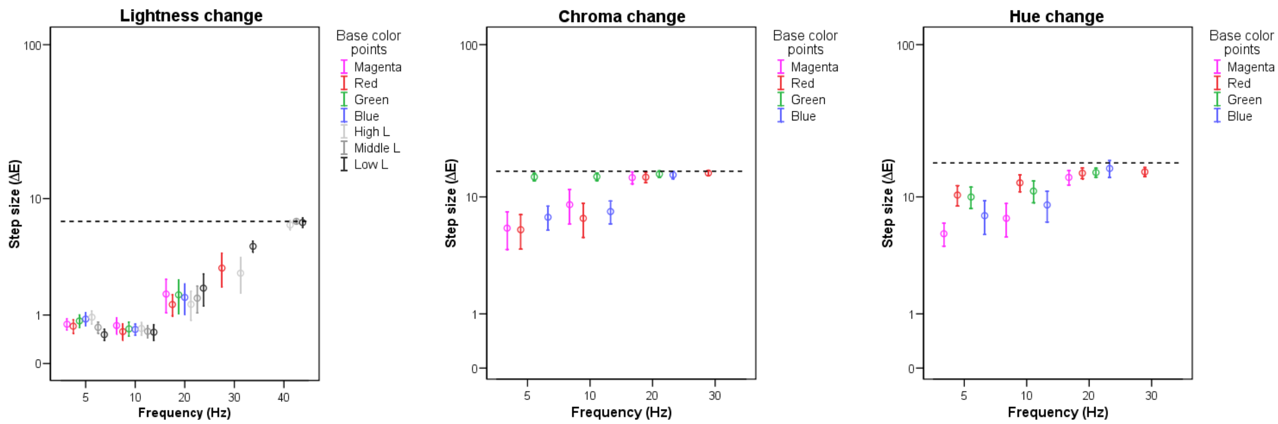

Figure 2. *Thresholds for smoothness perception of linear temporal transitions at different frequencies, different base color points and directions of change.*

sensitivity, while we use absolute step size thresholds. Furthermore, taking into account that the color space and distance metric used in the experiment are near to uniform for spatial differences in color, this result shows that the sensitivity to changes in lightness is higher than the sensitivity to changes in chroma and hue, when compared to spatial difference sensitivities.

Independence of lightness change on the chromaticity of the base color No main effect of the base color point on the thresholds for lightness changes was found for the chromatic color points (“Magenta”, “Red”, “Green”, “Blue”) for the joined data from 5Hz, 10Hz and 20Hz. For some of the frequencies the set of base colors were different, so the analysis is presented for each frequency separately. For 5Hz and 20Hz, the main effect of base color was caused by the condition “LowL”. For 10Hz there was no main effects of color point. This shows independence of the thresholds to changes in chromaticity and dependence on lightness. The independence of the thresholds for lightness changes on chromaticity the base color is in contradiction to the second hypothesis.

Dependence of chroma and hue on the chromaticity of the base color Contrary to lightness changes, both thresholds for chroma and hue changes had a significant dependence ($p < 0.01$) on the base color point for the joined data from 5Hz and 10Hz. For chroma changes, a post hoc test revealed that thresholds for “Green” were higher compared to all other base colors. For hue changes, a post hoc test revealed that both “Green” and “Red” had higher thresholds compared to “Magenta” and “Blue” that had the lowest threshold. This proves the second hypothesis for changes in chroma and hue.

Difference in behavior of chroma and hue changes A surprising effect can be observed in the behavior of the thresholds for the base color point “Red”. While for Chroma changes, the thresholds for the condition “Red” are not significantly different from the thresholds for conditions “Magenta” and “Blue”, the Hue changes for the same condition are significantly different to conditions “Magenta” and “Blue” and are in the same group as the condition “Green”. This shows that possibly different mechanisms are used in the processing of hue and chroma. One of the possible causes of this effect is a difference in speed of chromatic adaptation under changing hue or chroma.

Effect of frequency The behavior of the smoothness thresholds of lightness changes for different frequencies is in accordance with the behavior of the visibility thresholds for luminance flicker that can be found in literature, for example [7] . For easier comparison, the absolute thresholds are given as contrast sensitivity, or inverse contrast, computed using Michelson’s formula, and are depicted in Figure 3. The dependence of thresholds for chroma and hue changes were only tested at three frequencies, which makes the direct comparison with results from chromatic flicker sensitivity hard.

Flicker visibility thresholds

One of the limitations of the first experiment was that the amplitudes in which the attributes can be changed were limited and hence for large step sizes the transition speed becomes too large to find the smoothness thresholds. This results in unreliable data when the threshold becomes large, as shown for higher frequencies. The amplitude limitation has a smaller impact in the case of flicker where the light alternates between two values. Testing the flicker sensitivity in the same setup can show a connection between the smoothness thresholds for linear transitions and the visibility thresholds of flicker. A possible connection between the smoothness and flicker thresholds can be a step towards building a model for smoothness perception of temporal color changes. The same hypothesis as in experiment one are used in this experiment. Additionally, the same effects as in the first experiment were expected.

Method

The same setup as in the first experiment was used.

To be able to compare the results with the results from the first experiment, similar conditions were used. An overview of the stimuli used is given in Table 2. Standard square shaped flicker stimuli were used in the experiment, alternating between

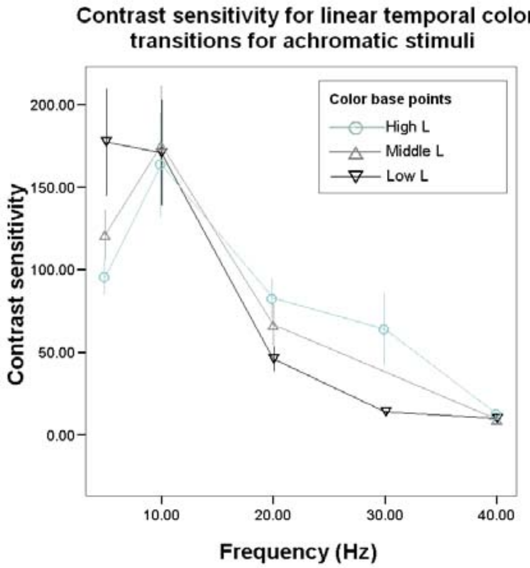

Figure 3. *Thresholds for smoothness perception at different frequencies and different base color points for lightness changes given in contrast sensitivity.*

$LCh_{base} - \frac{S}{2}$ and $LCh_{base} + \frac{S}{2}$ every $\frac{1}{f}$ seconds. As before LCh_{base} denotes the base (middle) point, S the step size, in this case equal to the amplitude of the flicker, and frequency f.

Name	L	c	h	x	y	Y	Frequency (Hz)
Magenta	60	60	350	0.397	0.254	0.281	10 20 40 60
Red	60	60	45	0.506	0.370	0.281	10 20 40 60
Green	60	60	150	0.274	0.484	0.281	10 20 40 60
High L	75	0	0	0.313	0.329	0.483	5 10 20 40 100
Middle L	50	0	0	0.313	0.329	0.184	5 10 20 40 100

Base color points in (LCh) and (xyY) used in the experiment, with corresponding frequencies.

Participants

Nine females and thirteen male subjects participated in the experiment. Their ages ranged from 22 to 40 years. All participants had normal color vision, tested with the Ishihara's test of color deficiency. Three of the subjects had experience with viewing dynamic color patterns.

Procedure

The same experimental procedure as in the first experiment was used.

Results

The results from the second experiment are the visibility thresholds on the flicker amplitude for which no flicker was visible anymore.

The resulting mean thresholds and 95% confidence intervals from the experiment are given in Figure 4.

The results were analyzed using an ANOVA with base color point, direction of change and frequency as fixed factors and participant as random factor. A number of significant effects, also visible in the Figure 4, were found. The independence of the thresholds for lightness changes on the chromaticity of the base color could not be checked due to the limited set of base colors used in the experiment.

Lower thresholds for lightness changes compared to chroma and hue changes As in the results from the first experiment, the visibility thresholds for lightness flicker were significantly lower ($p < 0.01$) than for chroma and hue flicker at the same frequency.

Dependence of chroma and hue on the chromaticity of the base color A significant dependence ($p < 0.01$) on chromaticity of the base color point on the visibility thresholds for hue and chroma flicker was found, in accordance with the results from the first experiment.

Difference in behavior of chroma and hue changes The same behavior for the base color "Red" as in the first experiment can be observed in the results for flicker visibility.

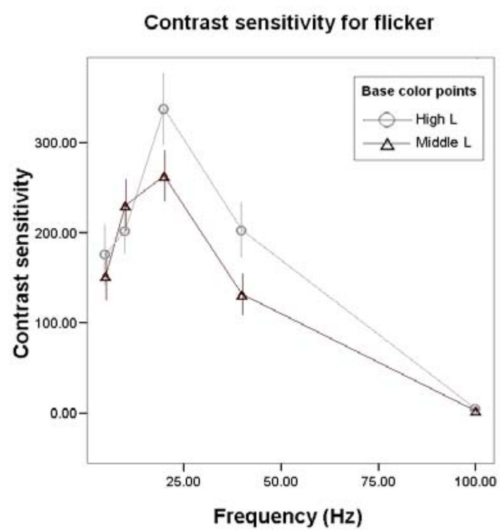

Figure 5. *Thresholds for flicker visibility at different frequencies and different base color points for lightness changes given in contrast sensitivity.*

Effect of frequency The behavior of the flicker thresholds of lightness, chroma and hue changes for different frequencies is in accordance with the behavior of the visibility thresholds for flicker that can be found in literature [4]. The contrast sensitivities computed from the flicker visibility thresholds, are depicted in Figure 5. It has to be noted, however, that the flicker frequency as given in literature is usually computed as the number of full cycles per second. In the results presented here, the frequency used is the frequency of change, thus twice the number of cycles per second. An interesting observation connected to the definition of frequency is that the peak in the sensitivity for linear transitions

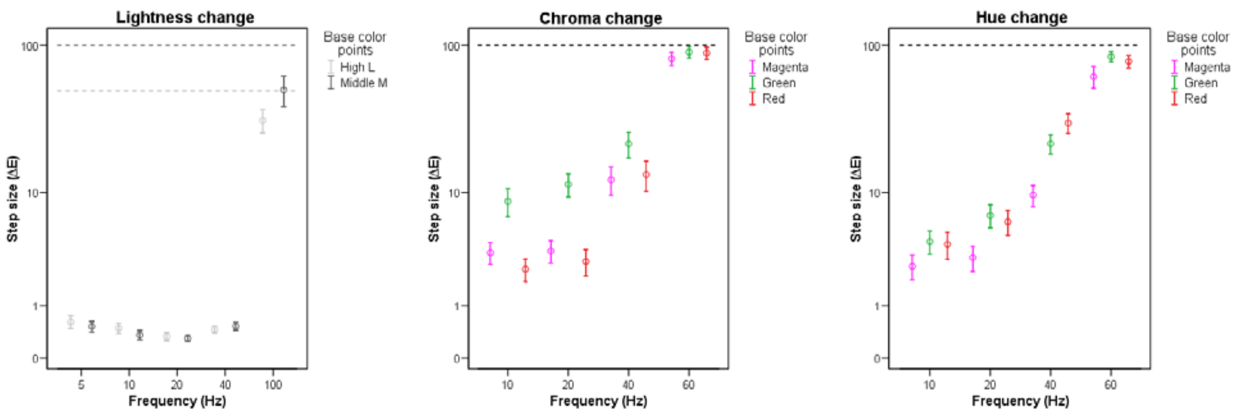

Figure 4. *Visibility thresholds for flicker at different frequencies, different base color points and directions of change.*

is around 10Hz, while for flicker sensitivity thresholds at 20Hz, corresponding to a frequency of 10 cycles per second.

Dependence of the type of change A significant difference was found between the smoothness and flicker visibility thresholds at all conditions in the intersecting set of the two experiments presented. In all cases the flicker thresholds were lower, showing a higher sensitivity to discontinuities in flicker. However, since all the effects found for smoothness perception found in the first experiment show the same tendencies as the thresholds for flicker in the second experiment, this suggests that it is possible use the results from flicker sensitivity to predict the differences for smoothness threshold under different conditions.

Conclusion

We present results from two experiments that support previous results from flicker sensitivity research and demonstrate new effects relevant to production and control of dynamic lighting. Using a spatially nearly uniform color space, CIE LCh, we show that the sensitivity for changes in the lightness direction is higher than in the chroma and hue directions compared to spatial sensitivity. Independence on the chromaticity of the base color point for lightness directions is demonstrated. Chroma and hue changes showed dependence on the base color point. The size of the above effects justify the use of a model of perceived smoothness for control of dynamic lighting over the traditional control in a device dependent color space.

Even though a difference in the absolute thresholds and different dependence on frequency was shown for smoothness thresholds for linear transitions and flicker visibility thresholds, the same base color and direction of change effects were demonstrated. The correlation of the results for different types of dynamic transitions enables building a model for perceived smoothness based on flicker visibility thresholds.

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Author Biography

Dragan Sekulovski received his MS in Computer Science at the University of Skopje, Macedonia. He is working at Philips Research Europe in Eindhoven towards a PhD in Computer Science. His main interests are design optimization and algorithms for ambient intelligent lighting systems and relevant perceptual models.