Changing Color over Time

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Abstract. The revolution in lighting we are experiencing goes beyond the basic capabilities of the light sources used and has enabled new ways of improving the overall experience of both lighting and displays. However, specifics of LEDs, the technical driving force behind the revolution, also introduce new challenges. One of those challenges is the temporal control of full-color light systems. In this work we explore the properties of human color vision relevant to the generation of pleasant dynamic light effects. We show that the spatial models of color are unsuitable for predicting temporal phenomena and give steps towards building a new, temporal model.

Keywords: dynamic light, color vision, smoothness perception, flicker perception, chromatic flicker, peripheral vision, preferred color path.

1 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.

Parallel to these developments is the evolution of displays and media presentation. Since the introduction of television, much has been done to improve the experience of watching television. Improvements in image quality and sound quality have contributed to a better overall experience. Nowadays, new dimensions such as depth are added to the displays to further enhance the viewing experience. The new capabilities of solid state lighting systems also enable the addition of new experience enhancing functionality to the display world.

The Philips Ambilight TV [1] is one of the examples of such new functionality. Not only does the additional light enable more pleasant viewing conditions, resulting in less eye fatigue [2], but the extended viewing extent provides a more immersive viewing experience. Seuntiens in [3] showed that the overall viewing experience on a display system with 3D and Ambilight capabilities depended on the quality of all the ingredients. Even though it was shown that the overall experience mostly depends on the image quality, the overall image quality of modern displays is already high and only minor improvements are to be expected. This makes the addition and the improvement of new functionality more important to the overall viewing experience. The relative importance of different functions also depends on the desired part of

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experience that needs to be improved. For example, the additional value of 3D is strongest in the presence (immersion) ratings.

The extension of the view produced by the Ambilight TV provides an interesting use case in the study of the desirable properties of produced light distributions. Even though the light distribution is based on the color distribution of the video, a pleasant rendering of the former is dependent on a new set of requirements. The produced light effect has a much lower spatial frequency compared to the one of the display, which in turn makes temporal variations in the light effects more visible. These variations are masked in the source content by the higher spatial distribution. The lower spatial frequency also makes the differences between adjacent light effects more noticeable, requiring better color matching.

The new challenges given by the new capabilities extend further when the light distribution covers a larger area, in the end covering the whole room. This natural progression makes results of research inspired by either improving viewing experience or atmosphere creation interchangeable.

In this work we give an overview of a selection of studies on the temporal control of light effects.

2 Perceived Smoothness

One of the largest differentiators of SSL 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. Given the smoothness requirement and the limitations of the hardware, it is interesting to look at the maximum speed with which a certain light progression can be rendered on a device without producing visible discontinuities. To understand the possible source of problems connected to smoothness perception, we discuss the design of most solid state 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 inappropriate 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, for example light effects computed from another medium (such as a video signal for the Philips Ambilight TV), this leads to seemingly unsolvable problems. If the parameters of the low pass filter are tuned such that the transitions 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, this introduces a mismatch between the color of the 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 [6, 7]. Moreover, the changes in chromaticity are smoothed by the human visual system more than the changes in intensity [8, 9]. 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 [10] 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 [11], which show a relatively good uniformity in the predicted differences, thus also the 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 and carried out a set of experiments. The stimuli in the first experiment [12] were linear transitions around a base color point (red, green, magenta, blue, white for the lightness transitions) in different directions (lightness, chroma, hue) in a spatially near uniform color space (CIE LCh), and at different frequencies of change (5, 10, 20, 30, 50 Hz) . Figure 1 depicts the base points and the chromatic change directions for the stimuli used in the first experiment in the CIE XYZ color space. To provide an easier task for the participants, the basic linear transition was repeated in alternating directions. The first and the last step in the transition were smoothed to diminish the effect of the edges of this compound transition.

Results demonstrated that the existing spatial difference based color spaces are not suitable in predicting the smoothness of temporal color transitions. Figure 2 shows a comparison of the step sizes of transitions that are just unsmooth, in different directions in a nearly spatially uniform color space, for different frequencies and around different base color points. If the spatial difference based color space could be used for the prediction of the smoothness of light effects, all the threshold step sizes for one frequency would have the same value. Contrary to that, it can be seen that the chroma change threshold for a color transitions around green and at a frequency with the highest sensitivity, 10Hz, is two orders of magnitude larger than the corresponding lightness change around the same color point and at the same frequency. Furthermore, the lightness threshold around 10Hz is below the spatial just noticeable difference, while the one for a hue transitions around red for example is ten times the spatial just noticeable difference.

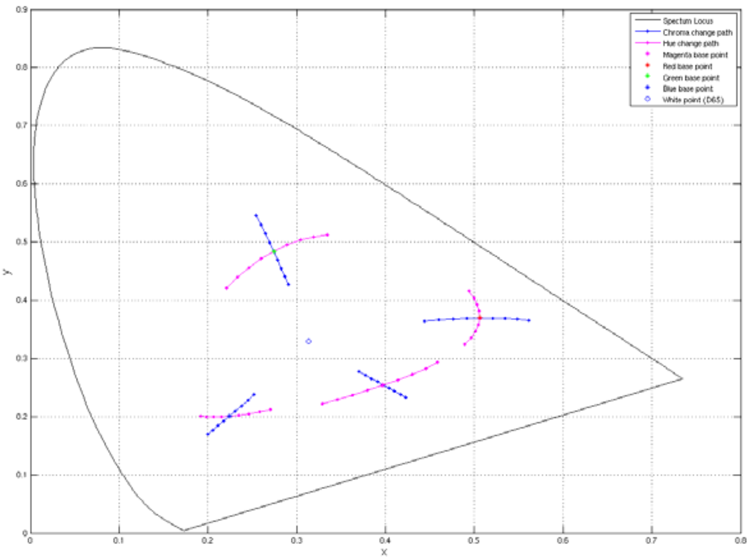

Fig. 1. The stimuli used in the first experiment, given in the CIE XYZ color space

Even though the results show that the spatial vision based model is unsuitable for the prediction of temporal visibility, the results demonstrate it can be used in a solution for the problem in the introduction. It is clear from the results that if the smoothing is done not in a device dependent space, but using a color space in which the intensity and chromaticity axes are orthogonal, the application of different amount of smoothing on those axes can produce a suitable temporal transition.

3 Flicker Perception

Based on the above, it is clear that a new model of temporal vision is needed. Measuring the perceived smoothness, however, becomes hard at higher frequencies due to fact that the duration of the transition becomes very small and the judgment of the smoothness of the linear transition is easily confused with the effect of beginning and the end of the transition. To overcome this, in [12] the smoothness perception thresholds were compared to flicker visibility thresholds. To compare, for every linear color transition with a certain step size, another temporal variation between two levels (flicker) with a difference equal to the step size was created. All the effects found for both types of temporal variations were the same and the thresholds were related by a function dependent on the frequency, where a linear transition of around 10Hz corresponded to flicker of around 20Hz. Furthermore, once the frequency dependent function was applied, the results of the smoothness experiment could be predicted by the results of the flicker experiment. Flicker visibility, being an easier question for the participants, can thus be used to predict the thresholds for both phenomena.

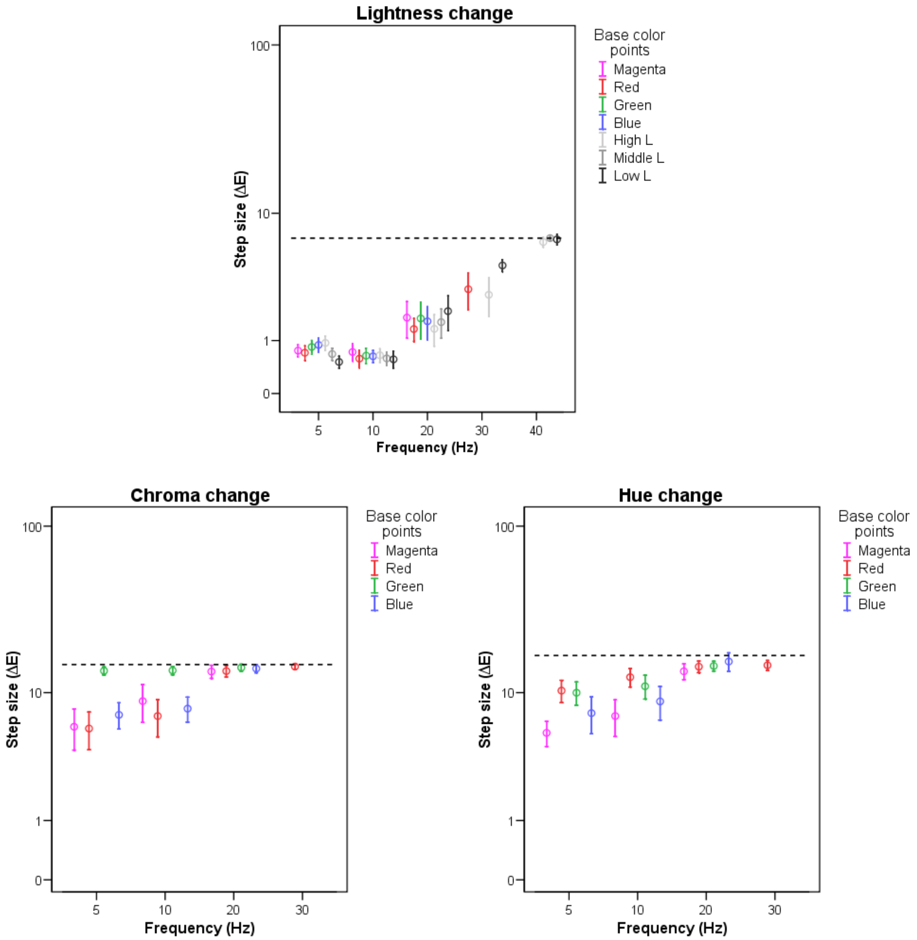

Fig. 2. Step sizes of just unsmooth temporal color transitions in different directions in a nearly spatially uniform color space

Frequency as an additional parameter makes modeling of temporal transition sensitivities harder than the simple spatial difference case. Fortunately, in [13] it was shown that there is an exponential relation between the speed of a transition given in ΔEab/sec and the frequency of change of the transition. Furthermore, even thought there is a large difference between the thresholds for lightness and chromaticity variation, they are different only in their absolute level, but the change over frequency (the slope in the graph) matches. Figure 3 depicts the speed of just unsmooth transitions (solid lines) and the amount of change of just visible flicker (dashed lines) for different directions and for different frequencies. The relation between the two types of temporal variations studied is also evident on Figure 3.

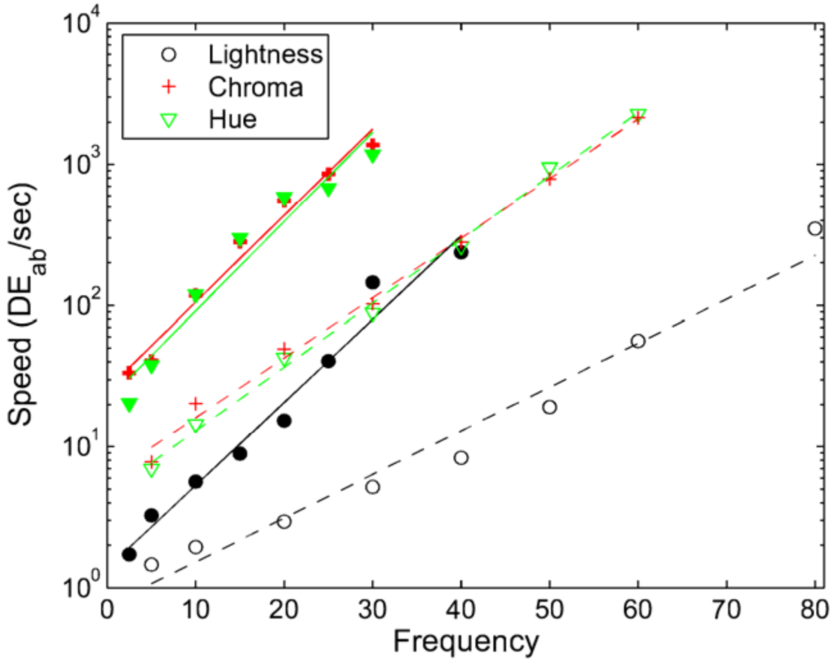

Fig. 3. Logarithm of speed of just unsmooth transitions (solid lines) and amount of change of just visible flicker (dashed lines)

4 Peripheral Vision

Light supports daily activities and as such is seldom the main focus of attention, resulting in the fact that light effects produced are often being perceived in the periphery of the visual field. This is also true in the example application in this work, the Philips Ambilight TV, where the light emitted supports the viewing experience. As the perception of both chromaticity and intensity and the density of the two basic types of light detectors, rods and cones, change at different angles in the visual field, the sensitivity to temporal changes should also be influenced by the eccentricity of the temporally changing stimulus.

In [14], a series of experiments are presented, designed to study flicker visibility in the peripheral vision. Similar to the experiments in central vision, the effect of the base point, the direction of change and the frequency of flicker were studied. Furthermore, an effect of an additional task in the central visual field was found. Results of the experiments show, as expected, a large deviation of the sensitivity in the peripheral vision, especially for chroma and hue changes, which are practically undetectable at any amplitude above 20Hz.

5 Path of Change

The series of experiments described so far explored the speed of temporal transitions and the visibility of flicker. Another question that arises in the creation and control of temporal color transitions is the one of the path between two colors. The question of what is a preferred way to make a transition from one color to another and the difference between transitions required to perceive them as different was studied in [15]. The influence of the starting and ending color, the type of transition, the speed and the presence of images with matching colors was studied. Possible transitions were: linear in RGB; linear in CIE Lab; transitions with a middle point higher and lower in luminance compared to the linear transition in CIE Lab; and transitions with the middle point more or less saturated than the middle point of the linear transition in CIE Lab. To select appropriate paths, first discrimination thresholds for different transitions were found. The discrimination thresholds ranged between 2.5 and 10.5 ΔEab, dependent on the color pair, direction and duration of the transition. Based on these results, transitions with a well noticeable difference were selected as stimuli in the preference part of the experiment. Results showed that the most preferred transitions were the linear transition in CIE Lab, a linear transition in RGB, and a transition that has a middle point having a lower lightness then the end points. This preference was not influenced by the presence of matching images. The preference for the linear RGB path suggests that appealing temporal color transitions can be created without complicated calculations.

6 Conclusions

This overview presented a selection of works studying the properties of the human visual system relevant to the creation and control of temporal color transitions. The results presented demonstrate the lack of general suitability of existing spatial vision based color models to temporal effects. Furthermore, the effect of a number of parameters on the perception of the resulting temporal transitions is shown and first limited modeling efforts are presented. Most notably, it is demonstrated that the frequency dependence of both smoothness and flicker sensitivity can be modeled by a simple exponential law. Lastly, the effect of the eccentricity of the stimulus is discussed.

The results of these studies can be used as a base in the design of both the direct controls of future light sources as well as the controls of complex light atmospheres.

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