Discrimination and preference of temporal color transitions

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Abstract

This study investigates what is perceptually the most optimal way to create a temporal color transition between two colors. The first experiment measured the ability to distinguish between two temporal color transitions. The reference transition was a linear interpolation between two colors in CIELab, the test transitions were arcs defined in different planes going through the linear transition. Discrimination thresholds ranged between 2.5 and 10.5 ΔE_{ab}, dependent on the color pair, direction and duration of the transition. In the second experiment, several perceptually different color transitions were evaluated. The most preferred transitions were a linear transition in CIELab and a linear transition in RGB. This suggests that appealing temporal color transitions can be created without complicated calculations.

Introduction

Many lighting applications generate colored light that varies over time. For instance, the color of the light surrounding an AmbiLight TV changes in accordance with the color of the content shown on the display to enhance the experience of watching TV. However, when the light follows the content from frame to frame, the resulting step-like pattern will be perceived as jerky or flickering. In order to produce slowly changing, smooth light effects, frame skipping and temporal sub-sampling can be used. As the color is specified only at certain moments in time, intermediate colors have to be calculated such that the light effect is perceived as consistent with the video. Dynamic light can also be used for atmosphere creation. By changing the color of the illumination of environments, such as shops or theatres, various ambiances can be created. When the illumination has to change gradually from one color to another, a suitable color transition has to be defined.

Currently, there is not much scientific knowledge on the discrimination and preference of temporal light effects. Since color is a three dimensional entity, there are innumerable ways to generate a transition between two colors. In applications where the light source is driven by an RGB signal, temporal light effects are usually generated by a linear interpolation in RGB space. However, since RGB is a device dependent color space, the actual color transition will depend on the physical characteristics of the light source. A second drawback is that RGB is not an appropriate space to describe color perception. Therefore, it is better to define color transitions in a device independent and perceptually uniform color space, such as CIELab.

The choice of an appropriate perceptual color space does not necessarily lead to color transitions that are appreciated by human observers, as there are still many algorithms that seem to be reasonable. Therefore, this paper aims at determining guidelines for the design of temporal transitions between two colors. In order to study what color transitions are preferred, one should know what color transitions can be distinguished. It makes no sense to ask people which of two temporal light effects they prefer, if they cannot see the difference. Therefore, two experiments were performed. The first experiment investigated when two different temporal transitions between two fixed colors are perceived as unequal. The results were used in the second experiment to develop six algorithms to create temporal color transitions. Participants evaluated these algorithms for two different applications: AmbiLight TV and atmosphere creation.

Although temporal properties of the human visual system have been subject of many psychophysical studies, only few studies bear reference to our research. First, studies on temporal contrast sensitivity have shown that the detection threshold for temporal sinusoidal fluctuations in luminance decreases with frequency up to about 10 Hz and then increases with frequency. Thresholds for temporal chromatic variations are constant for frequencies up to about 4 Hz and then increase with frequency. If the mechanisms underlying the perception of gradually changing light patterns are similar to those of the perception of alternating light patterns, one would expect that the ability to discriminate between two temporal color transitions depends on duration for luminance variations but not for chromatic variations (at least for durations larger than 1/4 s).

Second, studies on color discrimination have shown that the visual system is more sensitive to spatial color variations compared to temporal color variations. For example, the discrimination threshold for simultaneously viewed, closely juxtaposed colored patches is about two times smaller than the threshold for successively presented colors with a temporal delay of 200-550 ms [2]. Therefore, discrimination thresholds for temporal color transitions are expected to be larger than those for simultaneously viewed color pairs, which are usually around $\Delta E_{ab} = 1$ [3].

Finally, Montag [4] showed that the color with the appearance halfway between two other colors that have equal chroma and a hue difference of about 50º did not have the same chroma as the color pair. The selected color was closer to the geometric midpoint of the color pair. Hence, a linear transition between two colors in a perceptual color space might be a promising algorithm for color transitions.

Discrimination of temporal color transitions

This experiment aimed at determining how large the difference between two temporal color transitions should be before people can perceive the difference. Since the final aim was to obtain guidelines for the light effects of AmbiLight TV and atmosphere creation, it was decided to use a set-up that could be applied for both applications.

Method

Set-up

A 42'' WS Plasma TV was positioned at a distance of 23 cm in front of a white wall in a room of 4 by 6 m. Eight RGB LED-units were mounted at the back of the TV such that the LEDs were

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not directly visible but only the light reflected from the wall. A couch was placed at a distance of 4.5 m from the screen. The display and LEDs were controlled by a computer system. The chromaticity coordinates of the TV primaries were close to the EBU primaries. The driving values for the LEDs and display were calculated such that the white point corresponded to D65 and all colors were located within the gamut of the display. This was possible because the color gamuts of all LED-units were larger than that of the display. The refresh rate was 60 Hz for the TV and 50 Hz for the LEDs.

Stimuli

Four color pairs were used: blue-green, green-magenta, magenta-green and magenta-yellow. The order of start and end color were reversed in the second and third color pair, to measure the effect of chromatic adaptation. The chromaticity and luminance of the colors were based on four images that were used in experiment 2 and are presented in Table 1. For each color pair several color transitions were generated using MatLab software. The reference transition was a linear interpolation between start and end color in CIELab. The test transitions were arcs defined in one of two planes: 1) the plane through start and end color parallel to the lightness axis, called the lightness-plane and 2) the plane through start and end color perpendicular to the first plane, called the chromaticity-plane (see Figure 1a). The arcs were defined by three points: the start color, the end color and a color in the corresponding plane at a distance D from the color halfway the start and end color. Colors of the test transitions located in the lightness-plane had equal hue and chroma compared to those of the reference transition. However, the lightness of the colors was larger (L_+) or smaller (L_-). Colors of test transitions located in the chromaticity-plane had the same lightness compared to those of the reference transition. However, the colors varied in hue and chroma. The arc could bend towards the center of the gamut (C_{in}) or towards the boundaries of the gamut (C_{out}). Figure 1b shows examples of the directions C_{in} and C_{out} for each color pair. The Lab values of a color transition were transformed into RGB values for each LED-unit separately.

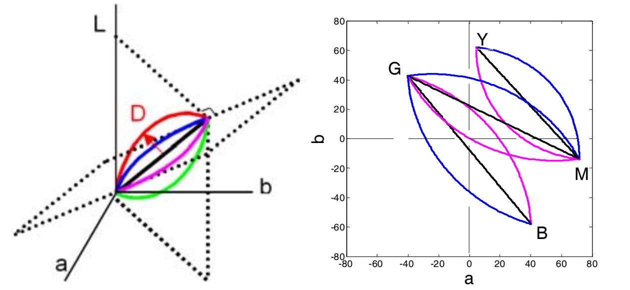
Each color transition was composed of three parts: first the start color was shown for 2 s, then the transition (0.5 s or 4 s) and finally the end color was shown for 2 s. The two durations of the color transitions are realistic speeds of fast and slow transition for both AmbiLight TV and atmosphere creation.

Table 1 : Luminance and chromaticity of the four colors expressed in 1931 CIE xyY and CIELab.

	Y	x	y	L	a	b
Blue	0.14	0.189	0.126	45	43	-74
Green	0.23	0.320	0.575	55	-50	55
Magenta	0.14	0.418	0.242	44	57	-9
Yellow	0.31	0.473	0.481	63	4	75

Participants

Ten male and nine female participated in the experiment. Their age ranged between 20 and 46 years, with an average of 29 years. All participants had normal colour vision, as measured with the Ishihara test.



(a) (b)

Figure 1: (a) Examples of the reference transition (black line) and the test transitions with direction L_+ (red arc), L_- (green arc), C_{in} (magenta arc) and C_{out} (blue arc). (b) Projection of the reference transition and test transitions C_{in} and C_{out} on the ab-plane for each color pair.

Procedure

Participants were seated at the couch in front of the display. During the experiment the ambient illumination and the display were turned off. Two temporal color transitions were shown on the LEDs immediately after each other: first the reference and then a test transition. Both transitions had the same start and end color and the same duration. After the second transition, all LEDs emitted white light, in order to avoid continuous adaptation of the eye to light and dark surround. Participants had to judge whether the two transitions were equal or not. By selecting a button on the screen of a notebook, participants could: 1) repeat the trial, 2) increase the difference between the transitions, 3) decrease the difference between the transitions or 4) go to the next trial. Participants were instructed to find the point at which the difference between the two color transitions was just detectable. The test transition that was initially shown was clearly different from the reference one and had a difference of D = 25 ΔE_{ab}. The step size of the tuning procedure was initially 1 ΔE_{ab} and decreased to 0.5 ΔE_{ab} for test transition smaller than D = 2 ΔE_{ab}.

The experiment consisted of 32 conditions: 2 durations, 4 color-pairs and 4 directions of the test transitions. Participants started with 6 practice trials to get used to the task before the 32 trials were presented. The experiment took about one and a half hour per participant.

Results

The maximum color difference D (in ΔE_{ab}) between the reference transition and the test transition that could just be distinguished is defined as the discrimination threshold. Figure 2 presents the thresholds as a function of the direction of the test transition (a) per color pair and (b) per duration.

An ANOVA was performed with color pair, direction and duration as fixed factors and participant as random factor. The analysis revealed a significant main effect of color pair, direction and duration and a significant interaction effect between color pair and direction and between duration and direction ($p<0.01$). The interaction between color pair and duration was not significant ($p=0.66$).

The effect of color pair was caused by the blue-green transition, for which the threshold was on average slightly lower compared to the other color pairs. However, this was mainly due to the interaction between color pair and direction. The difference between color pairs was only significant for the direction C_{in} (see Figure 2a).

The effect of direction was caused by a significant difference between transitions in the lightness-plane and transitions in the chromaticity-plane. Thresholds were on average lower for L_+ and L_- compared to C_{in} and C_{out}. However, the difference between directions depended on duration (see Figure 2b). At 0.5 s the difference between the two groups of transitions was large, but decreased for the slower transition.

Discrimination thresholds were on average smaller for color transitions of 0.5 s compared to 4 s. However, as mentioned above, the effect of duration depended on the direction of the transition. Thresholds increased with duration for the transitions in the lightness-plane, and slightly decreased with duration for the transitions in the chromaticity-plane.

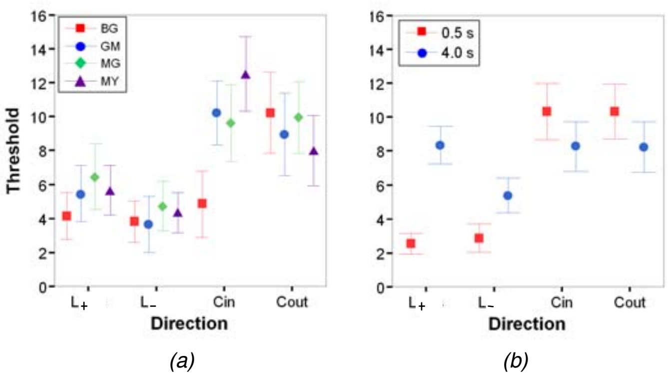


Figure 2: Discrimination threshold (in ΔE_{ab}) as a function of the direction of the test transition (a) per color pair and (b) per duration of the transition. The error bars correspond to the 95% confidence intervals.

Preference of temporal color transitions

This experiment aimed at finding the best way to make a temporal transition between two fixed colors. Since there are innumerable ways to create a transition between two colors in a 3 dimensional color space, it is hardly possible to find the most optimal solution. In addition, there might be a large range of transitions that are assessed as 'very appealing'. Therefore, it was decided to compare only a few possible solutions. Also, the effect of application on preferred color transition was measured.

Method

Stimuli

Two of the four color pairs of experiment 1 were used: blue-green and magenta-yellow. For each color pair, six color transitions were created: a linear transition in CIELab ('Lab'), a linear transition in RGB ('RGB'), and the four transitions of experiment 1 with a color difference ΔE_{ab} of about 3 times the average threshold value.

In some conditions, two images with a duration of 4 s were shown immediately after each other (see Figure 3). During the first 2 s, the LEDs emitted the start color, then the color transition was shown for 4 s, and finally the end color was shown for 2 s. Hence, the transition started 2 s before the second image was shown. The two images that were shown had either meaningful content or meaningless content. The average chromaticity of the start and end images was always the same as those of the start and end colors of the LEDs.

Participants

Fifteen male and fifteen female participated in the experiment. Their age ranged between 21 and 46 years, with an average of 27 years. All participants had normal colour vision, as measured with the Ishihara test.

Procedure

Participants were seated at the couch in front of the display. During the experiment the ambient illumination was turned off. Two color transitions with the same start and end color were shown on the LEDs immediately after each other. After the second transition, all LEDs emitted white light. Participants were asked to indicate which of the two transitions they preferred most. They had the possibility to repeat the trial.

The experiment consisted of three conditions: 1) the light transitions were shown while the display was turned off, 2) the light transitions were shown together with two images having meaningful content and 3) the light transitions were shown together with two images having meaningless content. All participants were exposed to the first two conditions, only half of the participants performed the third condition.

For each condition and each color pair, all possible combinations of the six different transitions were presented. This resulted in 30 trials per condition, which were presented in a random order. Half of the participants started with condition 1 and half of them started with condition 2. Condition 3 was always presented last for the people involved. Participants started with 4 practice trials before the first condition was presented. The experiment took about half an hour per condition per participant.

Figure 3: Images with meaningful content and meaningless content.

Results

The preference responses were analyzed using Thurstone's law of Comparative Judgment case V [5]. This analysis calculates a preference score (z-score) for each evaluated algorithm. The 95% confidence intervals on the difference between preference scores were calculated with the GLM procedure described in [6].

Figure 4 presents the obtained preference score of the six algorithms per color pair, taking into account the data of all participants and the three conditions. The difference in preference scores between two algorithms can be interpreted in terms of the percentage of participants that preferred one algorithm above the other, which can be calculated with the cumulative normalized probability function. To facilitate the interpretation, the least preferred algorithm was given a value of zero. The horizontal lines

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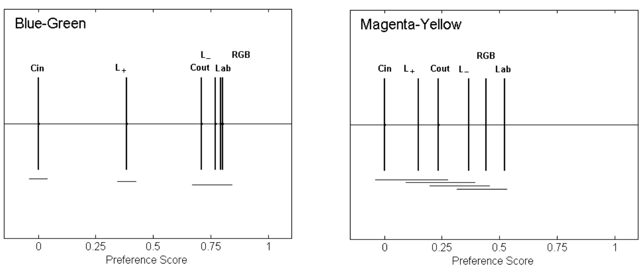
divide the algorithms into groups for which the preference scores are not significantly different ($p<0.05$). The GLM analysis revealed a significant effect of color pair ($p<0.001$). There was no significant difference between the conditions ‘no content’, ‘meaningful content’ and ‘meaningless content’ ($p=0.24$).

Figure 4 shows that the order of the algorithms was very similar for the two color pairs: C_{in} was the least preferred algorithm, whereas the algorithms L_-, Lab and RGB were preferred by most of the participants. However, the difference between the least and most preferred algorithms was larger for blue-green compared to magenta-yellow. When C_{in} was removed from the data, the effect of color pair disappeared. Apparently, this algorithm was differently evaluated for the two color pairs. This is consistent with experiment 1, where the discrimination threshold was found to depend on color pair only for C_{in}.



(a) (b)

Figure 4: Preference scores of the six algorithms for a temporal color transition between (a) blue-green and (b) magenta-yellow. According to Thurstone’s model, the percentage of participants that prefer one algorithm above the other is 50%, 69% or 84% for a difference in preference score of 0, 0.5 and 1, respectively.

Discussion

The ability to discriminate between two temporal color transition was found to be similar for all color pairs, except for the direction C_{in} thresholds were lower for the blue-green transition. This result might be related to the observation that two colors in different linguistic color categories are more easily distinguished than those in the same category [7]. Indeed, the intermediate color for the blue-green transition with direction C_{in} has a magenta tone and does not fall into the same color category as blue or green in contrast to the direction C_{out}, for which the intermediate color has a cyan tone. A second explanation might be that cyan is located between green and blue on the color circle, whereas magenta is located on the opposite site. Therefore, the transition via magenta might be perceived as unnatural and, hence, more salient. Since there was no difference between the color pairs green-magenta and magenta-green, it can be concluded that chromatic adaptation of the eye did not play a role in the ability to discriminate between temporal color transitions.

Discrimination thresholds were found to increase with duration for lightness variations and to be rather constant for chromatic variations. This result confirms the expectation stated in the introduction, which was based on research on temporal contrast sensitivity [1]. In addition, thresholds for temporal variations in lightness were lower compared to temporal variations in chromaticity. This could be caused by the fact that the size of the light spot on the wall increased with increasing lightness, as is the case for many light sources, which could have made transitions in the lightness-plane more visible. On the other hand, it could also indicate an intrinsic difference in sensitivity for lightness and chromaticity. However, the comparison between lightness and chromaticity strongly depends on the color space and color difference formula used to express the thresholds. Hence, it is difficult to compare the results with other studies.

Discrimination thresholds ranged between 2.5 and 10.5 ΔE_{ab}. Hence, in the most critical situation, thresholds were comparable to those for spatially separated color patches, which are usually around $\Delta E_{ab} = 1$ [3]. However, when the duration increased or the direction of the transition changed, thresholds for temporal color differences were considerably larger compared to spatial color differences. This is consistent with literature on the perception of temporal color differences [2].

The most preferred way to make a temporal transition between two colors was found to be independent on the application, i.e. whether the light effects had to enhance the experience of watching TV or whether they were used for atmosphere creation. A linear transition in CIELab was evaluated as one of the best algorithms, which is in agreement with the results of Montag [4]. Interestingly enough, this algorithm was evaluated to be as appealing as a linear transition in RGB. For magenta-yellow the maximum color difference between these algorithms was 6 ΔE_{ab} and, hence, hardly visible. However, for blue-green the difference of 20 ΔE_{ab} was clearly visible.

The results of this study suggest that it is possible to design a general algorithm for temporal color transitions that are appreciated by human observers, independent of color pair and application. However, additional research is needed including more color pairs to confirm this statement.

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Author Biography

Ingrid Vogels received a M.Sc. (1993) and Ph.D. in physics (1997) from the University of Utrecht in the Netherlands. She worked at the Instituut of Perceptie Onderzoek (IPO) for 3 years. Since then she has worked as a Senior Researcher at the department Visual Experiences of Philips Research Laboratories Eindhoven. Her work has focused on human perception, in particular, visual perception and the application of image quality improvement and ambiance creation with lighting.