# Speed perception of dynamic lighting around daylight

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Dynamic lighting is an integral part of our experience of illumination, both in daylight and increasingly in artificial lighting. Previous research has focused either on daylight or chromatic illumination exclusively, and most studies examined speeds near detection thresholds. This experiment investigated suprathreshold transitions between neutral and chromatic illumination to expand upon these findings. The perceived speed of lighting changes to and from the chromaticity of D65 in eight radial hue directions was measured in a two-interval forced choice (21FC) task. The relative perceived speed, computed as the point of subjective equality (PSE), of transitions moving away from D65 differed by radial hue direction, indicating that CIELAB is temporally nonuniform. Results show that the yellow-blue opponent colour component contributes less to speed perception, in line with previous literature. The experiment did not yield PSEs for many transitions moving towards D65, likely because the comparison was too difficult, an improper range of speeds was studied, or both.

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## Introduction

Dynamic lighting describes lighting systems that change gradually over time. Advancements in the management of LEDs have led to their increased use in a wide variety of applications, including photography and museum lighting [1]. Dynamic lighting has also been found to have a psychological impact with effects such as increased alertness and improvement in mood in office workers [2]. Aside from more architectural applications, dynamic lighting is an important aspect of entertainment, which relies on changes in lighting to set the scene and direct the audience's attention [3].

With more widespread applications of dynamic lighting, it has become important to characterize colour differences in the temporal domain. While there is much research on speed perception of grating stimuli, described in degrees per second, there is little focus on spatially homogeneous chromaticity changes. Such changes can instead be described by $\Delta E_{ab}$* per second, based on the assumption that CIELAB is approximately perceptually uniform. This perceptual uniformity in the spatial domain, of course, does not necessarily imply anything about perceptual uniformity in the temporal domain.

Indeed, those who have studied the topic so far have found CIELAB to be far from a temporally uniform colour space. Sekulovski *et al.* first used the $\Delta E_{ab}$*/s description of temporally changing stimuli to examine preferences in dynamic lighting [4]. Other studies by Sekulovski *et al.* and Murdoch *et al.* have investigated various aspects of perception of dynamic lighting, such as smoothness perception and visibility and subtlety thresholds, finding differences in perception depending on chromaticity and lightness [5-6].

Kong et al. first directly investigated speed perception of chromaticity changes around the Munsell principal hues, finding that speed perception depended on both the base hue and whether the transition changed in chroma or hue [7-8]. Pastilha *et al.* examined stimuli varying along different points on the daylight locus, finding that detection thresholds depended not only on the base chromaticity of the illumination, but also the direction of change relative to D65 [9].

This experiment built off of these studies on the perception of dynamic lighting. The experimental methods were similar to those utilised by Kong but examined transitions between lighting with the chromaticity of D65 and more chromatic lighting to connect the two areas of colour space. The stimuli were also linear rather than periodic, following the methods of Pastilha so as not to confound the possible effect of the orientation of the transition relative to the neutral D65 chromaticity.

## Methods

### *Lighting system*

The experiment took place in the Dynamic Visual Adaptation Lab at the Rochester Institute of Technology. The laboratory is lit by fourteen Philips SkyRibbon ceiling-mounted light fixtures directed at the matte white walls to yield smooth, though non-uniform, illumination. The fixtures are LEDs, addressable at 40 Hz, with five primaries: red, green, blue, mint green, and white. This immersive setting, rather than a smaller stimulus patch or fixation point, was used because of the interest in more natural, dynamic lighting applications. This setup has been characterised before by Murdoch, and his model was utilised to create stimuli with the desired colorimetry [10].

The model was verified before use in this experiment using a Konica Minolta CS2000 spectroradiometer pointed at the point of highest intensity on the longer wall. The spectral power distributions of the primary ramps of these lights were measured, and the model was updated with the new data. The updated model was verified with measurements of the desired endpoints of the transitions. The measured CIELAB coordinates were compared to those predicted by the model, which was found to have an average $\Delta E_{00}^*$ of 1.50, with a standard deviation of 0.31. As the point of highest intensity where the measurements were made was estimated visually, the predicted XYZ values of the stimuli were normalised by the measured luminance to better reflect the model's accuracy. This comparison yielded a mean $\Delta E_{00}^*$ of 0.77, with a standard deviation of 0.46, a marked improvement.

### *Procedure*

The experiment's human subjects procedures were approved by RIT's institutional review board. A two-interval forced choice (2IFC) task was designed using the method of constant stimuli, in which the observer was shown the reference stimulus and a test stimulus sequentially and reported which appeared faster. The chromaticity of CIE standard illuminant D65 was chosen as the adaptation point and neutral endpoint of the stimuli because Pastilha found the detection thresholds of transitions depended on their orientation relative to this chromaticity. The observer was first adapted to constant D65 illumination while instructions were being given. Observers also answered an Ishihara test under this lighting to screen for colour vision deficiencies. Subsequent trials began with three seconds of D65 illumination to 'top up' adaptation.

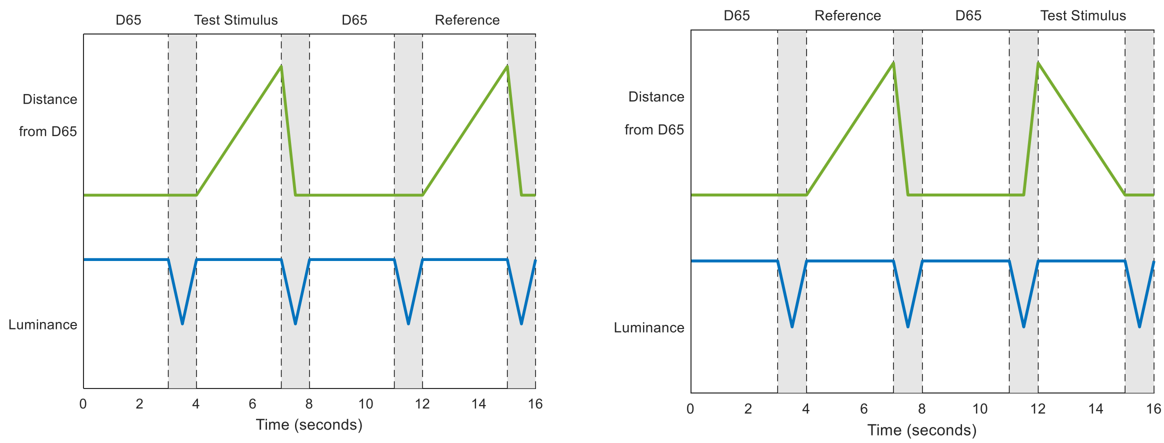


*Figure 1: Relative change in chromaticity and luminance over time during presentation of one stimulus pair for transitions away from D65 (left) and towards D65 (right). The reference interval was randomly chosen.*

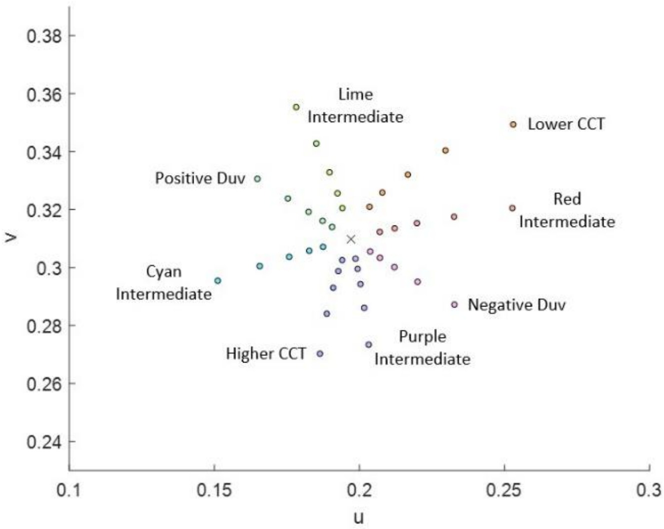


*Figure 2: Endpoints of all stimuli, plotted in CIE 1960 u,v chromaticity coordinates. X marks D65.*

The beginning of the first stimulus was denoted with an audio cue, after which the first three second transition was presented. After three seconds of D65 illumination, another audio cue marked the beginning of the second three second transition. Transitions were flanked by a one-second, smooth dip to 50% intensity before and after. These dips were used to interrupt the change from the adaptation state to the stimulus and vice versa. A direct comparison of the two could provide the observer information about the amplitude of the colour change, which could influence speed perception. Transitions that moved towards D65 were also found to cause afterimages, and the dip in intensity helped to mitigate this effect. Chromatic noise, which was utilized in a similar manner in the Pastilha study, was considered first, but this was found to be somewhat disorienting.

### *Stimuli definition*

Stimuli were equiluminant and transitioned to or from D65 in one of eight radial hue directions. The orange and blue transitions followed the daylight locus, and the pink and green transitions followed the line of Duv perpendicular to the daylight locus in CIE 1960 u,v space. The intermediate directions were linear in CIELAB with a hue $h_{ab}$ equal to the midpoint between the daylight and Duv lines. Transitions of five different speeds in $\Delta E_{ab}^*$/s, all three seconds in length, were created.

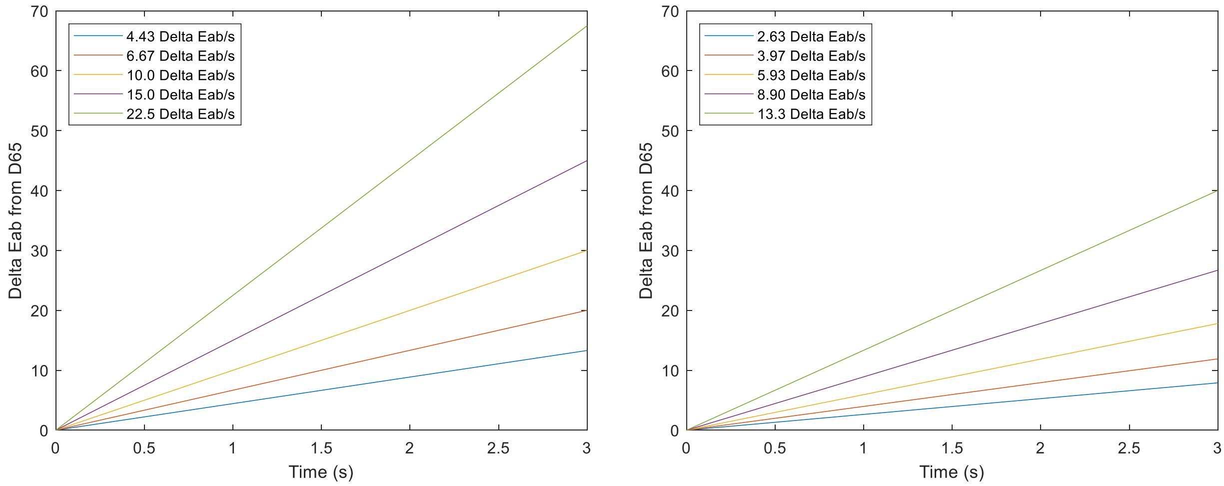


*Figure 3: Plots of $\Delta E_{ab}$* from the starting point versus time for the five different speeds of transitions in each radial hue direction. Left is the speeds used for the reference and lime transitions; right is all other transitions.*

The reference stimulus, chosen to be from D65 to decreasing CCT at the middle speed, was set at 10 $\Delta E_{ab}^*$/s for better comparison with previous studies. The speed was increased or decreased by a factor of 1.5 with each step, from 4.4 to 22.5 $\Delta E_{ab}^*$/s, so that stimuli were evenly spaced on a logarithmic scale. When all stimuli were tested at the same five speeds, the warm daylight transitions and the lime intermediate transitions appeared notably slower. Because of this, as well as gamut concerns, the other transitions were scaled back to a maximum of 40 $\Delta E_{ab}^*$ total, ranging from 2.6 to 13.3 $\Delta E_{ab}^*$/s, to make the range of speeds more perceptually even across all hues. There were 80 stimuli in total (8 radial hue directions × 2 orientations relative to the chromaticity of D65 × 5 speeds). Each was presented once to each observer, paired with the reference, with the reference interval randomly chosen. Presentations were blocked by orientation relative to neutral and randomly presented within that orientation.

## Results

Data were collected from thirty-four observers, ten male and twenty-four female. The average age of the observers was twenty-two years old. The proportion of times each test stimulus was judged to appear faster than the reference stimulus was calculated. Psychometric curves were fitted for each of the sixteen transition directions using a probit regression model in a logarithmic scale. Curves were first fitted in a linear scale, but the logarithmic scale was found to better fit the data. The logarithmic scale is also a natural choice because it better matches perception and was used to select the speed of the stimuli. The point of subjective equality (PSE) was calculated for each by interpolating the speed at which the proportion of times the test stimulus was judged faster was equal to 0.50. The PSE for each transition direction represents the measured speed of the transition required to appear the same speed as the reference stimulus.

Figure 4 directly compares the PSEs across hues. Error bars represent the 95% confidence intervals calculated through Monte Carlo resampling. For all transitions towards D65 except the blue higher CCT and purple intermediate transitions, PSEs were not calculable because the slowest speed tested was already judged to be faster than the reference in more than 50% of the observations; many observers judged these test stimuli to be faster than the reference for every speed presented. The psychometric curves of the transitions moving towards neutral were all quite flat, which was unexpected. This might have occurred because the task of comparing a reference transition moving away from D65 and a test transition moving towards D65 was too difficult to yield meaningful results or because the true PSEs lay outside the range of stimuli used.

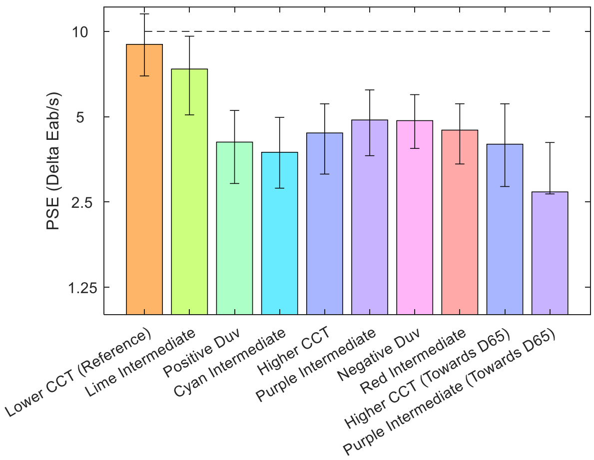


*Figure 4: PSEs for each transition direction with error bars representing 95% confidence intervals. All but the two rightmost bars represent transitions away from D65. The dotted line represents the speed of the reference.*

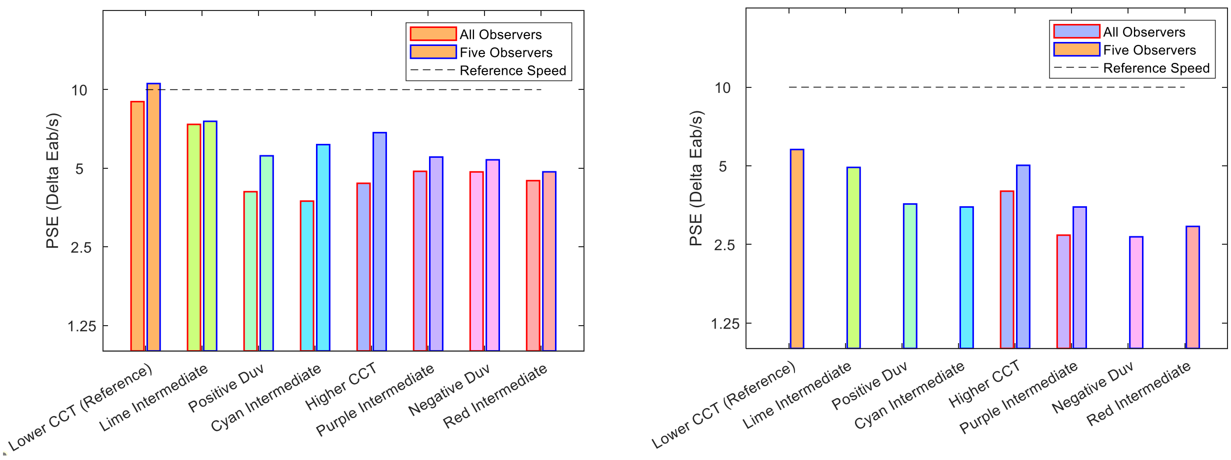


*Figure 5: Bar charts comparing the PSEs calculated using all observers (red outline) to those calculated using five observers (blue outline) for transitions away from (left) and towards (right) D65.*

To obtain thresholds from these transitions, observers who behaved differently than expected were identified and removed from the calculations. Observers with the lowest number of transition directions for which all five speeds were judged faster than the reference or the lowest speed was judged slower and the greatest speed faster than the reference were removed until PSEs were calculable for all transitions. All transitions had a calculable threshold only when all but five observers were removed. These PSEs should not be taken as actual values of the relative perceived speed of these transitions. Rather, they should be interpreted as upper bounds for these thresholds to be studied further, as there is still the possibility that the difficulty arose from the range of stimuli not including low enough speeds. As plotted in Figure 5, compared to the PSEs calculated for the transitions away from D65 with all of the observers, all eight calculated with the reduced number of observers are higher in value, supporting this interpretation.

## Discussion

These results confirm CIELAB is not a temporally uniform colour space, as found previously in Kong's speed perception experiments. For the transitions away from D65, the lower CCT radial hue direction was not significantly different from the reference speed. As this was the hue used as the reference, this indicates that observers were able to correctly accomplish the task. The only hue with a threshold not significantly different from that of the reference hue was the lime intermediate hue direction. All of the remaining hue directions had PSEs lower than the reference speed, indicating that they are perceived as faster than the reference. The thresholds of these six hue directions were not significantly different from each other. In Kong's study focusing on medium-saturation Munsell principal hues, the highest PSE was around the blue hue and the lowest around the red hue. In contrast, this data had the highest PSE at the orange hue and the lowest at the green hue. This suggests that the dependency of speed perception on hue varies with chroma level. However, the results better align when considering colour opponent axes: both have the smallest PSEs around the red-green axis and the largest around the yellow-blue axis.

### *Scaling colour spaces*

In a temporally perceptually uniform colour space, all of the PSEs would be equal, so their standard deviation would be zero. A simple alteration to CIELAB to make it more uniform, first computed by Kong, would be to weight $\Delta a^*$ and $\Delta b^*$ so as to minimise the standard deviation of the PSEs. The equation for $\Delta E_{ab}^*$ did not include $L^*$ because all transitions were designed to be constant in $L^*$. $\Delta E_{ab}^*$ was weighted according to:

$$\Delta E_{ab}^* = \sqrt{(1-\alpha)(\Delta a^*)^2 + \alpha(\Delta b^*)^2} \quad (1)$$

The analysis was not performed in $L^*C^*_{ab}h_{ab}$ coordinates because, with the exception of the transitions along the daylight locus, the stimuli were designed to be constant in hue angle as well as $L^*$; therefore, this difference metric would collapse to just a chroma difference, which does not allow for different weightings of at least two terms. The values for $\Delta a^*$ and $\Delta b^*$ for each transition were the overall change along these axes from the beginning to the end of the transition. As the transitions were designed to be linear in $\Delta E_{ab}^*$/s, the weighted speed was simply calculated by dividing by three seconds, which was the duration of the stimulus. The standard deviation of the PSEs was then calculated and was minimised at $\alpha = 0.159$ (see Figure 6).

This value cannot be directly compared to that found by Kong, as they only scaled the $\Delta b^*$/s term. This scaling was not utilised because it allows the speed to increase indefinitely as the coefficient increases, which is not desirable because standard deviation scales with magnitude. The shape of the plot of coefficient versus standard deviation, however, is very similar to that found by Kong. This analysis also aligns with Kong's result that the standard deviation is minimised when $\Delta b^*/s$ is given a much smaller weight than $\Delta a^*/s$.

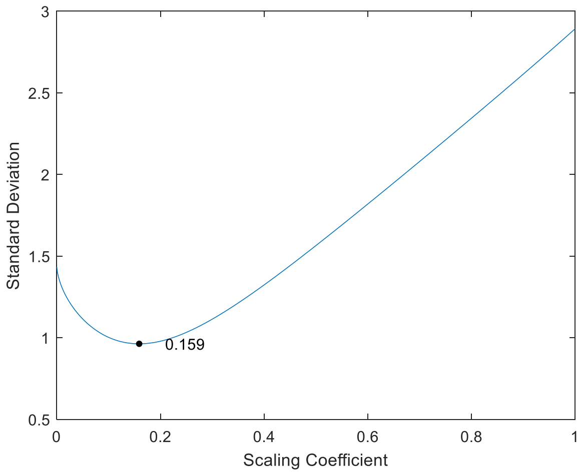


*Figure 6: Plot of the scaling coefficient α versus the standard deviation of the PSEs in CIELAB.*

Kong also performed similar analysis in other colour spaces. In LMS cone space, the minimum standard deviation of the PSEs was found to be when the weights of both the M- and S-cone responses were set to zero, an unsatisfying result; consequently, this space was not considered here. The other colour space utilised by Kong was the cone-opponent DKL space, in which the axes are linear combinations of cone responses: L + M, L – M, and S – (L + M) [11]. The L + M axis was taken to be the luminance axis, which was held constant here. The cone responses of the transitions were calculated using Stockman and Sharpe cone fundamentals and the measured spectra of the transition endpoints [12]. Δ(L – M) and Δ(S – (L + M)) values were computed from the beginning to the end of each transition, and the weighted ΔDKL values were calculated according to:

$$\Delta DKL = \sqrt{(1-\alpha)\big(\Delta(L-M)\big)^2 + \alpha\Big(\Delta\big(S-(L+M)\big)\Big)^2} \tag{2}$$

The ΔDKL values were divided by three seconds to yield the weighted speeds, and the PSEs were calculated for all transitions. The standard deviation was minimised at $\alpha = 0.013$ (see Figure 7).

Just as with the analysis of standard deviations in a weighted CIELAB space, the scaling coefficient for DKL space cannot be directly compared to that found by Kong because of the differences in how the terms were weighted. However, the plot of the scaling coefficient versus the standard deviation is again very similar to the previous result. Additionally, both this and Kong's analysis yielded a very small weight to the Δ(S – (L + M))/s term.

The scaling coefficients for different axes of these colour spaces provide information about the factors contributing to speed perception as well as the nature of a hypothetical temporally uniform colour space. A small weighting suggests that changes in that direction are less important in determining the perceived speed of a stimulus than changes along other axes. The analysis of CIELAB coordinates then supports the conclusion drawn from the previous research that $\Delta b^*/s$ does not contribute as much to speed perception as $\Delta a^*/s$. The scaling coefficient decreased the standard deviation of the PSEs in DKL cone-opponent space by a larger factor than in CIELAB space, suggesting that the former may be a better starting point for temporal uniformity. The analysis of DKL coordinates indicates that Δ(S – (L

+ M))/s contributes little to speed perception, in line with the past research on speed perception. This result also suggests a possible connection to motion perception, as several studies have found that the L – M channel contributes more to perception of chromatic motion than the S – (L + M) channel [13, 14]. However, at least one study has found results to the contrary [15], and the conclusions are not directly comparable.

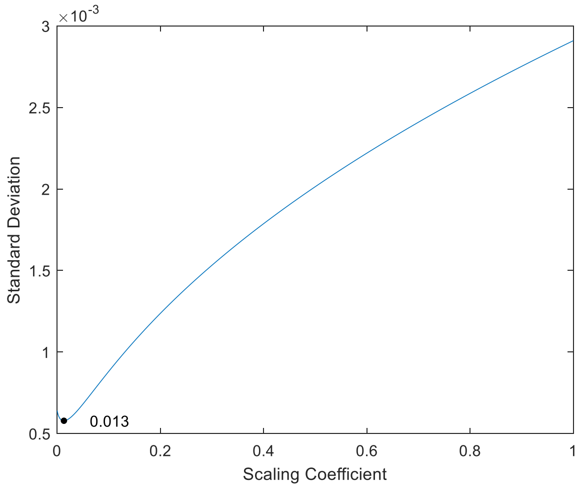


*Figure 7: Plot of the scaling coefficient a versus the standard deviation of the PSEs in CIELAB.*

### *Comparisons of orientations relative to neutral*

Although the thresholds of the transitions towards D65 cannot be analysed directly, some discussion of these results can be had based on the interpretation of the PSEs computed using five observers' data as upper bounds of the true values, though further investigation is needed to verify it. The transitions towards D65 have lower PSEs across the board and must therefore be slowed down even further to match the perceived speed of the reference. Interestingly, Pastilha found that detection thresholds were lower for transitions away from D65. This yields the unintuitive result that we are more sensitive to the set of transitions with an overall lower perceived speed. However, it should be noted that Pastilha was investigating transitions limited to along the daylight locus. The only PSEs that remained high enough to be calculable with all observers' data in the transition towards D65 were the lower CCT transition and one of the hue directions adjacent to it. Consequently, it seems plausible that the perception of transitions along the daylight locus may differ from those of transitions in other radial hue directions. This would align more intuitively with Pastilha's results and suggest that that phenomenon may be limited to the daylight locus. In considering possible mechanisms behind this effect, Pastilha posited a possible neutral daylight illumination prior, as well as the hypothesis that people might be more sensitive to transitions that are more frequently seen in nature. If the results of transitions along the daylight locus are indeed different from those of different hue directions, this provides some evidence against the first of these theories, as a neutral daylight illumination prior would impact the perception of all transitions to and from that neutral chromaticity, not only those remaining on the daylight locus.

## Summary and conclusions

This study investigated the non-uniformity of speed perception of low chroma transitions. A 2IFC experiment was performed to compute the relative speeds of transitions in eight radial hue directions and two orientations relative to neutral. For transitions away from D65, the PSEs of the lower CCT and lime intermediate transitions were not significantly different from the reference speed. The PSEs of the transitions in all of the six remaining radial hue directions were lower than the reference speed and not significantly different from each other, indicating that they were perceived as faster than transitions in the reference direction.

The PSEs for the transitions towards D65 were all incalculable except for the higher CCT transition and one of the adjacent intermediate transitions, possibly because of the difficulty of the task or because the true PSEs lay outside the range of speeds of stimuli tested. Using the data of only five observers to calculate an estimated upper bound on these PSEs, all had lower thresholds than their counterparts transitioning away from the chromaticity of D65. Further study is needed to determine if the relationship between perception of dynamic lighting and orientation relative to neutral indicated by Pastilha's research applies to these higher speed stimuli, though these results suggest that that phenomenon may be limited to the daylight locus.

A comparison of the PSEs computed for the transitions away from D65 with those calculated for the chroma changes studied by Kong revealed different patterns in the PSEs across hue directions, though differences in the stimuli used make a direct comparison not the most illuminating. The same standard deviation analysis outlined by Kong was performed in CIELAB and DKL space, suggesting that $\Delta b^*/s$ and $\Delta(S-(L+M))/s$ contribute less to speed perception than $\Delta a^*/s$ and $\Delta(L-M)/s$, respectively, closely aligning with past results. Thus, though different specific hue dependencies are seen in transitions of lower chroma than studied previously, similarities emerge when examining the results in terms of colour- or cone-opponent axes.

## Future work

Adaptation to continually changing illumination is little studied. Most past experiments have investigated instantaneous changes in illumination, which are unnatural and unlike the conditions of dynamic lighting, and those that have used smoother transitions have used more gradually changing stimuli. An accepted model of the time course of chromatic adaptation has been developed for discontinuous changes in chromaticity. This was first investigated by Fairchild and Reniff, who studied adaptation after chromaticity changes in six colour directions [16]. They proposed a two-phase model of chromatic adaptation, one on the order of a few seconds and the other around one minute, at which point chromatic adaptation was roughly 90% complete.

Rinner and Gegenfurtner expanded upon this model, examining step-change transitions along the equiluminant colour axes of DKL cone contrast colour space [17]. They proposed a three-phase model, including an extremely rapid phase in addition to the fast and slow phases described by Fairchild and Reniff, which they posited was likely a colour contrast phenomenon.

Spieringhs *et a*l. measured the time course of chromatic adaptation with both a step change and a gradual change in chromaticity in order to expand the accepted model beyond discontinuous chromaticity changes [18]. The step change results agreed reasonably well with the Rinner and Gegenfurtner slow adaptation curve. The results of the gradual transitions agreed better with the Rinner and Gegenfurtner fast adaptation curve, yielding a different time constant than the discontinuous changes. There was a good fit for both transition speeds, indicating a similar physiological response.

Adaptation has a role to play in shorter transitions such as those used in this experiment as well, and measuring the adaptation state would shed light on how this impacts their perception. Using stimuli with the same speeds and transition directions as in the first experiment, achromatic appearance could be tracked and the time course of adaptation during these illumination changes pinpointed. This would enable a more thorough characterisation of the perception and appearance of temporal transitions in lighting.

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