Conspicuity of chromatic light from LED spotlights

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Chromatic light in achromatic luminous surroundings has the effect of attracting attention to the area of coloured light. The strength of the effect of attracting attention and arousing visual interest depends on the intensity and spectral composition of the light. Light-Emitting Diodes excel in providing chromatic light of high saturation and are likely to produce light of higher chromatic strength than the light most users have experienced before. An experiment was performed to quantify the luminance for red, orange, yellow, green, cyan, blue and purple hues that give rise to levels of attraction value equal to those for achromatic light. It was found that the luminance required for the hues tested varied by more than a factor of 4. The results for the attraction value were found to be correlated with modelled equi-brightness predictions.

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Introduction

The visual appearance of our physical surroundings depends on the light with which these surroundings are illuminated. Many spaces in the built environment demonstrate that careful lighting design can add pleasant experiences to the specific purpose of a room. One of the most commonly used lighting techniques is accent lighting. This is used predominantly in retail spaces to make merchandise look as appealing as possible. The general purpose of accent lighting is to emphasise a specific area of the visual field and to direct attention to it, as stated by the IESNA definition for accent lighting: “directional lighting to emphasize a particular object or surface feature or to draw attention to a part of the field of view” [1]. Accent lighting therefore works on the basis that specific properties of the visual stimulus can increase visual interest and can influence what people look at. In practice, accent lighting is created by dedicating additional light to the object or surface feature to be emphasised. This means the spatial distribution of light is manipulated so as to create a higher contrast between the area in a scene that is to be emphasised and the adjacent areas.

Research has demonstrated that the spatial distribution of light does indeed influence people's behaviour. For instance, La Guisa [2] confirmed that brightness distributions in classrooms that feature accent lights are able to transfer and hold human attention more effectively than light distributions without accent lighting. Hopkinson [3] observed that if workplaces were lit with local lighting rather than with general lighting people were able to remain focused on their work more effectively. Just because a visual focus is established for a lighting condition, this does not necessarily mean that the intended behavioural reactions will be achieved. A visual focus located in an unfavourable place might cause distraction, and may only create the intended reaction if it is placed in the right location. Hopkinson concluded from evidence in projects carried out that brightness distribution and colour do influence attraction [3]; he states: "The eye gravitates naturally to bright and colourful objects." [4]. In general, lighting literature provides only sparse information on conspicuousness of accent lighting with chromatic lights. According to Flynn [5] the luminance to achieve equal attraction value in an accent lighting situation depends on the hue of the accent light; lowest luminance values are required for red and highest for yellow. Luminance ratios are reported for four different hues with respect to achromatic light. Unfortunately, the information given lacks any specific description of the chromaticity characteristics of the light sources.

Our study examined the strength of the effect of attracting attention using highly saturated light from today's LED (Light-Emitting Diode) sources. LEDs generally produce coloured light with chromaticity coordinates close to the boundary of the CIE chromaticity diagram. According to the CIE definition of luminance, a summation procedure is used to derive the photometric quantities of light with any spectral radiance distribution from the photometric quantities at each wavelength. The disadvantage of this photometric addition procedure is that it fails to give psychological correlates of what is perceived [6].

From literature it is known that the brightness of spectral colours depends on the hue. Results of heterochromatic brightness studies that support this claim have been collected by Wyszecki and Stiles [7]. The visual sensation of the apparent proportion of grey in related colours is another aspect of human perception that has been shown to depend on hue. Evans and Swenholt [8] explored the state of zero-grey content for monochromatic light that is placed in the centre of an achromatic circular stimulus. They found that the luminance required to reach the zero-grey point depends on the wavelength of the monochromatic light. Nayatani [9] found that despite their different definitions, equal perceived brightness and zero-greyness phenomena bear close relation to each other. According to his results, the zero-grey luminance proposed by Evans has approximately the same perceived brightness irrespective of hue.

The aim of the current study is to quantify the effect of hue on the arousal of visual interest using trichromatic spotlights. The measure we applied for positive attributed conspicuity is attraction value. Spontaneously judged, it expresses the potential of an area to attract attention and arouse visual interest. The exhibited attraction value was judged under different conditions, with and without an additional task. The chosen blind contour drawing assignment required participants to visualize the scene and sketch it on paper without looking at the paper. This task was given to test the impact of a goal-directed activity that required conscious visual observation and eye-hand coordination while making a spontaneous judgement of conspicuity.

In order to address the known shortcomings of determining luminance values for spectral radiance distributions according to the CIE 1924 luminosity function, we tested an alternative method suggested by Nayatani [10] to calculate luminance values that correlate to perceived brightness.

Study design

The spatial situation of the experiment was an interior room measuring 3.7 m × 6.2 m and 3.0 m in height. The room was empty, enclosed and had no decoration. The walls and ceiling were painted white (reflection factor: 0.8), the floor material was a grey carpet (reflection factor: 0.2). The lighting installation consisted of linear LED fixtures providing general room lighting and two LED spotlights. The general room lighting sources were placed on the floor behind the observers to illuminate the surroundings indirectly via the back wall. The two ceiling-mounted spotlights were directed towards the front wall, creating two patches of light next to each other. Both patches were of the same shape, they were brightest in the centre and the intensity decreased gradually with distance from the centre. In each experimental trial, the spotlights produced a chromatic and an achromatic patch on the same background. Both patches appeared to be luminous, with their intensities being considerably higher than the luminance of their surroundings.

The experimental setup for this study was chosen to closely resemble a common lighting application: accent lighting. The LED spot-luminaires used were regular products with a beam angle of 2 × 15 degrees and a maximum total light output of approximately 600 lumen. They generate achromatic and chromatic stimuli by tri-chromatic mixing of red, green and blue LEDs (see Table 1). A typical feature of LED sources is their high spectral purity, which is caused by the narrow bandwidth of light emission (see Table 1). In perceptive terms, such chromatic light is described as ‘vibrant’ and ‘saturated’.

Colour	LED	Peak wavelength (nm)	Bandwidth FWHM (nm)
Red	R	625	21
Green	G	518	35
Blue	B	448	23

Table 1: Characteristics of the LED light sources used in the spotlights: peak wavelength and spectral bandwidth measured at half the value of the maximum.

The chromatic light stimuli were varied in hue but also differed in saturation. Our specific interest was to provide chromatic stimuli with maximum saturation achievable by an RGB system with LED light sources. Seven different hues were presented: red, green, blue, orange, yellow, cyan and purple. Yellow, cyan and purple were chosen with chromaticities of the complementary colours of blue, red and green. With orange, an additional mixture of red and green was added. Each experimental trial featured a chromatic light patch next to an achromatic reference (see Figure 1). The achromatic RGB mixtures emitted from the reference spot and the general lighting were equal to a correlated colour temperature of 6500 K. The maximum luminance in the middle of the achromatic light patch was approximately 9.2 cd/m^2, and the luminance around the patches was approximately 1.1 cd/m^2. General room lighting was provided to ensure that stimuli were viewed under photopic conditions. The presence of light in the surroundings created a situation that was close to real-life indoor conditions. The general lighting and the fact that the achromatic reference was not completely shielded off from the chromatic stimulus limited the maximum possible chromatic intensity.

Each chromatic stimulus was presented at several fixed luminance levels. Cyan was presented at 4, purple, yellow and orange at 5, red and green at 6 and blue at 7 different luminance levels. The spatial position of the chromatic patch (left or right) and the order of presentation were randomized. After each trial the lighting was switched to provide achromatic general room lighting. This was present for a period of 10 seconds prior to each stimuli onset. Participants judged whether the left or right patch had a higher attraction value.

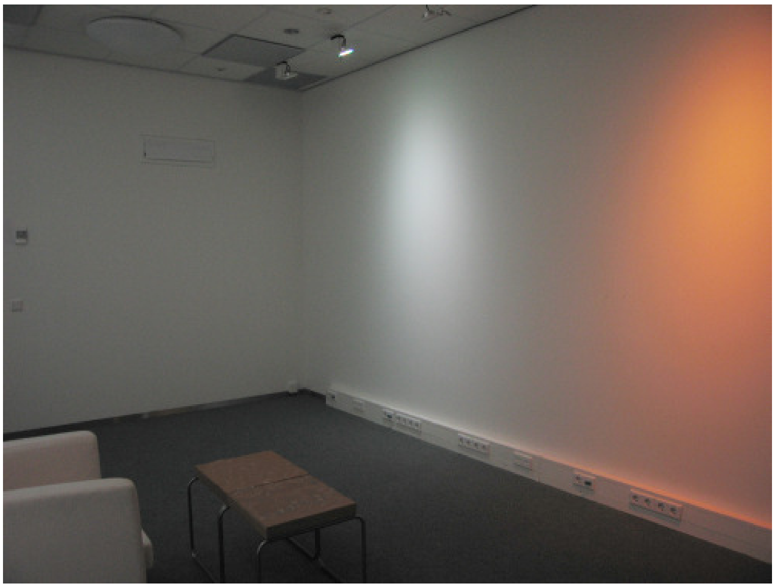

Figure 1: Spatial situation of the experiment with stimulus example.

Twenty-three participants – 11 male and 12 female – with an average age of 28 years took part in the experiment. All participants passed the Ishihara test for colour deficiency [11]. Participants judged from a seated position at a distance of about 3 m from the wall with the two light patches. Each participant judged all seven colours at all intensities in two runs. In one run the 38 conditions were assessed without an additional task; in the other run the assessment was made while the individual was drawing the scene without looking at the paper on which they were drawing. Participants reported verbally to the experimenter whether the chromatic or achromatic light patches had the higher attraction value.

Study results

The influence of hue, position (i.e. left or right), gender and task on the attraction value judgment was assessed by means of a logistic regression analysis. For the analysis, the responses were represented as a percentage of people who found the chromatic patch to be more attracting. The analysis revealed that hue had a significant effect on attraction value ($p<0.001$). All other main effects were not significant ($p>0.05$). Given that the performance of a drawing task had no significant influence, the data from both runs were pooled. For each of the seven colours the proportion of participants who responded with 'more attracting' was plotted against the luminance of the chromatic spot (see Figure 2). All colours showed similar tendencies, except cyan, which produced a flattened function. The data was fitted with a cumulative normal distribution, providing the luminance values for equal attraction at a proportion of $p=0.5$. Goodness of fit was assessed by chi-square statistics considering observed data points with $0.1<p<0.9$. Because calculated values did not exceed, for any hue, the critical value determined by a probability of 0.1, the null hypothesis was not rejected and hence a good fit was confirmed. The results show that the luminance of the chromatic lights that was required to generate a level of attraction equal to that of an achromatic reference of 9.2 cd/m² varied between 1.7 and 7.4 cd/m².

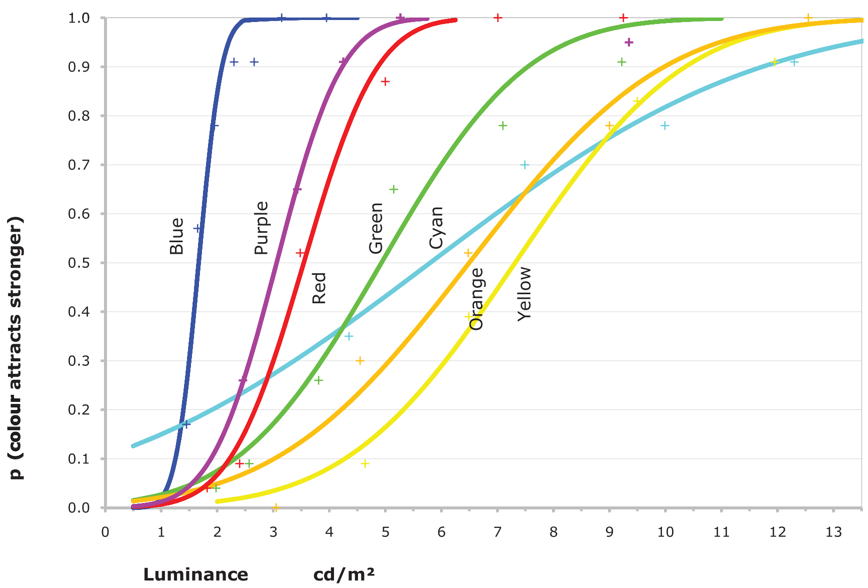

Figure 2: Psychometric function for the seven chromatic light stimuli.

Table 2 shows the absolute luminance and the luminance ratio at which the stimuli have equal attraction value. The chromaticity coordinates u' and v' were measured after the experiment had been completed and the spots had been tuned to the luminance given by the p=0.5 value. In Figure 2 deviations for cyan are observed that are probably to attribute to the very low CIE saturation of the cyan stimuli used.

Colour	LED	L (cd/m²)	L/L_o	u′	v′	h_{uv}°	S_{uv}
Achromatic	R+G+B	9.2	1	0.20	0.47		0.0
Red	R	3.5	0.39	0.43	0.50	9	3.1
Orange	R+G	6.5	0.71	0.34	0.53	23	2.0
Yellow	R+G	7.4	0.80	0.20	0.54	90	1.0
Green	G	5.0	0.54	0.09	0.55	143	1.7
Cyan	G+B	5.8	0.63	0.11	0.46	188	1.1
Blue	B	1.7	0.19	0.20	0.20	272	3.5
Purple	B+R	3.1	0.33	0.34	0.36	323	2.3

Table 2: Resulting luminance L at equal attraction value, relative luminance L/L_o, chromaticity coordinates u′ and v′, the hue angle and the saturation in u′v′ space.

Arranged according to increasing hue angle, the luminance ratios L/L_0 for equal attraction value do approach a sinusoid shape with a maximum in the yellow and a minimum in the blue (Figure 3). Although obtained results for equal attraction value suggest an inverse relationship between S_{uv} and luminance, the experimental setup did not allow clarification of the impact of saturation. But despite such limitation, the results are to be considered of practical relevance for application of chromatic LED lights.

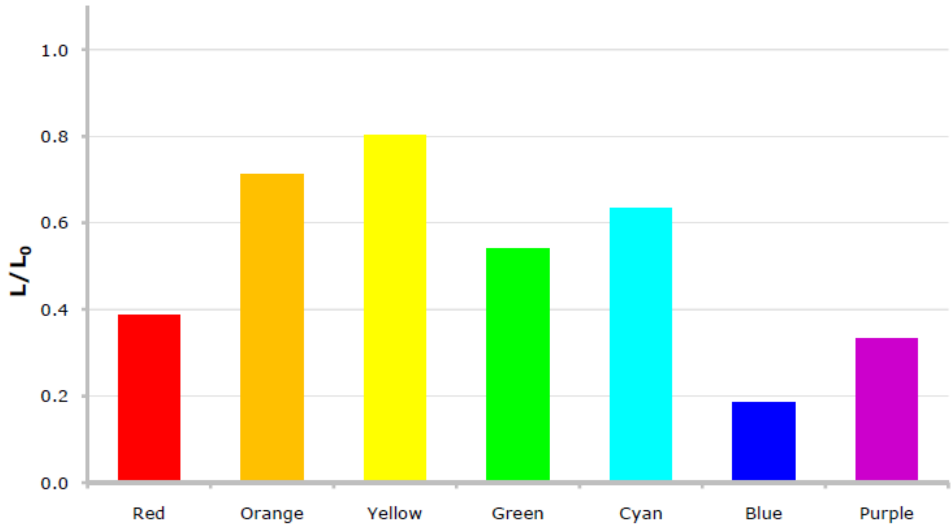

Figure 3: Relative luminance for equal attraction value; colours arranged according to hue angle.

Comparison with results obtained by Flynn

The results of our experiment do not align well with the values reported by Flynn [5] and summarised in Table 3. Note that for the data obtained by Flynn no exact chromaticity characteristics are known. The relative luminance (L/L_0) required for red is similar. For green the relative luminance differs numerically, but at least for both studies green is the stimulus with a luminance that is larger than but closest to red. The main differences were found for yellow and blue chromatic light.

Colour	Red	Yellow	Green	Blue
L/L_0 (our study)	0.39	0.80	0.54	0.19
L/L_0 (Flynn)	0.30	1.20	0.40	0.60

Table 3: Relative luminance (L/L_0) results of our study and the results obtained by Flynn [5].

Both studies found that the luminance required for yellow is highest, although in our study the luminance was lower than that of the achromatic reference. According to Flynn, the luminance for blue is higher than for red and green, but in our findings the luminance required for blue was lowest of all.

Comparison with predictions for equal brightness

Luminance values obtained according to the CIE 1924 photometric system are not suitable for providing psychological correlates of perceived brightness irrespective of their spectral power distributions [10]. On the basis of the Nayatani colour appearance model [12,13], Nayatani suggested a method to calculate equi-brightness estimates for any spectral power distribution [10]. The formulae use CIELUV space.

$$L_o/L = 0.4462 \times (1.3086 + (-0.866 \times q(\theta) + 0.0872 \times K_{Br}) \times S_{uv}(x,y))^3 \quad (1)$$

$$\theta = \tan^{-1}((v'-v'_o)/(u'-u'_o)) \quad (2)$$

$$q(\theta) = -0.01585 - 0.03017 \times \cos\theta - 0.04556 \times \cos(2\theta) - 0.02667 \times \cos(3\theta) - 0.00295 \times \cos(4\theta) + 0.14592 \times \sin\theta + 0.05084 \times \sin(2\theta) - 0.019 \times \sin(3\theta) - 0.00764 \times \sin(4\theta) \quad (3)$$

$$K_{Br} = 0.2717 \times ((6.469 + 6.362 \times L_a^{0.4495})/(6.469 \times L_a^{0.4495})) \quad (4)$$

where L_o: luminance of specified reference, L: luminance of chromatic stimulus that is perceived as bright as the reference, θ: metric hue angle of chromatic stimulus in u′v′, x,y: chromaticity of chromatic stimulus, S_{uv}: metric saturation of chromatic stimulus calculated in u′v′, L_a: adapting luminance.

In Equation 4 the maximum luminance of the achromatic reference patch was taken to provide the adaptation luminance to calculate the coefficient K_{Br}. The luminance value is in accordance with the CIE 1924 photometric system. For Equations 1 and 2 input from the CIE 1931 colorimetric system was transferred to CIE u′v′ to calculate saturation S_{uv} and hue angle θ. The results of the calculations are given in Table 4.

Colour	Red	Orange	Yellow	Green	Cyan	Blue	Purple
L/L_o estimate	0.43	0.72	1.28	0.83	0.84	0.30	0.41
L/L_o our study	0.39	0.71	0.80	0.54	0.63	0.19	0.33

Table 4: Relative luminance (L/L_o) estimates for equal brightness according to Nayatani [10] and our results for equal attraction value; colours arranged according to hue angle.

The relative luminance predictions for equal brightness do show clear similarities to the results for equal attraction value. The maximum values are demonstrated for yellow, the minimum values for blue. The correlation coefficient between predictions of equal brightness and demonstrated attraction value is high (0.91). Nayatani's prediction suggests that luminance for yellow must be higher than for the achromatic reference in order to match in brightness. This deviates from our results, which demonstrated the same attraction value as the achromatic reference at a level of 0.8. Although orange shows numerically very similar values, it proved to have the same attraction value at a higher luminance than green and cyan, whereas the predicted luminance for a brightness match was lower for orange than for green or cyan.

Discussion

The power of chromatic light to attract attention and visual interest in accent lighting situations has been shown to depend on the chromatic properties of the light. This is in line with results obtained previously by Flynn. For colours with a high colourfulness the luminance required to equal the attraction value with an achromatic reference was generally low, whereas for colours with a low colourfulness the luminance required was high. Such an inverse relationship is also known from literature on heterochromatic brightness matching of complex stimuli, as summarised by Wyszecki and Stiles [7]. The actual differences between Flynn's results and our own data can perhaps be explained by differences in the hue and purity of the stimuli. LEDs are expected to provide more highly saturated chromatic light than the light sources used by Flynn.

The experiment has successfully demonstrated that attraction value is a judgment criterion that could be applied by the participants spontaneously, without the need for further instruction. By measuring attraction value, we covered quick and immediate reactions. The fact that the evaluation of attraction value proved robust against the influence of another task underpins the effortless and immediate character of this kind of judgment. Neither the judgment process nor the performance seemed to be hampered by the additional visual, imaginative task that demanded manual action.

Brightness can be considered to be directly related to the strength of the visual sensation that a visual stimulus elicits. The predictions for equally bright chromatic stimuli calculated according to Nayatani's method proved to correlate with attraction value. The high correlation between our experimental results and brightness estimates suggests that the power to attract is at least partly determined by brightness. The specific influence of the purity of the chromatic stimuli could not be studied in this experiment because purity was determined by the characteristics of the light source and the amount of general light present.

Conclusions

The high spectral purity that coloured LED sources provide is able to induce the perception of considerable brightness. The current experiment has demonstrated that in typical accent lighting conditions chromatic light requires lower luminance levels to attract equal attention compared to an achromatic reference light. The luminance at equal attraction value has been shown to depend on the hue of the chromatic light. The results showed that for blue the relative luminance was lowest, followed by purple, red, green, cyan, orange and yellow.

Attraction value proved to be a judgment criterion that can be applied spontaneously and remains unaffected by interference from another visual task. For accent lighting applications the results clearly indicate the potential of chromatic light to realize similar attracting conditions with much less radiant energy.

Acknowledgement

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