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Development of a Colour Quality Assessment Tool for indoor luminous environments affecting the circadian rhythm of occupants

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A B S T R A C T

The colour of indoor luminous environments affects the circadian rhythm and awakening of humans. If the blue colour of a luminous environment perceived by an observer's circadian action factor (CAF), which represents the impact of light on the hormones and biorhythm of an observer, is high, the secretion of melatonin is suppressed. To design an appropriate indoor luminous environment, the final colour of a space perceived by an observer must be accurately predicted and its effects on the observer must be considered. Therefore, this study developed a Colour Quality Assessment Tool (CQAT) that utilizes the spectral reflectance factor of interior finishes and the spectral power distribution (SPD) data of luminaires to accurately calculate the luminous exitance radiated by interior finishes and the colour quality components of the SPD, luminance, CAF, colour coordinates, and correlated colour temperature (CCT) based on the colours of the interior finishes and light sources. In addition, the colour quality was evaluated considering the angle between the interior finishes and the view of an observer from a specific direction and position. The colour quality of different interior finishes was assessed using the CQAT, and the results showed that the luminous environment CCT perceived by observers differed by 1882 K (approximately 31%) or more and that the CAF differed by 0.16 (approximately 14%) or more based on the colour of the interior finishes.

1. Introduction

1.1. Study purpose

In architectural spaces, the luminous environment is an important factor that has physiological and psychological effects on recent lifestyle trends, indicating that many people spend the majority of their time indoors. In the past, luminous environment studies have focused on the development of luminaires with high efficiency and high colour rendering to achieve observer visual satisfaction. In contrast, recent studies have examined the non-visual effects of luminous environments on observers and have developed luminaires that consider both psychological and physiological factors [1–10].

The brightness of an indoor luminous environment influences work efficiency, and excessive glare caused by luminaires can lead to observer discomfort or visual impairment. In addition, an indoor luminous environment can provide psychological stability and stimulation depending on the colour (wavelength), intensity and exposure time, which can also affect the hormones and biorhythms of occupants [11–19]. In particular, if the colour of a luminous environment perceived by an observer is close to blue, the circadian action factor (CAF, a_{cv}), which represents the impact of light on the hormones and biorhythm of an observer, is high and suppresses the secretion of melatonin [20–25]. The suppression of melatonin can cause adverse effects, such as sleep disorders, melancholia and growth impairment. Therefore, to design an appropriate indoor luminous environment, the final colour of a space perceived by an observer must be accurately predicted and its effects on an observer must be considered.

For interior finishes, design and evaluation criteria have been established for brightness and glare in indoor luminous environments, and these factors can be predicted using various simulation programmes or simple calculation methods. The colour of a luminous environment is generally designed using the colour temperature of the luminaires and does not account for the interior finishes; therefore, the design colour differs from the actual colour perceived by observers. Since the lighting colour perceived by an observer is a combination of the colour radiated by the luminaires and the colour of the light reflected by the interior finishes, this colour is difficult to accurately predict using a simplified equation. Therefore, this study developed a Colour Quality Assessment Tool (CQAT) that utilizes the spectral reflectance factor of interior finishes and the spectral power distribution (SPD) data of luminaires to accurately calculate the luminous exitance

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Abbreviations

CAF	Circadian action factor
CQAT	Colour quality assessment tool
SPD	Spectral power distribution
CCT	Correlated colour temperature
UGR	Unified glare rating
CLA	Circadian lux
RGB	Red, green, and blue
CBS	Colour bleed scale

radiated by interior finishes and the colour quality components of the SPD, luminance, CAF, colour coordinates, and correlated colour temperature (CCT) based on the colours of the interior finishes and light sources. In addition, using the unified glare rating, the luminous flux entering the field of view of an observer and the colour quality (SPD, luminance, CAF, colour coordinates, and CCT) are evaluated considering the angle between the interior finishes and the view of an observer from a specific direction and position.

1.2. Previous research

Several previous studies have analysed the effect of light reflected by interior finishes on the circadian rhythm. Konis (2016) developed a framework for predicting the non-visual effect of daylight entering an indoor environment on an observer. This prediction model can analyse the non-visual effect of daylight throughout the year based on the daily effect of daylight on an observer, and the model can aid architectural design by identifying areas inside a building where long-term residence may hinder the biorhythms of the occupants [26]. The Konis study is similar to this study and developed a model for evaluating and predicting the effect of an indoor luminous environment on an observer. However, that study only used the quantity of daylight entering the building and the SPD data and did not consider the effect of reflected light. Bellia et al. (2014, 2017) installed luminaires with different colour temperatures in a space and measured and analysed the circadian lux (CL_A) and circadian stimulus of observers to analyse the effect of the interior finish colour on their circadian rhythms [27,28]. Bellia analysed the circadian effects of the indoor reflected light, but Bellia's studies were only performed ex-post evaluation under specific circumstances by analysing the effects using actual measurements. In contrast, the prediction model developed in this study can be used for preliminary evaluations of different environments and luminaires. Hraška et al. (2015) and Hartman et al. (2015) constructed a 1/5 scale room with orange, yellow and dark-brown finishes, and they measured and analysed the CL_A by measuring the daylight SPD data to analyse the circadian effects of the interior finish colour [29,30]. The studies of Hraška et al., Hartman et al., and Bellia et al. analysed the effect of indoor reflected light, but the studies were based on actual measurements, unlike this study. In addition, Pechacek et al. (2008) used RADIANCE to analyse changes in the interior lighting colour due to the colour of the interior finishes in a hospital ward with either daylight or artificial lighting [31]. Similar to this study, Pechacek et al. analysed the effect of indoor reflected light using a simulation instead of actual measurements; however, Pechacek et al. used a 3-channel ray tracer in RADIANCE instead of the spectral reflectance factor of the interior finishes to calculate the red, green, and blue (RGB) colour values of the light reflected by the finishes. The RGB values are different from the CQAT values developed in this study because they cannot be used to calculate an accurate spectrum of the final reflected light and cannot be used to evaluate circadian properties.

One previous study analysed the effect of the luminous environment from the view of the observer. Nardecchia et al. (2015) measured the colour, intensity and light direction from the view of an observer using a spectroradiometer and proposed a methodology for determining a qualitative indicator to describe the lighting stimulation that reaches the retina. This indicator can be used to evaluate the stimulation that occurs in a specific view area depending on the surrounding environment [32].

Other previous studies quantitatively analysed the effect of luminaires on the circadian rhythm of the observer. Liu & Zhang (2013) defined the circadian efficacy and circadian irradiance to develop an integrated standard to evaluate the non-visual biological effects of light and measured these values for various light sources [33]. Kakitsuba (2016) analysed the psychological and physiological reactions of 10 subjects to the colour temperature and illuminance to identify pleasant indoor lighting conditions. The psychological stability of the subjects was determined by analysing their electrocardiograms and brain waves when they were exposed to specific luminous environments [34].

One study analysed how the interior finish colour affected the psychology of an observer. Yildirim et al. (2007) analysed how the interior finish colour affected the mood and cognitive ability of observers based on their sex and age. Approximately 250 subjects were evaluated at cafés and restaurants with yellow and violet walls. The results showed that the violet interiors resulted in more positive moods than the yellow interiors, and men evaluate spaces more positively than women. In addition, young participants had more positive evaluations than old participants [35].

In a previous studies related to calculating the circadian effect, Gall et al. (2004) defined the circadian action function c(λ) and how to measure a_{cv} values [36]. Moreover, Žukauskas et al. (2015), Bellia et al. (2011), and Oh et al. (2014) also introduced calculations for the CAF and circadian stimulus [5,8,37]. In addition, Rea & Figueiro (2016) developed an argument for adopting a circadian stimulus as a metric for quantifying light in an architectural space [38]. Hraška & Hartman (2014) presented results from measuring the influence of the colour of external shading obstacles on the interior circadian stimulus in a lighting climate [39]. In addition, Escofet & Bará (2015) analysed the circadian effect (circadian stimulus) from self-luminous devices using hardware filters and software applications [41].

In summary, previous studies have examined the effects of light reflected by interior finishes on the biorhythm of observers, but most of the studies involved ex-post evaluation of actual measurement data from real spaces. Studies based on actual measurements can provide an

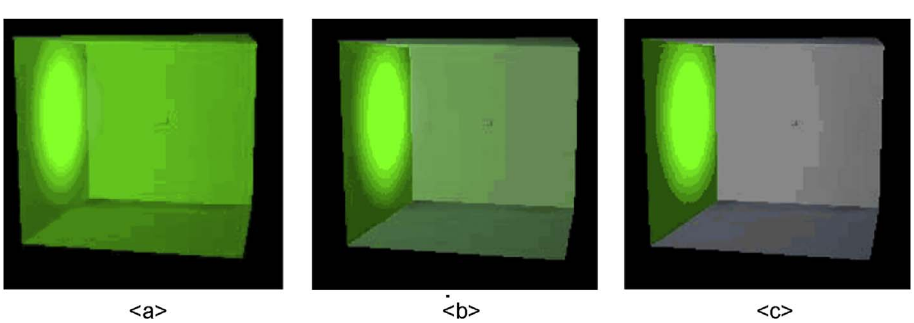

Fig. 1. Colour rendering scenes according to the colour bleed scale (< a > CBS = 1, CBS = 0.5, and < c > CBS = 0). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)