A holistic approach for a natural light variation experience: a pilot study of a practical application for office lighting

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Abstract. Lighting is crucial for vision and has important effects beyond vision, influencing a variety of physiological and behavioral processes. When designing lighting, visual aspects, effects beyond vision, and perception of the environment should be considered together in a holistic approach. As humans evolved under daylight, a lighting protocol, based on a room context and daylight characteristics, was developed and described. The lighting, with customized light levels, spectral composition and light distribution that changed dynamically to evoke a perception of daylight conditions, was realized using commercially available luminaires and a digital control system. The resulting lighting conditions are described by measurements.

Keywords: holistic approach, natural light variation, light distribution, dynamic lighting, spectral composition, practical application

1. Introduction
During the past 30 years, there has been a significant increase in the knowledge about light’s essential role in the health and wellbeing of humans [1]. Regarding our understanding of the effects of light on the visual system, theoretical models are well established [e.g., 2,3]. Moreover, the current body of research demonstrates that daily exposure to light and darkness is of fundamental importance to people’s health and psychological wellbeing [4-6]. Previously reported data show that light has acute effects in addition to circadian effects, and nowadays, there is much on-going research relating to models and concepts for effects of light beyond vision [7,8].

Originally, most lighting was primarily designed from a visual perspective, dimensioned to provide illuminance levels adequate for supporting the intended visual tasks. New knowledge regarding light effects that are influenced by the intrinsically photosensitive Retinal Ganglion Cells (ipRGC-influenced light responses) on humans suggests that lighting should be dynamic, as the natural light source, for suitable entrainment of the endogenous circadian rhythm and regulation of daily sleep- and activity patterns. Several studies [4,9-13] show that most people prefer daylight due to assumed beneficial health effects and its perceived environmental qualities (i.e., color rendering, rendering of shadows, variation or information about weather conditions and time of day). Daylight differs from electric lighting in many ways. Apart from daily changes in light levels and spectral composition, there will be a daily change in the spatial distribution of the entering daylight due to the diurnal changes of the sun’s altitude and azimuth.
To achieve a successful solution, a lighting designer must recognize various factors. As mentioned earlier, often visual effects are taken into account, and these days maybe also effects of light beyond vision. However, perception of the environment is rarely taken into consideration as well [i.e., 14]. Therefore, with a holistic approach integrating perceptual, physiological, and psychological aspects, a dynamic lighting scene, inspired by variations of natural light, was composed and described in this pilot study. In the context of a laboratory setting with vertical windows in the façade, the objective was to develop, describe and test a lighting solution with customized light levels, spectral composition and light distribution that will dynamically change to evoke a perception of daylight conditions.

2. Method

2.1 Setting

The study was conducted in a laboratory setting consisting of a rectangular room (depth 5.7 m; width 8.5 m; ceiling height 3.1 m) with vertical windows in the façade. The walls were white, and the floor comprised a grey carpet (see Figure 1 for a layout of the experimental room).

2.2 Lighting system

The dynamic lighting scene was realized using twelve ceiling-mounted luminaires with a diffuse/direct light distribution (Zumtobel Mellow Light Inf EA LED3600-830-60 M6 00Q L00 KA WH). The output from the diffuse (indirect) and the direct components were controlled separately. Additionally, ten wall-washer luminaires (Zumtobel Panos Inf E200WW 22 W LED927-65 LDEWH) were used. All luminaires were equipped with tunable white LEDs (Correlated Colour Temperature (CCT) 2700-6500 K) with a Colour Rendering Index, CRI >80. A DALI-based protocol was used in the lighting control system (LITECOM, Zumtobel Group) (see Figure 1 for the locations of the luminaires).

![Figure 1. Layout of the experimental room, the locations of luminaires as well as the positions of vertical and horizontal measuring points.](image)

The lighting control protocol was based on simulations of daylight using VELUX Daylight Visualizer 3 (Velux Group) lighting simulation tool. The diurnal distribution of daylight on the surfaces of the room was simulated by animations with overcast and sunny skies on March 21. Furthermore, field measurements reported by Dai et al. [15] were used as a point of departure for estimating the daily change of CCT and illuminance. Visual assessments were performed by the research team and were used for fine-tuning the luminaire settings.

Based on the daily variation of light distribution on the various surfaces of the room and incoming solar radiation identified in the simulations, the luminaires were divided into 16 control groups. The daylight conditions comprised two components: skylight (diffuse component) and sunlight (direct...
component). The daylight components were realized using a combination of ceiling-mounted luminaires and wall-washers. The skylight was achieved with the diffuse component in the ceiling-mounted luminaires and the wall-washers. Maximally 60 percent (range: 15-60 percent) of the luminous flux available in the luminaires was used for the diffuse component. The sunlight was accomplished using the direct component in the ceiling-mounted luminaires and a mix of wall-washers’ contribution. Maximally 100 percent (range: 15-100 percent) of the available luminous flux was used for realizing the daylight conditions that included sunlight.

To test the lighting scene, a dynamic 15-minute sequence was programmed, simulating a period from 6 a.m. to 6 p.m. The first 5 minutes of the sequence related to the “morning” (from 6 a.m. until 10 a.m.), the next 5 minutes to “midday” (from 10 a.m. until 2 p.m.) peaking halfway at “noon”, and the last 5 minutes to the “afternoon” (from 2 p.m. until 6 p.m.).

2.3 Measurements
The lighting conditions resulting from the lighting control protocol were documented by continuous measurements (with a time delay of 30 seconds) of illuminance, CCT, and CRI using a spectroradiometer (Lighting passport, Asensetek). Measurements were carried out vertically at six points on the walls (height 1.5 m) and horizontally at nine points (0.76 m) (see Figure 1 for positions of measuring points). The collected data was analyzed in the software Spectrum Genius (Asensetek). In total, thirty measurements were recorded at each point.

Furthermore, a luminance measuring system with an 18-50 mm lens (LMK mobile advanced, TechnoTeam Bildverarbeitung GmbH) was used for continuous recordings of luminance distribution in the room at thirty points in time (with a time delay of 30 seconds). LMK Labsoft (TechnoTeam Bildverarbeitung GmbH) was used for analyzing the data from the luminance measurements.

The room was shaded entirely from daylight by an opaque curtain during all measurements.

3. Results
The continuous measurements of the lighting conditions in the room show low illuminance levels and higher CCTs during the time before the sun has risen over/above the horizon. Subsequently, during the “early morning”, the average CCT decreases, and the sunlight reaches the west wall (see Figure 4a). Simultaneously, during the “morning” until approximately “noon”, the average illuminance level in the room increases. Also, gradually, the sunlight reaches further into the room. In the “afternoon”, due to the change in solar height and azimuth, the illuminance levels decrease, and the sunlight light up the opposite wall (see Figure 4d). As the sunlight withdraws from the room, the average CCT increases concurrently with decreasing illuminance levels.

Figure 2 shows the illuminance and CCT values, horizontally measured at the nine points, throughout the 15-minute dynamic lighting scene. Horizontal illuminance varied between 47 lux and 647 lux at the different measuring points, and values of CCT between 3582 K and 5750 K were recorded. As can be seen in Figure 2, the illuminance uniformity was quite low in addition to a rather considerable variation in CCT at different locations of the room.

Recordings of illuminance and CCT at the six points measured vertically on the walls during the 15-minute scene are presented in Figure 3. Illuminance values between 55 lux and 384 lux were recorded. Concerning CCT, the values varied between 3649 K and 5694 K.

Measurements of CRI showed minimum values of 85 and 86 for the horizontally and vertically measurements. Correspondingly, maximum values of 89 and 90 were recorded at the horizontal and vertical measuring points.
Figure 2. Illuminance and correlated color temperature (CCT) at the horizontal measuring points (P01-P09) during the dynamic 15-minute sequence.

Figure 3. Illuminance and correlated color temperature (CCT) at the vertical measuring points on the walls (P10-P15) during the dynamic 15-minute sequence.
Examples of results from the measurements of luminance are displayed in Figure 4. The pictures show luminance distributions in the room during four points in time across the dynamic scene, viewed from a point in the back of the room facing the façade. Moreover, the figure illustrates the effect of the sun moving over the sky on an early spring day when the sunlight maximally reaches approximately halfway into the room, assuming no shading from surrounding buildings or other objects.

![Figure 4. Luminance measurements after a) 3 min, b) 6 min, c) 9 min and d) 12 min into the 15-minute dynamic sequence.](image)

4. Discussion
This study has been concerned with the objective of developing a dynamic lighting solution for a natural light variation experience. A holistic approach, considering visual and ipRGC-influenced light effects as well as perceptive aspects, was taken focusing specifically on the dynamic variation of light distribution in the room. As we humans have memories and experiences, we relate to them when we are in a space. For example, we expect sunlight to appear first on a west wall of a building and create a sun path in the room from west to east, and deeper into the room or closer to the façade depending on the sun’s altitude. Concerning illuminance levels and spectral composition, the lighting was based on the daily variation of daylight. However, illuminance levels were scaled for an indoor application.

The resulting lighting environment shows a varied light distribution like daylighting from the vertical windows in the context of the actual room. Initially, the illuminance levels are low although with higher CCTs which have a rather high relative content of short-and middle wavelength radiation. Subsequently, the general illuminance level increases while CCT decreases somewhat. A sunlight component and the movement of the sun in relation to the window placement were also included. In the case simulated in this pilot study (spring), sunlight was assumed to reach halfway into the room. During the “afternoon”, the general illuminance level decreases and the CCT increases, similar to daylight withdrawing from the room. A closer consideration of the design of a room and its openings may contribute to improved opportunities for good integration of daylight and the complementing electric light.

The dynamic lighting solution was realized using commercially available luminaires and lighting control equipment, demonstrating the possibilities of adjusting lit environments with technology that is often used in lighting design nowadays. Concerning customization of spectral composition to the
characteristics of daylight, there were certain limitations regarding the technique that was available in this study. The rapid development of lighting technology will probably allow even more elaborate tuning of the spectral composition soon, as has been demonstrated in recent studies [16].

The current pilot study forms a starting point for the continued development of principles and solutions for designing lighting that is experienced as having a natural light variation. Future research activities will include assessments and appraisals by users and experts.

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