CLIMATE-BASED DAYLIGHT PERFORMANCE: BALANCING VISUAL AND NON-VISUAL ASPECTS OF LIGHT INPUT

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ABSTRACT

This study uses a domestic dwelling as the setting to investigate and explore the applicability of daylighting metrics for residential buildings, including the formulation of metrics for non-visual effects. The simulation approach used to generate the performance data from which the metrics are derived is called climate-based daylight modelling (CBDM). This approach delivers predictions of various luminous quantities using sun and sky conditions that are derived from standardised annual meteorological datasets.

Although there are uncertainties regarding the precise calibration, there is now sufficient empirical data to parameterise models that also simulate the non-visual aspects of daylight, e.g. for circadian entrainment and a general sense of ‘alertness’. For these non-visual aspects, vertical illuminance at the eye was predicted using a modified climate-based daylight modelling approach. In the paper, we consider what relation there might be between the three aspects of daylight provision and if these relations appear to be complementary or conflicting in nature: for task; to reduce electric lighting usage; and, for non-visual effects. The implications for future building guidelines for daylighting are also discussed.

INTRODUCTION

It is now widely accepted that the standard method for daylighting evaluation - the daylight factor - is due for replacement with metrics founded on absolute values for luminous quantities predicted over the course of a full year using sun and sky conditions derived from standardised climate files [1]. The move to more realistic measures of daylighting introduces significant levels of additional complexity in both the simulation of the luminous quantities, and the reduction of the simulation data to readily intelligible metrics. The simulation component, at least for buildings with standard glazing materials, is now reasonably well understood and is widely known as climate-based daylight modelling (CBDM). Typically, these metrics address daylight provision for task and electric lighting usage [2,3]. There is no consensus however on the composition of the metrics, and their formulation is an ongoing area of active research.

This study uses a domestic dwelling as the setting to investigate and explore the applicability of daylighting metrics for residential buildings. In addition to daylighting provision for task and disclosing the potential for reducing electric lighting usage, we also investigate the formulation of metrics for non-visual effects such as entrainment of the circadian system, which is the focus for this paper. This fomulation is built upon a methodology developed by Pechacek, Andersen & Lockley [4].

Previously thought of mainly in terms of task illumination and aesthetics/design, it is now believed that daylight in buildings might serve another purpose through non-visual effects. In addition to building occupants having subjective preferences for daylit spaces, it has been firmly established that daylight has measurable biochemical effects on the human body, in particular with respect to maintaining a healthy sleep-wake cycle [5]. Recent findings on these non-visual aspects of occupant light exposure have led to a reconsideration of the function of daylight in buildings. Evidence is indeed suggestive of links between daylight exposure and both health and productivity. The duration, intensity and spectrum of the light received at the eye are the principal factors determining the suppression in the production of melatonin by the pineal gland (mostly during nightime), and thus a key component in the entrainment of the circadian cycle - the maintaining of which is believed to have significant short and long-term beneficial health effects [5]. Another important factor is the time of day when the light is applied. Compared to the luminous efficiency function of the eye, which has a peak value at 555nm, the action spectrum for the suppression of melatonin is known to be shifted to the blue end of the spectrum [6]. The body of empirical data from photobiology studies is now sufficient to elaborate preliminary non-visual lighting evaluation methods, which has become a relevant quantity to consider when assessing the overall performance of a space. The various modelling procedures and assumptions that were developed for this purpose are described in the paper, and a novel means of visualising the 'circadian potential' of a point in space is presented.

GENERAL METHODOLOGY

In this study, conventional climate-based daylight modelling [2] is combined with a refined approach for occupant exposure to non-visual effects. These refinements include accounting for the variation in spectrum between light from 'grey' overcast skies, 'clear blue' skies and 'warm' direct beam sunlight.

The setting, a residential building with and without skylights, was evaluated using climate-based daylight modelling for all 32 combinations of eight European climates (Hamburg (D), Madrid (E), Paris (F), London (UK), Rome (I), Warsaw (PL), Moscow (RU) and Ostersund (SE)) and four building orientations (N, S, E, W). Daylight for task was assessed using the Useful Daylight Illuminance (UDI) schema [7]. Electrical lighting usage was predicted on the basis of typical schedules and daylight availability using the RT 2005 switching model [8]. For non-visual effects, the eye-level vertical illuminance was predicted at sixteen locations, and at each one, for four cardinal view directions to account for the arbitrary nature of view direction in a residential space.

The CBDM approach used in this study delivers predictions of various luminous quantities using sun and sky conditions that are derived from standardised annual meteorological datasets. Thus the performance data accounts for the prevailing local climate, the building orientation and light from both the sun and the sky [2].

However, their application in a model for non-visual effects (N-VEs) requires that the spectral characteristics of the various sources (i.e. direct beam, overcast skylight and light from a clear blue sky) be inferred from values in the basic climate data. It also requires new threshold values to be determined, which would be relevant to generating non-visual effects yet would be based on traditional building simulation methods.

INCORPORATING NON-VISUAL EFFECTS

Overall, the proposed approach uses outcomes of photobiology research to define threshold values for illumination in terms of spectrum, intensity, and timing of light at the human eye, and translates these into goals for simulation and, ultimately, into goals for building design.

Relevant findings from the photobiology field

An action spectrum was determined for our non-visual circadian photoreceptor system (melanopsin) by Brainard et al in 2001 [6]. It led to the sensitivity curve illustrated in Figure 1(a) (for now called C(λ)) that peaks in the blue region of the spectrum and is represented alongside our well-known photopic curve V(λ).

On the other hand, threshold photon densities (photons/cm^2 s^{-1} on the retinal surface) have been found to be necessary to have a significant effect on circadian photoreception, and a dose-response curve was determined by Cajochen et al in 2000 for subjective alertness during a prolonged night-time exposure to polychromatic light [9]. This particular study found that a (visual) illuminance of about 300 lux[1] was required to achieve a 100% subjective alertness effect when the light source was fluorescent lighting (4100K) and exposure duration was 6.5 hours. As of yet, very few alertness studies for polychromatic light are available during daytime exposure and none provides a dose-response curve. One daytime study of reference is the one conducted by Phipps-Nelson et al in 2003 [10] that compares the effect on alertness of daytime exposure to bright (1000 lux) and dim (< 5 lux) light for 5 hours, for slightly sleep-deprived subjects and using fluorescent lighting. Unlike previous related studies [11,12] that used higher `dim' light levels (50 lux e.g.), this one reported a significant effect of bright light exposure during daytime, probably due to the combination of having particularly dim comparison levels and having sleep-deprived subjects.

Light timing and exposure history have a critical influence on how the circadian system is stimulated and how the circadian clock is reset or can be slightly shifted, such as to help combat jet-lag for example. Research in this area indicates that the above-mentioned thresholds will be strongly dependent on the duration of light exposure. This discussion being beyond the scope of the present paper and not advanced enough to provide more tangible hypotheses, we will use these thresholds as indicative exposure levels for which one might expect a non-visual effect (alertness increase e.g.) during nighttime and daytime, respectively.

The following sections will describe how these selected findings in the photobiology field can be applied to building simulation and the assessment of the `circadian potential' of a space.

Spectral properties and conversion factors

The spectral properties of the daylight are important because the action spectrum C(λ) for the non-visual photosensitive ganglion cells in the eye is different from the visual sensitivity curve V(λ). Thus, the vertical daylight illuminance assessed at the eye for a person inside a building has to be considered as a set of individual contributions from direct sunlight, diffuse daylight from the blue sky and diffuse daylight from an overcast sky, but also account for the spectral alteration of light when transmitted through glass and when reflected on internal & external surfaces before reaching the eye.

As a first approximation, we will consider that all surfaces and glazings that daylight will encounter are spectrally neutral (grey). While this is obviously a rough assumption, it becomes acceptable if the aim is – like here and in [4] where this point was discussed previously - to build a methodology rather than trying to get to quantitative conclusions. Thus, the calculated vertical illuminance only has to be split into the different daylight ‘sources’ involved because they have a distinct relative spectra. To convert climate-based vertical illuminance calculations into their equivalent ‘circadian-lux’ (based on the C(λ) action spectrum), we use the approach described [4] and illustrated in Figure 1(a). We can then use this relationship to derive preliminary ‘circadian-lux’ thresholds from photobiology findings.

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[1] Based on a visual reading of Fig 5 (left), p. 81 in [10].

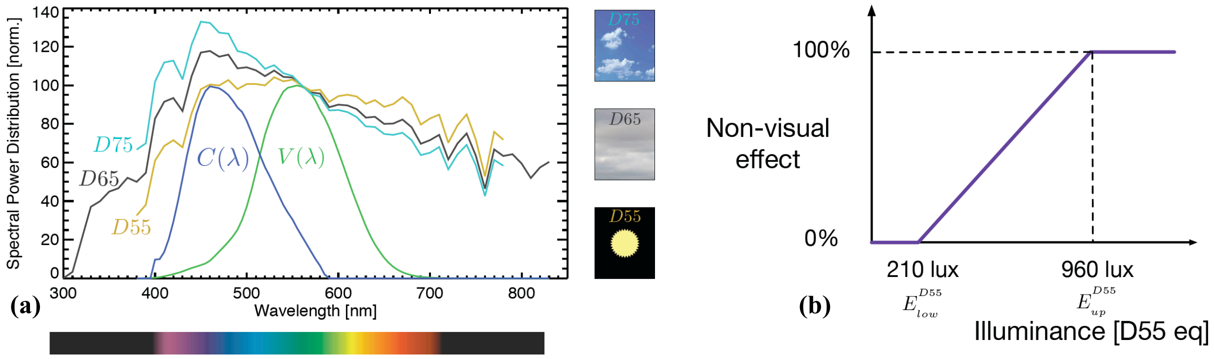

Figure 1: (a) Spectral power distribution for CIE daylight illuminants and sensitivity curves V(λ) and C(λ) (b) Ramp function for likelihood of non-visual effect.

Intensity of illumination

Until these more reliable thresholds are determined, and the duration of exposure is more reliably included, we can prospectively use the dose response curve from the night-time Cajochen study [9] in combination with the daytime Phipps-Nelson results [10] as a lower and an upper bound, respectively, for alertness effects: one can reasonably assume that the illuminance threshold required to have a significant effect on alertness during daytime will be at least as high as what was found out during night-time. On the other hand, one can also reasonably assume that if an effect was found during daytime with a given illuminance, those effects will also be observed with a higher illuminance. One should note that the Phipps-Nelson study was run with slightly sleep-deprived subjects but the argument for now is more on the method than the exact values. In both cases, fluorescent tubes were used as the light source (approximated as Illuminant F7), so we can determine that the threshold for a 100% alerting effect would be equivalent to an illuminance at the eye of 210 lux, 190 lux, and 180 lux for Illuminant D55 (used for sunlight), D65 (used for overcast sky light) and D75 (used for clear (blue) sky light) respectively, based on the 'circadian-equivalent' relationships discussed in [4]. As one would expect, the bluer spectrum corresponds to the lowest equivalent illuminance threshold.

We then have all the data necessary to determine the 'circadian' illuminance with daylight that would be equivalent to 1056 lux of fluorescent (F7) light [4]: we find 960 lux, 870 lux and 830 lux for Illuminants D55, D65 and D75. To avoid having to calculate the equivalent circadian illuminance, and then apply the relevant alertness thresholds independently for overcast sky light, clear sky light and sunlight, we will arbitrarily choose a single light source of reference, and thus consider 210 lux as the lower bound 'circadian' threshold and 960 lux as the upper bound 'circadian' threshold for the Illuminant D55 used to approximate sunlight.

Accounting for the noted uncertainties, a simple ramp-function appears as a reasonable proxy to represent the likelihood that the vertical illuminance at a given point in time and for a given view direction is sufficient to affect the circadian system and have either circadian entrainment and/or subjective alertness effects: low likelihood (0%) below 210 lux and high likelihood (100%) above 960 lux with a linear interpolation between these, as illustrated in Figure 1(b), expressed in terms of D55 equivalent. This and other parameters will be refined with advances in measurements from photobiology studies.

Timing of exposure

The timing of the exposure determines the type of effect and whether it is beneficial or detrimental. Given our incomplete knowledge, the boundaries are 'fuzzy', but nevertheless it is possible to delineate three distinct periods, illustrated in Figure 2(a): early to mid-morning (where sufficient daylight illuminance can serve to 'lock' and maintain a preferred (i.e. healthy) sleep - wake cycle); mid-morning to early evening (where high levels of daylight illuminance may lead to increased levels of subjective alertness); and the rest as notional night-time (daylight exposure that might trigger the N-VE is to be avoided so as not to disrupt the natural wake-sleep cycle). The timing factor includes not only the duration and time of occurrence but also the history, i.e. recent exposure. However we do not know enough yet to warrant the additional complexity of including this factor, so we consider only time of occurrence in isolation of the duration and history of the exposure.

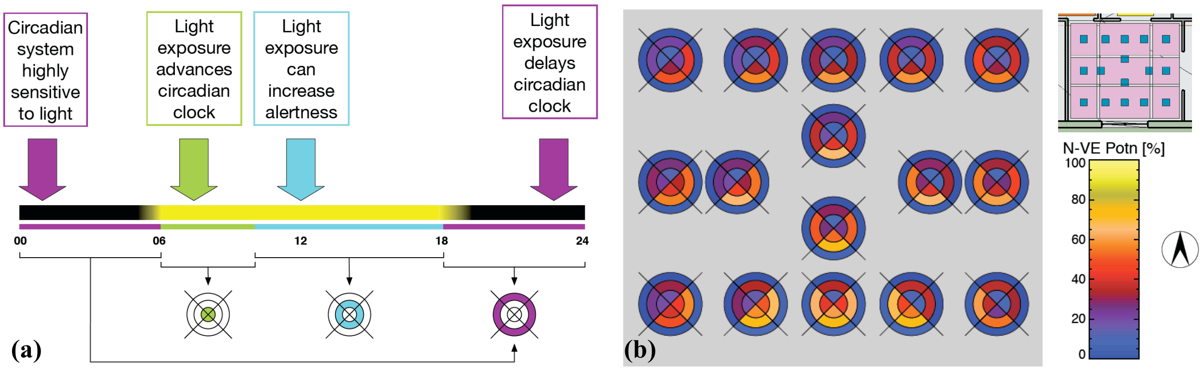

Figure 2: (a) Three day periods according to type of non-visual effect (b) Sombrero plot

Visualizing 'circadian potential'

We present the cumulative N-VE occurring in these three periods using a simple graphical device that we have called the 'sombrero', illustrated in Figure 2(b). The boundaries for the periods were set following the above-mentioned periods of the day: 06h00 to 10h00 (inner circle of the 'sombrero'); 10h00 to 18h00 (middle circle of the 'sombrero'); and, 18h00 to 06h00 (outer circle of the 'sombrero'). The cumulative effect of N-VE for these three periods is apportioned to the respective segments in the three circles according to view direction.

The four quarter-segments of the sombrero indicate the view direction, i.e. to the 'bottom', 'top', 'left' and 'right' according to the inset floor plan. Each ring segment gives the cumulated percentage of that time period across the year for which the circadian potential (likelihood of having an effect) would be achieved for that view direction and at that location.

STUDY RESULTS

The resulting eye-level vertical illuminances predicted on a 15 minute time-step are shown using annual temporal maps in Figure 3(a). The four maps are for the four view directions. Illuminances of 960 lux or greater are shaded white (i.e. 100% likelihood of non-visual effect) and illuminances 210 lux or less are shaded black (i.e. 0% likelihood of effect). Hours of darkness are shaded grey. Although the quantities in the temporal maps and the sombrero are different, they share the same scale (i.e. 0-100%) and false-colour shading.

The lower and right-hand temporal maps represent views away from the corner and directed towards the opposing walls, i.e. 'right' and 'down'. These views look in part towards the window wall and the centre of the room, which, in this case is illuminated by a skylight. These directions show a much greater occurrence of N-VE than the other two view directions (which look away from the middle of the room and into one corner, 'up' not shown here). The pattern is what we might expect. The 'sombrero' plot shows the percentage of the cumulative occurrence of N-VE across the year for each of the three periods described in the previous section. Thus a cumulative value of 40% could represent a full N-VE occurring for 40% of the time, a 40% N-VE occurring for all of the time, or, as is more likely, something in between.

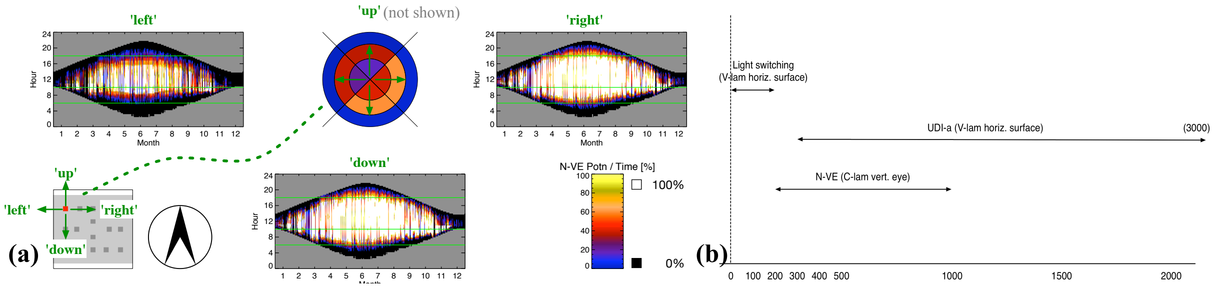

Figure 3: (a) Example time-series (temporal maps) and cumulative occurrence (sombrero) plot for skylit living room in Ostersund. (b) Application ranges for three lighting perspectives.

DISCUSSION

The methodology and initial findings from an exploratory study of three aspects of daylight in a residential building have been described in this paper, with a focus on non-visual effect evaluation that was an extension of the method proposed by Pechacek, Andersen & Lockley [4]. Key enhancements include the concept of a ramp-function from a lower to an upper vertical illuminance threshold, based on photobiology findings, that expresses the increasing potential for circadian effects. Another enhancement is the ability to treat independently light from the sun and sky, thereby accounting for the varying circadian efficiency of the light according to its spectral type, i.e. D55, D65 or D75. And, in terms of data visualization, we introduce the sombrero plot as a simple graphical device to display the cumulative non-visual effect at a point in space and as a function of view direction.

When considered in combination with the other two aspects of daylight – electric lighting savings and visual illumination – we realize that the electric light switching sensitivity is essentially contained within a 0 to 200 lux band, which makes it somewhat separate from UDI or N-VE considerations that both start around 200 lux or more (Figure 3(b)). Relations between UDI-a [7] and N-VE will probably depend on the nature of the daylight illumination (more likely for top-lit situations e.g.). One must however keep in mind that given the very early developmental stage of photobiology in this field, any finding has to be considered as a possible approach to solve the problem rather than as a design guideline.

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