DAYLIGHTING METRICS FOR RESIDENTIAL BUILDINGS

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Abstract

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. 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 reasonably well understood. There is no consensus however on the composition of the metrics, and their formulation is an ongoing area of active research. Additionally, non-domestic and residential buildings present very different evaluation scenarios and it is not yet clear if a single metric would be applicable to both. 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.

Keywords: Daylight, metrics, circadian, photo-biology.

1 Introduction

Design guidelines recommend daylight provision in terms of the long-established daylight factor (DF). Formulated in the UK over fifty years ago, the daylight factor is simply the ratio of internal illuminance to unobstructed horizontal illuminance under standard CIE overcast sky conditions [Hopkinson, 1963]. It is usually expressed as a percentage, so there is no consideration of absolute values. The luminance of the CIE standard overcast sky is rotationally symmetrical about the vertical axis, i.e. about the zenith. And, of course, there is no sun. Thus for a given building design, the predicted DF is insensitive to either the building orientation (due to the symmetry of the sky) or the intended locale (since it is simply a ratio). In other words, the predicted DF value would be the same if the building had north-facing windows in Stornoway or south-facing windows in Brighton. The same would be true if the locations were Seattle and Miami - or indeed for any city in any country. It now appears to be widely accepted that the daylight factor method does not allow for improvement by incremental means (e.g. the ‘clear sky’ options in LEED/ASHRAE) and that significant advancement can only be achieved by considering predictions for absolute values of daylight illuminance founded on realistic meteorological data, i.e. climate-based daylight modelling [Mardaljevic, 2006]. Climate-based modelling delivers predictions of absolute quantities (e.g. illuminance) that are dependent both on the locale (i.e. geographically-specific climate data is used) and the building orientation (i.e. the illumination effect of the sun and non-overcast sky conditions are included), in addition to the building’s composition and configuration. In short, CBDM delivers realistic predictions of absolute daylight quantities (e.g. lux levels) allowing for the prediction of a wide range of performance data that is essentially unachievable using the daylight factor approach.

The primary concern in the daylighting of buildings has generally been to provide illumination for task, e.g. 500 lux on the horizontal work plane. In the last few decades however there has been a gradual increase in awareness of the non-visual effects of daylight/light received by the eye [Webb, 2006]. It is well-known that building occupants almost without exception will prefer a workstation with a view of the outdoor environment to a windowless office [Collins, 1976]. A view to the outside indicates of course the presence of daylight, although the relation between view and daylight provision is not straightforward being dependent on many factors. In addition to subjective preferences for daylit spaces, it is now firmly established that the light has measurable biochemical effects on the human body, in particular with respect to maintaining a healthy sleep - wake cycle. Could the quality and nature of the internal daylit environment have a significant effect on the health of the human body which can proven through the measurement of, say, hormone levels? Evidence is indeed suggestive of links between daylight exposure and both health and productivity [Heschong, 2002].

This study uses a domestic dwelling as the setting to investigate and explore the applicability of daylighting metrics for residential buildings. The metrics address daylight provision for task and electric lighting usage. In addition to these we also investigate the formulation of metrics for non-visual effects. The setting, a residential building with and without skylights, was evaluated for all 32 combinations of eight European climates and four building orientations. Daylight for task was assessed using the useful daylight illuminance schema [Mardaljevic and Nabil, 2005]. Electrical lighting usage was predicted on the basis of typical schedules and daylight availability using the RT 2005 switching model and occupancy scenarios. Although there are uncertainties regarding the precise calibration, there is now sufficient empirical data to parameterise models that 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.

2 Methodology

A residential dwelling was used a 'virtual laboratory' for the investigations described below. The dwelling is based on a real house which has a design commonly found throughout Europe. The following sections describe the 3D model of the building, the configuration of calculation planes and the climate data. Then follows an outline of simulation approach.

2.1 Outline

The 3D model for the residential building is shown in Figure 1. The sensitivity of metrics to daylight design interventions was investigated by predicting for cases with and without skylights - the 3D graphics in Figure 1 show the building with skylights. The coloured areas in the plan view show the horizontal calculation planes where illuminance was predicted. The spaces evaluated were: the living room (wg01); the kitchen (wg02); the entrance hall (wg03); small bathroom (wg04); large bathroom (wg05); and the stairs to the basement (wg06). The calculation planes are at table and work-top height for the living room and kitchen respectively. For the other spaces the calculation planes are at floor level, which for the stairs was the individual steps. General daylighting provision and the requirement for electric lighting were based on daylight illuminance predicted at these planes. Additionally, there are smaller square planes in three of the spaces: sixteen in the living room (wg01); four in the kitchen (wg02); and, one in the larger bathroom (wg05). These represent locations at head-height where vertical illuminance at the eye was predicted for the determination of non-visual effects. At each of these locations, the vertical illuminance was determined for four view directions, i.e. at 90 increments.

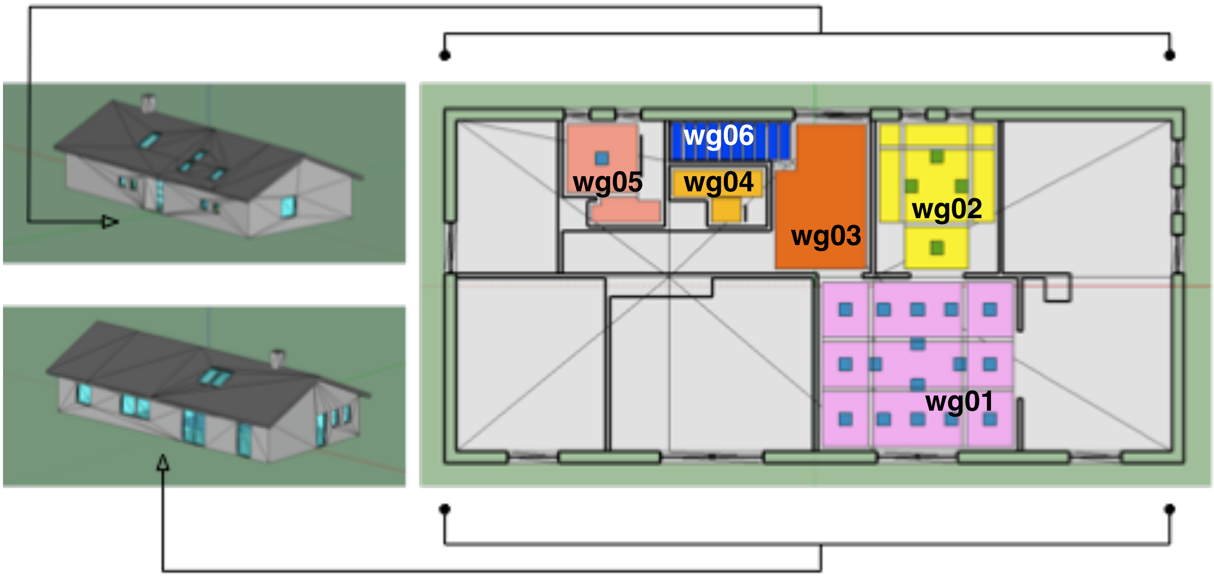

Figure 1. Images of the two main building facades (variant with skylights) together with a plan view showing the calculation planes for the spaces and the smaller, square planes for the N-VE model.

2.2 The climate data

The principal sources of basic data for climate-based daylight modelling are the standard climate files which were originally created for use by dynamic thermal modelling programs [Clarke, 2001]. These datasets contain averaged hourly values for a full year, i.e. 8,760 values for each parameter. For lighting simulation, the required parameters may be either of the following pairs:

- Global horizontal irradiance and either diffuse horizontal irradiance or direct normal irradiance.
- Global horizontal illuminance and either diffuse horizontal illuminance or direct normal illuminance.

Standard climate data for a large number of locales across the world are freely available for download from several websites. One of the most comprehensive repositories is that compiled for use with the EnergyPlus thermal simulation program [Crawley et al., 2001].

The eight locales were Hamburg (Germany), Madrid (Spain), Paris (France), London (UK), Rome (Italy), Warsaw (Poland), Moscow (Russia) and Ostersund (Sweden). The lat/lon coordinates of each city/station and the short name ID given for this study are listed in Table 1. The climate file data used for the simulations was diffuse horizontal illuminance and direct normal illuminance. The pattern of hourly values in a climate dataset is unique and, because of the random nature of weather, they will never be repeated in precisely that way. Climate datasets are however representative of the prevailing conditions measured at the site, and they do exhibit much of the full range in variation that typically occurs. Furthermore, these standard datasets provide definitive yardstick quantities for modelling purposes. The last column in Table 1 gives the number of "sunny" days for each of the climate files. There is no widely accepted definitive definition for the occurrence of a sunny day in a climate file. Here, a sunny day was taken to be one where more than half of the daily total of global horizontal illuminance was due to direct solar radiation. This quantity varied from 49 days (Moscow) to 194 (Madrid) and appears to serve as a sensitive discriminator to summarize the overall degree of "sunnyness" for the climates.

Table 1. The six climate files used in the study.

ID	City/ Station	Country	Latitude	Longitude	"Sunny" days
DEU-Hamburg	Hamburg	Germany	53.63	-10.00	50
ESP-Madrid	Madrid	Spain	40.41	3.68	194
FRA-Paris	Paris	France	48.73	-2.4	64
GBR-London	London	UK	51.15	0.18	71
ITA-Roma	Rome	Italy	41.80	-12.50	107
POL-Warsaw	Warsaw	Poland	52.17	-20.97	53
RUS-Moscow	Moscow	Russia	55.75	-37.63	49
SWE-Ostersund	Ostersund	Sweden	63.18	-14.50	59

The climate file illuminance data for two locations are shown in Figure 2. The original hourly data were interpolated to a 15 minute time-step. The shading in Figure 2 represents the magnitude of the illuminance with zero values shaded light-grey. In the plot for diffuse illuminance the grey area indicates the hours of darkness. Presented in this way it is easy to appreciate both the prevailing patterns in either quantity and their short-term variability. Most obvious is the daily/seasonal pattern for both illuminances: short periods of daylight in the winter months, longer in summer. The hour-by-hour variation in the direct normal illuminance (smoothed by interpolation to a 15 minute step) is clearly visible, though it is also present to a lesser degree in the diffuse horizontal illuminance (i.e. from the sky). The horizontal green lines delineate the different periods in the day for the simulation of non-visual effects, which will be described later.

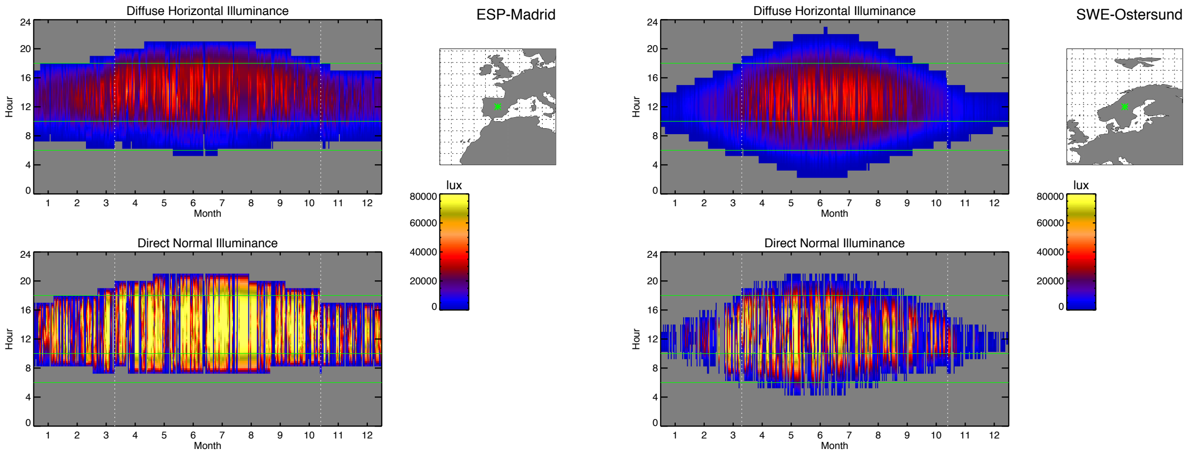

Figure 2. Two of the eight climates: Madrid and Ostersund.

2.3 Climate-based daylight modelling

The term climate-based daylight modelling does not yet have a formally accepted definition - it was first coined in the title of a paper given at the 2006 CIBSE National Conference [Mardaljevic, 2006]. However it is generally taken to mean any evaluation that is founded on the totality (i.e. sun and sky components) of contiguous daylight data appropriate to the locale for a period of a full year. In practice, this means sun and sky parameters found in, or derived from, the standard meteorological data files which contain hourly values for a full year. Given the self-evident nature of the seasonal pattern in daylight availability, an evaluation period of a full year is needed to fully capture all of the naturally occurring variation in conditions that is represented in the climate dataset.

A climate-based analysis is intended to represent the prevailing conditions over a period of time rather than be simply a “snapshot” of specific conditions at a particular instant. Because of the seasonal variation of daylight, the evaluation period is normally taken to be an entire year, although sometimes seasonal or monthly analyses may be required. Analyses may be restricted to include just those hours in the year that cover, for example, the working period. There are a number of possible ways to use climate-based daylight modelling [Mardaljevic, 2000] [Reinhart and Herkel, 2000] [Reinhart et al., 2006]. A cumulative analysis is the prediction of some cumulative measure of daylight (e.g. total annual illuminance) founded on the aggregated luminance effect of (hourly) sky and the sun conditions derived from the climate datset. A time-series analysis involves predicting instantaneous measures (e.g. illuminance) based on all the hourly (or sub-hourly) values in the annual climate dataset. The evaluation described here is founded on an analysis of a time-series of predicted daylight illuminance values across calculation planes in various rooms. The calculation planes were horizontal areas to represent either physical surfaces for specific tasks (e.g. kitchen work-tops) or more generally to characterise the overall daylighting provision of the various spaces. Time-varying daylight illuminance values were predicted at hundreds of points evenly distributed across the horizontal calculation planes. Another set of calculation planes were used for the prediction of daylight illuminance for the non-visual effects (N-VE) model, discussed in section 5. The N-VE model requires as input vertical illuminance at the eye. The horizontal planes used in the N-VE model were 30cm squares located at approximate head height for a seated person. At the points that comprise these planes, the vertical illuminance was predicted, in turn, for four orientations in 90 steps. These squares represent possible locations in the various spaces for an occupant’s head.

3 Daylight metrics

3.1 Useful daylight illuminance: A human factors-based metric

The metric used to evaluate the daylighting provision was the “useful daylight illuminance” (UDI) scheme [Mardaljevic and Nabil, 2005] [Nabil and Mardaljevic, 2005] [Mardaljevic, 2006]. Put simply, achieved UDI is defined as the annual occurrence of illuminances across the work plane that are within a range considered “useful” by occupants. The range considered “useful” is based on a survey of reports of occupant preferences and behaviour in daylit offices with user operated shading devices. Daylight illuminances in the range 100 to 300 lux are considered effective either as the sole source of illumination or in conjunction with artificial lighting. Daylight illuminances in the range 300 to around

3,000 lux are often perceived either as desirable or at least tolerable. Note that these values are based on surveys carried out in non-residential, largely office buildings where daylight-originated glare on visual display devices is a common problem. Many of these surveys were carried out before LCD display panels - which are much less prone to glare than CRT screens - became commonplace. In contrast to office buildings, tasks in the domestic setting are not, of course, largely desk and display screen orientated. Accordingly, the upper limit for preferred/tolerated daylight illuminance used for this study was 3,000 lux. However it should be noted that there is considerable uncertainty regarding preferred/tolerated upper limits for both non-domestic and residential buildings, and that the UDI ranges for this application should be seen as illustrative.

UDI achieved therefore is the defined as the annual occurrence of daylight illuminances that are between 100 and 3,000 lux. The UDI range is further subdivided into two ranges called UDI-supplementary and UDI-autonomous. UDI-supplementary gives the occurrence of daylight illuminances in the range 100 to 300 lux. For these levels of illuminance, additional artificial lighting *may* be needed to supplement the daylight for common tasks such as reading. UDI-autonomous gives the occurrence of daylight illuminances in the range 300 to 3000 lux where additional artificial lighting will most likely not be needed. The UDI scheme is applied by determining at each calculation point the occurrence of daylight levels where:

- The illuminance is less than 100 lux, i.e. UDI 'fell-short' (or UDI-f).
- The illuminance is greater than 100 lux and less than 500 lux, i.e. UDI supplementary (or UDI-s).
- The illuminance is greater than 300 lux and less than 3,000 lux, i.e. UDI autonomous (or UDI-a).
- The illuminance is greater than 100 lux and less than 3,000 lux, i.e. UDI combined (or UDI-c).
- The illuminance is greater than 3,000 lux, i.e. UDI exceeded (or UDI-e).

As noted, the UDI ranges were based on a distillation of values from surveys carried out in office spaces, and many of them before LCD screens became commonplace. Also, the recent findings regarding the role of illumination in maintaining the circadian rhythm suggest that regular exposure to high illuminances during daytime could have long-term beneficial health effects [Webb, 2006]. Webb notes a Japanese study by Noguchi who found that:

…bright lighting in the office (2500 lux compared to 750 lux, provided for 2 hours in the morning and one hour after lunch for several weeks) boosted alertness and mood, especially in the afternoon. It also seemed to promote melatonin secretion and fall in body temperature at night, changes that should improve the quality of sleep. Although this work was based on a small number of people and further work is needed, it shows promise for alterations in office lighting in terms of productivity and health of the workers.

Thus it is suggested here that the occurrence of illuminances greater than 3,000 lux (i.e. UDI-e) should not, by design, be eliminated altogether, and that moderate occurrence may in fact be beneficial. What exactly the "optimum" levels of exposure might be is not yet known. For those cases where solar gain in summer must be controlled to minimise cooling requirements, careful attention should be paid to the degree of occurrence of the UDI-e metric. The findings here will be re-evaluated at a later date to include actions resulting from over-heating predicted by dynamic thermal modelling using the same climate data files..

3.2 UDI and "good" daylighting

Whilst there are no official guidelines or recommendations yet for illuminance levels predicted using climate-based modelling, there is sufficient evidence in the published literature to propose the following:

Good daylighting for task is deemed to be that which offers high levels of useful daylight (i.e. 100 to 3,000 lux), and where a significant part of the occurrence of useful daylight is due to illuminances that fall within the autonomous range (i.e. 300 to 3,000 lux). Furthermore, recent findings regarding the beneficial health effects of occasional high illuminances (i.e. greater than 3,000 lux) suggest that moderate occurrences of UDI exceeded should de considered desirable and not excluded altogether.

Provision of adequate levels daylight illuminance is known to affect the use of electric lighting. For non-domestic buildings a number of studies have found that the switch-on probability is small for desktop illuminances above 250 lux [Hunt, 1979, Reinhart and Voss, 2003]. At present, it is uncertain how these findings for users in office buildings might relate to user behaviour in a domestic setting - this is clearly an area where information is lacking at present. Nonetheless, it is reasonable to suppose that similar behaviour might ensue, and so good levels of daylight illuminances are likely to be associated with lower levels of electric lighting usage. Consequently, the following can be reasonably assumed or stated:

• The switch-on probability will be high for illuminance less than 100 lux (i.e. UDI-e).

• The switch-on probability will reduce from high to low as the illuminances increase from 100 to 300 lux (i.e. that covered by the UDI-s range).

• There is significant variability and associated uncertainty in user switching behaviour over the illuminance range where the probability of switching on reduces from high to low.

Thus, there is reasonable certainty that an illuminance in the UDI-a range (i.e. 300 to 3,000 lux) will *not* result in a switch-on, whereas there is considerable uncertainty regarding the probability of a switch-on event when the illuminance is in the UDI-s range (i.e. 100 to 300 lux). Accordingly, maximization of the occurrence of the UDI-a metric should be taken as the most reliable indicator that the overall level of electric lighting usage (for that space) will be low.

3.3 Example UDI results

Useful daylight illuminance plots are shown for the case without and with skylights for just one climate/orientation combination (Ostersund/000), Figure 3. The time period considered for the UDI plots is 08h00 to 20h00. And so for the Ostersund example this period includes hours of darkness in winter (Figure 2).

The false-colour shading shows the annual occurrence in hours of illuminances in the various UDI ranges that were achieved across the nine calculation planes for this room. The annotation on each calculation plane gives the mean value of the achieved hours across the plane. The addition of skylights significantly increases the occurrence of illuminances in the 300 to 3,000 lux range, which now extend across the planes into the corners of the room. Illuminances greater than 3,000 lux are also predicted to occur more frequently, particularly in the centre of the room.

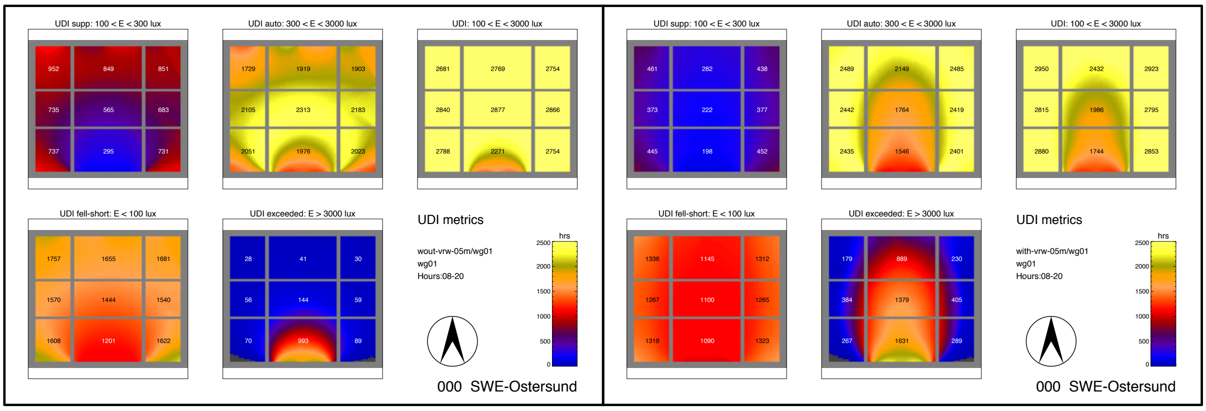

Figure 2. UDI plots for living room without and with skylights (Ostersund climate).

4 Electric lighting model

Building users entering a space where there is little daylight will of course switch on the electric lights. The probability that users switch-on electric lights was found to be correlated with the minimum daylight illuminance on the working plane [Hunt, 1980]. The correlation presented by Hunt in 1980 was based on just a handful of samples and there was considerable scatter in the switch-on probability when the daylight illuminance was in the range 50 to 500 lux, which is typical of the range experienced in many buildings. A later study provided support for the Hunt model, but as with the original study there was large scatter in the measured daylight illuminances that triggered the switching on of lights [Reinhart and Voss, 2003]. In addition to the switch-on probability, there will also be switch-off probabilities. Relatively little field study data has been published regarding switch-off behaviour, and determining a correlation with daylight is more confounding than for switch-on since other factors come into play. For example, switch-off probabilities could be significantly determined by the overall appearance of the space and the particular design of the lights, since it is sometimes not obvious to the occupant that lights have been left on when daylight provision is high. Furthermore, the studies that have been carried out are mostly for non-domestic buildings, commonly office spaces. One of the few domestic models is known as RT 2005 which originated in France.

4.1 The RT 2005 residential model

In the RT 2005 residential model the calculation of consumption in each zone is determined from:

$$Q_z = \frac{P_z C_1 C_2}{1000}$$

The installed lighting power for the zone is P_z. No artificial lighting control other than hand switch is used, which indicates that the coefficient C_1=0.9. The coefficient C_1 corresponds to an average percentage of use of artificial lighting. It is further weighted by a coefficient C_2 which gives the probability of activation of artificial lighting depending on the level natural lighting. It is determined by linear interpolation between the four points given in Table 2.

Table 2 Parameterisation of the C_2 coefficient in the RT 2005 Model.

Daylight illuminance [lux]	Coefficient C_2
0	1
100	1
200	0.05
2,800	0

These points are plotted in Figure 4. The steep fall-off in switch-on probability in going from 100 to 200 lux of daylight is shown using a reduced lux scale in the inset plot. Note that this steep-fall occurs within the UDI-a range, i.e. between 100 and 300 lux. We consider three periods when the lights may be on: 7am to 9am; 9am to 7pm; and, 7pm to 10pm. Rather than present results for particular occupancy patterns, e.g. weekdays and weekends, our intention instead is to delineate overall sensitivities in the model to various input parameters. Here we present results for just the living room (wg01). The basecase occupancy profile for the three periods is [1,0.3,1] i.e. [full occupancy, average 30%, full occupancy]. Additionally, we predict for a case where there is full occupancy for all three periods, i.e. [1,1,1]. Another parameter we investigate is the number and location of 'active planes' - the daylight illuminance on these is used as a potential trigger to switch on electric lights. For the living room there are nine possible planes (Figure 1). The basis of the switching model is that, regardless of the number of active planes, the daylight on the active plane with the *lowest* illuminance is used in the light switching algorithm. The rationale for this model is that the occupant may switch on the lights even though most of the planes may be receiving sufficient daylight provided that there are one or more less well illuminated planes in the space. Here we consider two extremes, the basecase where it is just the daylight on the central plane in the living room that is active, i.e. which is used is the light switching algorithm. The vector describing this is [0,0,0,0,1,0,0,0,0]. And another where all nine planes participate in the switching, i.e. [1,1,1,1,1,1,1,1,1]. Thus there are four combinations of occupancy schedule and number/location of active planes. We would expect that, with increasing occupancy and having a greater number of active planes, both of these would lead to a greater use of electric lighting, and, potentially a greater saving resulting from increased daylight provision (i.e. from the addition of a skylight).

4.2 Potential lighting energy savings due to addition of a skylight

The potential for increased daylight provision from a skylight to save electric lighting energy was determined as follows. The distribution in daylight illuminance across the nine calculation planes in the living room was predicted at a 15 minute time-step for a full year. Approximately 10,000 calculation points were used to represent the nine planes. This was done for all 64 combinations of eight climates, four building orientations and two building types (i.e. with and without skylights). At each time-step, the mean daylight illuminance across each calculation plane was determined from the collection of points that comprise each plane. Next, the coefficient was determined using the smallest of the mean illuminances for all the active planes considered, i.e. for the results here, either just the central plane or all nine. The instantaneous electrical power was determined using Equation 1 and stored. The annual electric power consumption for electric lighting in this space was determined for all 32 combinations of climate and orientation, and for cases with and without skylights. The potential to save electric lighting energy is simply the difference between the with and without skylight cases.

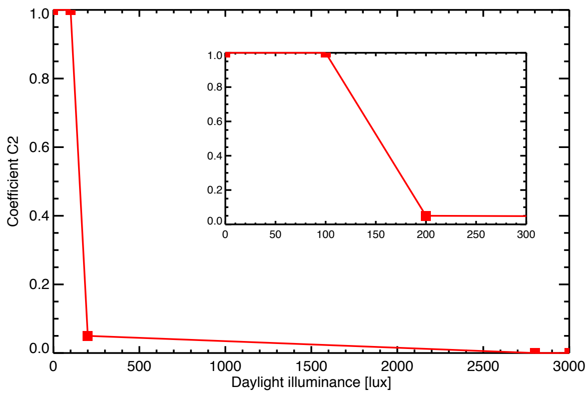

Figure 4: Electric light switch-on probability as a function of daylight illuminance

The results are shown in Figure 5. As noted in the previous section, there are four scenarios covering the combinations of two occupancy profiles and two arrangements for active planes used in the switching model. For each of these scenarios, there are 32 predictions of energy saving covering all the combinations of climate and building orientation. The energy saving predictions for each scenario are presented as a set of points along a horizontal line. For this stage in the study we are interested primarily in the range of predicted savings rather than wishing to note the identity of any particular case.

For the first scenario S1 (i.e. minimal occupancy profile and using only the central plane for switching), the predicted saving ranges from 11.6 to 28.6 kWh/yr. For the next scenario S2 the range is 17.6 to 38.8 kWh/yr. For S3 the range is 25.1 to 55.3 kWh/yr and, lastly, for S4 it is 39.0 to 77.6 kWh/yr.

The predicted energy saving due to illumination provision from a skylight is shown to be highly sensitive to the occupancy schedule and the consideration of surfaces used to trigger light switching (i.e. the number and location of active planes). In addition to a consistent pattern showing a steady increase in the overall saving (in progressing from scenario S1 to S4), there is also a widening of the range of predictions within each scenario, i.e. a consequence of the variations in daylight provision due to the different climates and building orientations. For S1 the size of the range is 17.0 kWh/yr, but for S4 it is 38.6 kWh/yr.

5 A simulation model for non-visual effects

The daily cycle of day and night plays a major role in regulating and maintaining biochemical, physiological, and behavioural processes in human beings. This cycle is known as the circadian rhythm - the term “circadian” comes from the Latin circa, “around”, and diem or dies, “day”, meaning literally “approximately one day”. Circadian rhythms occur in almost all organisms from bacteria to mammals. The circadian rhythm is endogenous meaning that it is produced from within the organism, i.e. what is commonly referred to as the ‘body clock’. However for many organisms the cycle needs to be adjusted or entrained to the environment by external cues, the primary one of which is daylight.

The primary circadian “clock” in mammals is located in the suprachiasmatic nucleus (or nuclei) (SCN), a pair of distinct groups of cells located in the hypothalamus. The SCN receives information about illumination through the eyes. The retina of the eye contains not only the well-known photoreceptors which are used for vision (i.e. rod and cones) but also ganglion cells which respond to light and are called photosensitive ganglion cells. The SCN in turn coveys signals to the pineal gland, which, in response, controls the secretion of the hormone melatonin. Secretion of melatonin peaks at night and ebbs during the day; its presence modulates the wake/sleep patterns [Lockley and Dijk, 2002, Wehr et al., 2001].

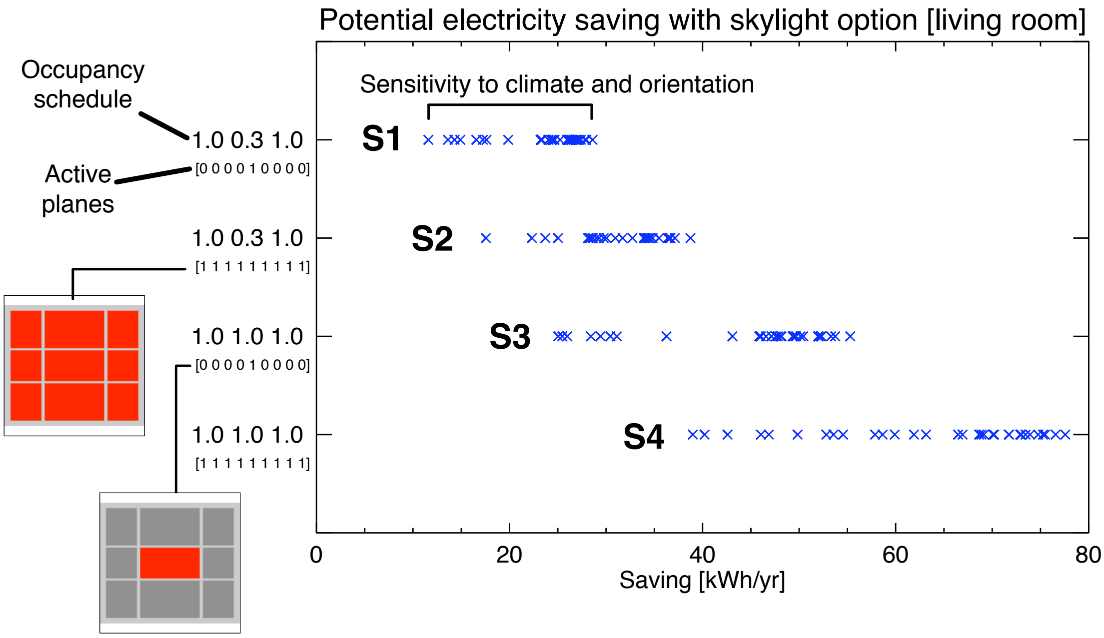

Figure 5: Sensitivity in predicted lighting energy saving (living room) across all combinations of climate and orientation for four scenarios. In the inset graphics for the calculation planes, the two combination of active planes are illustrated (i.e. 1 = red = active).

The failure to maintain a circadian rhythm that is firmly entrained to the natural 24 hour cycle of daylight results in many negative health outcomes for humans, though not all are fully understood. The degree and severity of the outcomes usually depends on the period over which the cycle is disturbed. A transitory disturbance to the circadian cycle familiar to many who have experienced a long-haul flight is jet-lag. When traveling across a number of time zones, the body clock will be out of synchronisation with the destination time, as it experiences daylight and darkness contrary to the rhythms to which it has grown accustomed. Depending on the individual it can take a few days to re-set the body clock to the local day - night cycle [Lockley, 2008].

Less immediately obvious in its effects than jet-lag is the chronic persistence of a poorly entrained circadian rhythm [Lockley, 2008, Veitch et al., 2004]. This was first noticed in shift-workers, however it is believed to be one of the factors in the increasing occurrence of sleep-disturbance and related conditions in the wider population of the developed world [Boyce et al., 1997]. Whilst the symptoms of sleep-disturbance can be at first mild, e.g. sleepiness, fatigue, decreased mental acuity, etc., the long term persistence of the condition may result in significant impacts on both health and worker productivity [Mills et al., 2007] [Viola et al., 2008] [Wilson, 1972] [Walsh et al., 2005, Beauchemin and Hays, 1998] [Riemersma-van der Lek et al., 2008].

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, and thus a key factor in the entrainment of the circadian cycle, Figure 7(a). Another important factor is the time of day when the light is applied. Inadequate light exposure can disrupt normal circadian rhythms and have a negative effect on human performance, alertness, health or safety.

Daylight often provides illuminances significantly higher than the design level, though this is only in close proximity to windows and perhaps also highly daylit spaces such as atria. If the typical illuminances in these zones are high - but not so great that blinds are needed - then those building users that regularly occupy the well-daylit spaces may perhaps experience stronger and more regular circadian entrainment stimuli than those users away from windows who are habitually exposed to lower illuminance levels at the eye. These considerations have resulted in the notion that a building through its daylighting may possess a *circadian efficiency* [Pechacek et al., 2008]. Given the current state of knowledge, it needs to be understood that the process of determining this 'circadian efficiency' is more one of carefully considered judgement than commonly agreed procedure. Notwithstanding this caveat, a workable schema was devised by Pechacek under the supervision of Andersen (then at MIT) together with the assistance of Lockley from the Division of Sleep Medicine, Harvard Medical School, Boston [Pechacek et al., 2008].

Given the evident limitations in delivering significant amounts of daylight from vertical windows more than a few metres into a deep-plan space, it is plausible that residential dwellings and lo-rise buildings with some form of top-lighting (e.g. skylights) have a greater potential to achieve the daylight illuminance levels at the eye required for non-visual effects. While no actual recommendations can - or should - yet be made because of our limited understanding of the effects of exposure to light on human health and circadian organisation, especially during daytime, the relevance of some critical design parameters on the perceived light spectrum, intensity and duration is certainly a topic of investigation. Now is also the right time to start developing calculation methods and simulation workflows that would allow us to extract circadian-relevant information from traditional, vision-based building simulation results. From there, the light exposure and timing influenced by design and environmental factors such as opening size and orientation, climate type, or dominant view directions can be evaluated prospectively. The components of a model to predict non-visual effects for daylight exposure are given in the schematic shown in Figure 6.

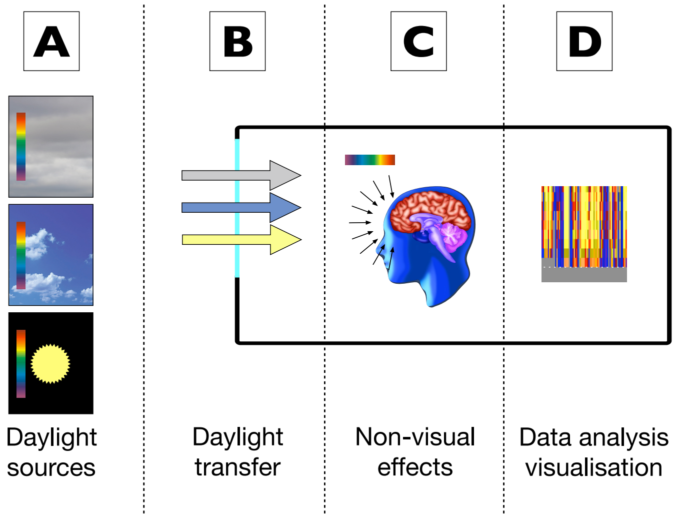

Figure 6: Components of a simulation model for non-visual effects

The first two components of the model have already been largely covered in previous sections. The daylight sources are the standardised climate files. However, their application in a model for N-VE requires that the spectral characteristics of the various sources (i.e. direct beam, overcast skylight and light from a clear blue sky) are inferred from values in the basic climate data. It is possible to approximate the spectral composition for these daylight sources - this will be described shortly. The light transfer component of the model is that which determines the vertical illuminance at the eye resulting from instantaneous sky and sun conditions derived from the climate data. This is achieved using a modified version of the climate-based daylight simulation approach already described.

The following sections will expand on the other two components: the model for non-visual effects and the data analysis/visualisation procedures required to meaningfully present and interpret the results.

5.1 Relevant findings from photobiology research

Our 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 perhaps, ultimately, into goals for building design.

Compared to the luminous efficiency function of the eye which has a peak value at 555 nm, the action spectrum for the suppression of melatonin is known to be shifted to the blue end of the spectrum and has a peak around 450 nm [Brainard et al., 2001]. This is illustrated in Figure 7(b). The C(λ) curve is based on that derived by Pechacek, Andersen & Lockley [Pechacek et al., 2008].

On the other hand, threshold photon densities (photons/cms 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 night-time exposure to polychromatic light [Cajochen et al., 2000] (most other studies were based on monochromatic light exposure). This particular study found that a (visual) illuminance of about 300 lux was required to achieve a 100% subjective alertness effect when the light source was fluorescent lighting (4100K).

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 that conducted by Phipps-Nelson *et. al.* in 2003 [Phipps-Nelson et al., 2003] which compares the effect of daytime bright (1000 lux) and dim (<5 lux) light on alertness. The latter was assessed through measures of subjective and objective sleepiness for subjects slightly sleep-deprived, and also used fluorescent lighting. Unlike previous related studies [Badia et al., 1991] [Lafrance et al., 1998] 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 sleep-deprived subjects.

The next sections describe how these selected findings in the photobiology field have been applied to building simulation and the prospective assessment of the 'circadian potential' of a space.

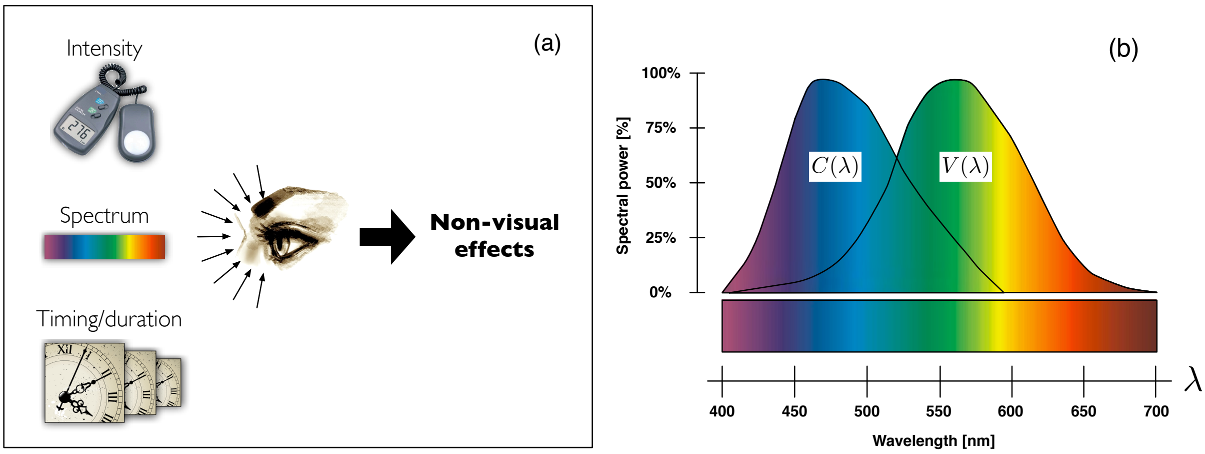

Figure 7: Factors influencing the non-visual effects of daylight (a), and the spectral responses of visual system, i.e. photopic curve $V(\lambda)$, and circadian system, i.e. melanopsin action spectrum $C(\lambda)$ (b).

5.1.1 Illumination spectrum

To determine light levels relevant to our circadian photoreception system (as opposed to our visual system), we need to convert climate-based vertical illuminance calculations, that are derived from our visual system's sensitivity curve $V(\lambda)$, into their equivalent 'circadian-lux', based on the $C(\lambda)$ action spectrum illustrated in Figure 7. In other words, assuming one can calculate the illuminance at the eye - expressed in (visual) lux - independently for overcast sky light, sunlight and clear sky light (which is how the climate-based simulation used here operates), then one can also determine an equivalent 'circadian' illuminance using the approach described by Pechacek *et. al.* [Pechacek et al., 2008] and illustrated in Figure 8. This conversion comes down to determining the 'circadian' efficacy of light, starting from a known illuminance and relative spectral distribution and thus being able to define an absolute radiometric spectrum. By multiplying the latter by the 'circadian' sensitivity curve $C(\lambda)$ discussed above, one can extract a 'circadian-lux' value. The normalization factor (683 lm/W for photometry) is considered equal to 1 for lack of a standardized value.

As a result, one can account for the greater 'circadian' efficacy of, say, 1000 lux of diffuse light from a clear blue sky compared to 1000 lux of light from the sun. As already noted, it is possible to infer sky model type (e.g. overcast, intermediate, clear) from diffuse horizontal and direct normal illuminance in the climate data. It then becomes possible to categorise the daylight into three distinct sources and approximate each of these to a CIE standard illuminant. Thus solar beam radiation is approximated to D55, overcast sky to D65 and light from a clear blue sky to D75. For the analysis reported here, we consider the reflecting surfaces (e.g. walls, floor, ceiling, ground, etc.) and the glazing elements to be achromatic, i.e. the spectral properties of the light are not modified by reflection or transmission. This seems a reasonable approximation for spaces with a neutral decor.

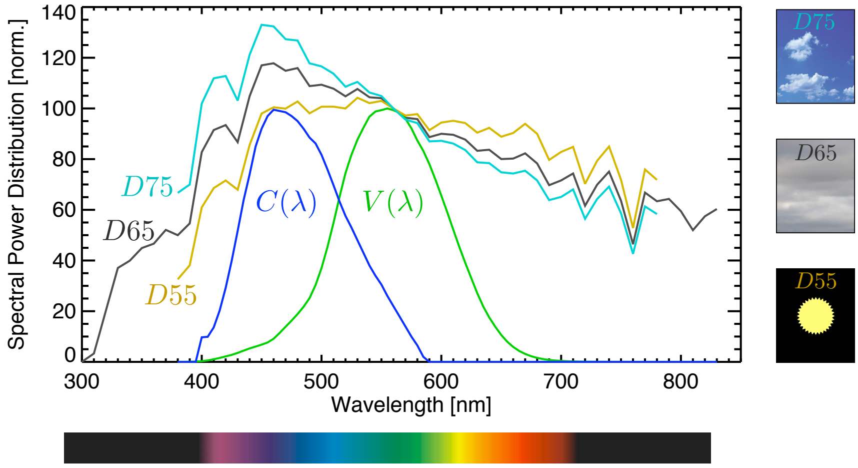

Figure 8: Spectral power distribution for the three daylight sources with photopic and circadian system curves.

5.1.2 Intensity of illumination

Figure 9 shows the number of lux that, based on the $C(\lambda)$ efficacy curve and the method described above, a given value of (visual) illuminance for a specific source would correspond to for another source: for example, 190 lux of Daylight Illuminant D65 would correspond to 700 lux of 555nm LED light in terms of circadian effectiveness. This figure also shows how subjective alertness would correlate with illuminance thresholds (based on the night-time study by Cajochen *et. al.* [Cajochen et al., 2000]), depending on the light source.

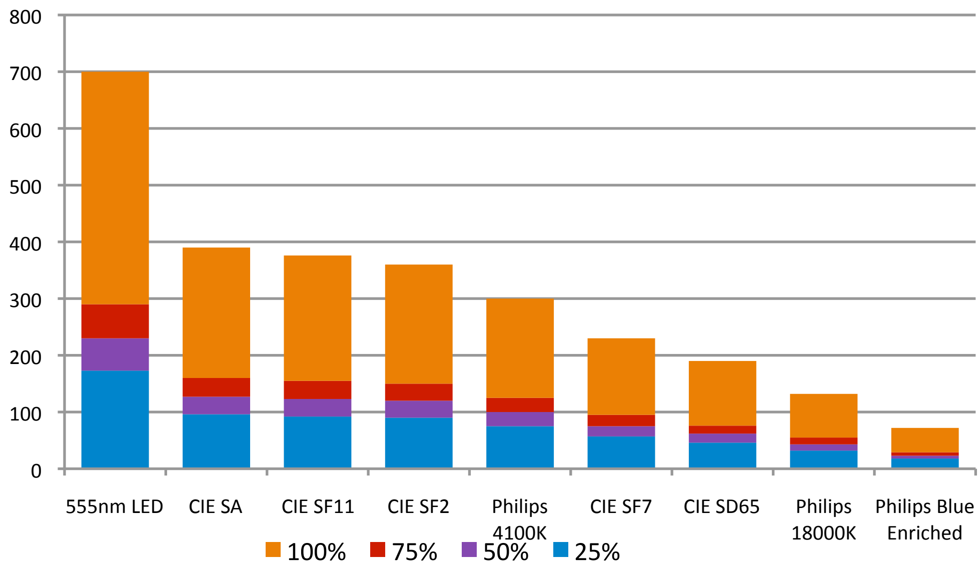

Figure 9: Circadian-equivalent illuminances for a selection of light sources.

While it is too early to derive any reliable illuminance threshold for alertness from the night-time and daytime studies published so far, we already know that daytime 'circadian-lux' thresholds are likely to be determined in the future in association with subjective and objective alertness, as well as other physiological and health effects.

Until these more reliable thresholds are determined we can prospectively use the dose response curve from the night-time Cajochen study [Cajochen et al., 2000] in combination with the daytime Phipps-Nelson results [Phipps-Nelson et al., 2003] 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: Philips Color 840 4100K fluorescent tubes in the former study and Thorn 2L (36 W) tubes in the latter.

We find out 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 [Pechacek et al., 2008]. As one would expect, the bluer spectrum corresponds to the lowest equivalent illuminance threshold.

The Phipps-Nelson study used a mean eye illuminance of 1056 lux as the bright light condition to evaluate daytime alerting effects. We do not have spectral data for the particular fluorescent tubes that were used but can assume that they approximate the Illuminant F7 (Daylight Fluorescent) reasonably well (given that the thresholds themselves require further photobiology research, it actually does not really matter how precise the spectrum is). 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 [CIE, 2006]: 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. Given the noted uncertainties, a simple ramp-function appears as a reasonable proxy to represent the likeliness that the vertical illuminance at a given point in time and for a given view direction is sufficient to affect the circadian system: zero effect at a lower bound of 210 lux and full effect at an upper bound of 960 lux with a linear interpolation between these, Figure 10. We use this function this for both non-visual effects, i.e. circadian entrainment and subjective alertness. Note that the illuminance is in terms of D55 equivalent, as noted above.

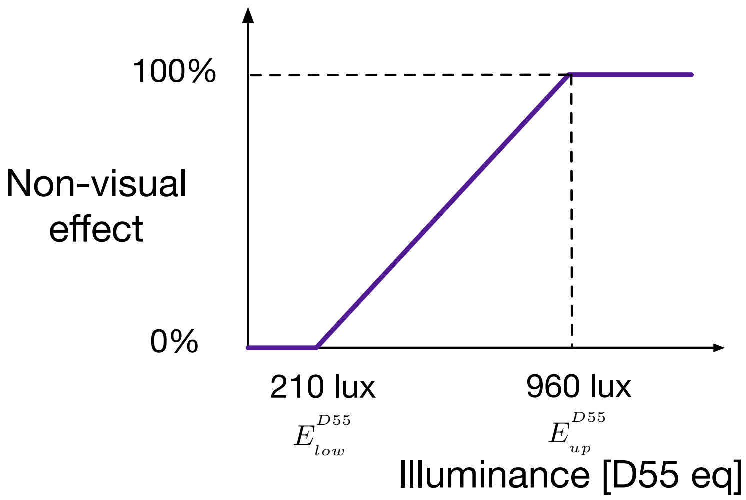

Figure 10: Schematic showing ramp-function for non-visual effect.

5.1.3 Timing factors for illumination

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: early to mid-morning; mid-morning to early evening; and the rest as notional night-time, Figure 11. In the early to mid-morning period, sufficient daylight illuminance can serve to ‘lock’ and maintain a preferred (i.e. healthy) sleep - wake cycle. From mid-morning to early evening high levels of daylight illuminance may lead to increased levels of subjective alertness. For the remainder of the day (mostly hours of darkness) 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.

We present the cumulative N-VE occurring in these three periods using a simple graphical device that we have called the 'sombrero'. The boundaries for the periods were set as follows: 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 use of the sombrero plot is further explained below.

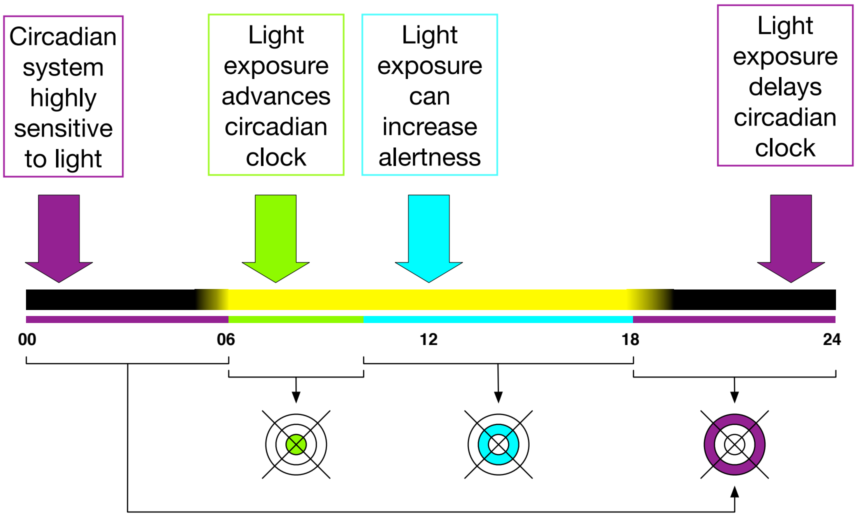

Figure 11: The day is divided into three periods according to type of non-visual effect. The cumulative occurrence of the degree of N-VE determined for each of these periods is represented using the 'sombrero' plot.

5.2 Example output

Using the model described above, the magnitude of the non-visual effect produced by daylight illumination at the eye was predicted at a number of locations in the living room for the entire year at a 15 minute time-step, and for four horizontal view directions at 90 increments. This was done for all 64 combinations of climate, building orientation and building type. Example output showing both the time-series (temporal maps) and cumulative occurrence (sombrero) plot for one location in the living room is given in Figure 12. The small inset graphic in the figure shows the position in the room of the calculation plane (red square) and the arrangement of the four temporal maps corresponds to the view directions illustrated by the green arrows. In the temporal maps, the instantaneous magnitude of N-VE is shown as a percentage, i.e. 0% = zero N-VE (black shade), 100% = full N-VE (white shade) and false colour for values between 0 and 100%. 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 (Figure 1). 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. 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.

The same 0-100% false-colour scale as for the temporal maps is used to shade the 'sombrero' plot. The following can be determined from the plot. For the 06h00 to 10h00 period (inner circle - syncing of circadian clock), the cumulative N-VE at this location was approximately 40% for the views 'right' and 'down'. Because the shaded value in the 'sombrero' plot is a cumulative measure, it 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. For the other two view directions the cumulative N-VE is around 20% each for both.

For the 10h00 to 18h00 period (middle circle), the cumulative N-VE for illuminances that promote subjective alertness is around 60% for the views 'right' and 'down', and just under 40% for the other two view directions. For the 18h00 to 06h00 period, the cumulative N-VE is less than 3% for the views 'right' and 'down' and less than 1% for the other two views.

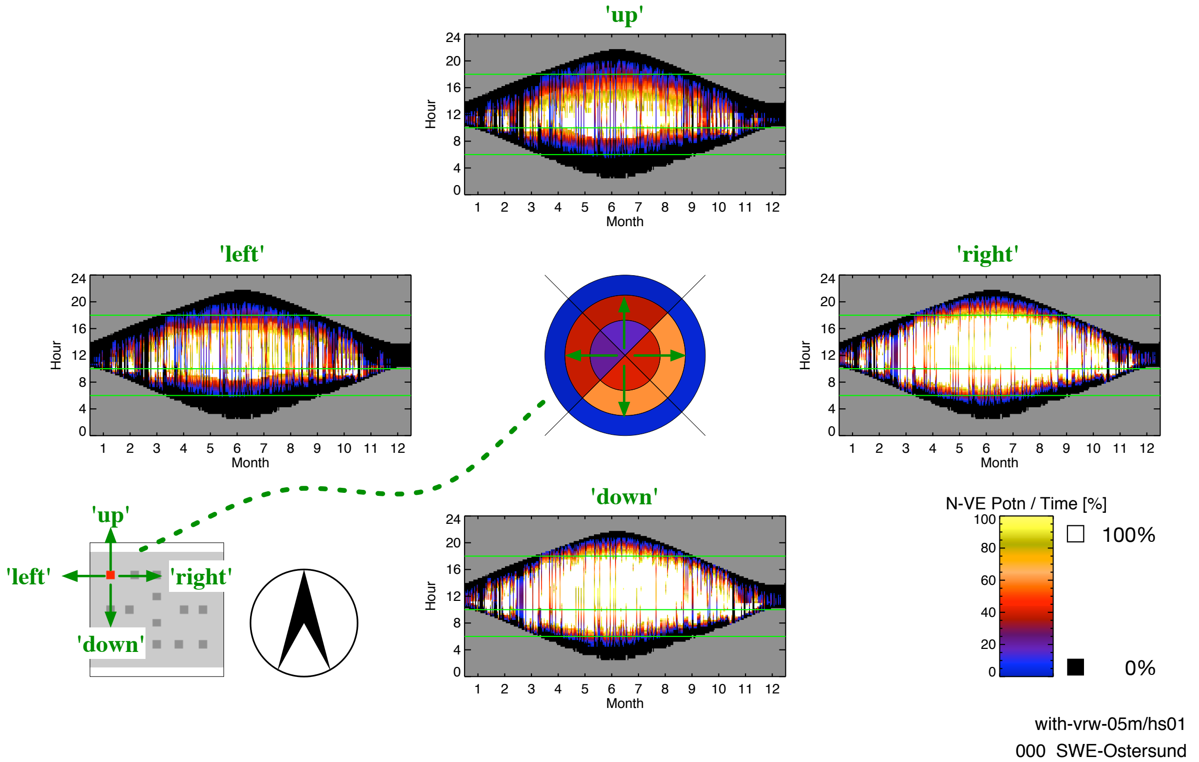

Figure 12: Example output showing both the time-series (temporal maps) and cumulative occurrence (sombrero) plot for the living room with skylight. The Ostersund (Sweden) climate file was used and the building had the default orientation 000 (i.e. north at the 'top').

We shall not dwell on small numerical differences in predicted cumulative N-VE, rather our intention in this initial paper is to reveal using graphical means significant differences in cumulative N-VE due to various factors, e.g. the addition of a skylight. For example, in Figure 13 we compare the predicted cumulative N-VE for the cases without and with skylights for the Ostersund (Sweden) climate (building orientation as indicated in the figure). Comparison of the two cases gives an immediate impression of the potential of the space to produce illuminances which have a non-visual effect. For the case without skylights, the degree of N-VE is greatest for those view points/directions located closest to and directed towards the (external) window. The case with skylight shows a greater cumulative N-VE for all locations, and with less of a preference for those views directed towards the window.

6 Discussion

The methodology and initial findings from an exploratory study of three aspects of daylight in residential building have been described. The overall daylight provision for task was assessed using the useful daylight illuminance scheme. Originally devised using data from studies of non-domestic buildings, the UDI approach is effective in disclosing the consequence of daylight design interventions such as the addition of skylights. The boundary values for UDI are not fixed and it is possible that, for residential dwellings, the tolerated upper limit may be higher than that indicated from studies of office buildings. Also, it is quite likely for residential buildings that overheating rather than excessive daylight might be the more common trigger that results in the closing of blinds. An exception may be when the watching of TVs, home cinema screens, etc. causes the blinds to be closed on largely visual considerations.

The most comprehensive set of results presented in this paper are for the potential lighting energy saving due to the addition of a skylight. The results show a marked sensitivity to assumptions regarding the occupancy profile and the selection of active calculation planes to trigger the switching of lights. Regardless of those assumptions, the effect of climate and building orientation for any one scenario accounts for approximately a factor two difference between the highest and lowest predicted energy saving.

The model of non-visual effects presented here is an extension of that described by Pechacek *et. al.* [Pechacek et al., 2008]. Key enhancements of the previous implementation 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. The sombrero plot provides a means of representing cumulative data which has properties of position (i.e. multiple plots can be used to show the distribution across a space) and view direction, in addition to showing the effect for the three different periods over a full year.

The field of circadian daylighting in architecture is a new one. Because photometric quantities such as lumens are keyed to visible light rather than circadian-sensing blue-shifted-light, they are not useful to determine if a space has sufficient light of the correct spectrum for circadian realignment without considerable calculations. The proposed approach aims to lead to a better understanding of the relative effect of certain design decisions on the overall 'circadian potential' of a space. 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.

The next stage in developing the analysis begun here is to determine what, if any, relation exists between the three measures predicted here. Here are some of the questions/issues that will be addressed in follow-on work:

• Is it possible for one measure to act as a proxy for others? For example, could the UDI schema be refined to act as a proxy for lighting energy usage, or even N-VE?

• As far as broad trends are concerned, do the measures work in concert or in conflict? For example, is it desirable to select building designs that offer the potential of high levels of N-VE for occupants, or might that result in the over-provision of daylight causing undue visual discomfort and overheating?

• Because the N-VE model requires the prediction of vertical illuminance at the eye, it will be a relatively straightforward matter to predict measures of visual discomfort that rely only on this quantity. Furthermore, it may be possible to use the individual components of vertical illuminance at the eye to estimate (directly visible) source luminance, and so allow computation of glare metrics such as DGP [Wienold and Christoffersen, 2006].

Despite its length, this paper presents just a small sample of the the results that were generated. One of the end-products of this study will be an atlas of daylighting performance showing the sensitivity of the various metrics to building design and climate parameters.

Acknowledgements

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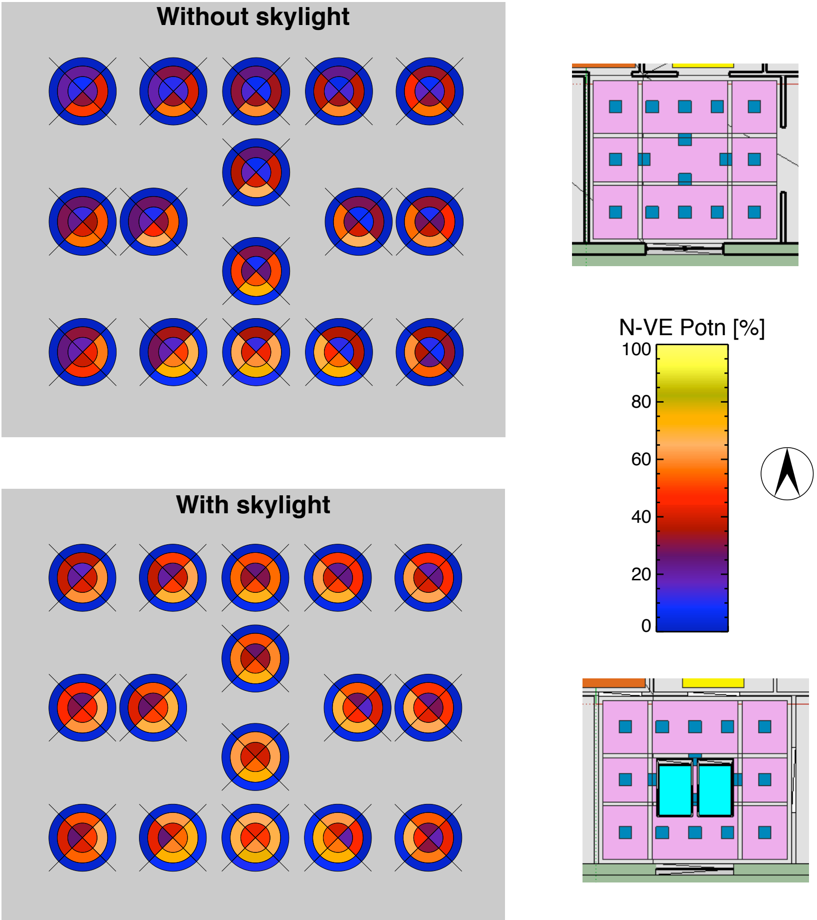

Figure 13: Predicted cumulative N-VE for case without and with skylights (Ostersund/000)..

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