Assessing melanopic equivalent daylight illuminance in office spaces using a simplified approach for predominantly cloudy climates

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Daylight is essential for circadian entrainment, yet current daylighting metrics and guidance do not address this aspect. Latest recommendations for light exposure suggest a daytime melanopic equivalent daylight illuminance (EDI) of 250 lux at the eye. This paper investigates the feasibility of these recommendations using daylight data from Watford, England, and computer modelling in example offices achieving the minimum and high levels of recommendation in EN17037. In predominantly cloudy climates it is impractical to require a specific melanopic EDI every day of the year. Instead, it is more feasible to aim for a certain number of daily hours on a given proportion of annual days. This paper evaluates a metric of achieving four hours with 250 lux melanopic EDI on 90% of annual days. Daylight may be sufficient for circadian entrainment in spaces that meet the high level of recommendation in EN17037 and if facing unobstructed windows. However, facing large windows can cause glare. It is easier to achieve 250 lux melanopic EDI over any four hours throughout the day than just in the morning, although this may not guarantee adequate circadian entrainment. Balancing daylight provision targets and daylight levels for circadian stimulation while limiting glare from daylight is challenging.

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1. Introduction

There is growing evidence of the non-visual effects of light, and the CIE has recently introduced the concept of 'integrative lighting' as lighting aimed at producing beneficial physiological and psychological outcomes, encompassing both visual and non-visual effects.[1] This approach aims to enhance well-being, health, and performance by considering how light impacts not only vision but also circadian rhythms and overall biological functions.

Much recent research has focused on the impact of light on circadian rhythms and human health.[2] In humans the circadian clock, or body clock, regulates the body's internal processes to the time of day. This controls not just sleep and alertness, but core body temperature, metabolism, hormone secretion, cardiac function, and ageing.[3] The master clock, or pacemaker, is located in the Suprachiasmatic Nucleus (SCN) of the brain's hypothalamus.[4] Most research suggests that light exposure is the key driver affecting circadian rhythms regulated by the SCN.[5]

In addition to the photoreceptor (rod and cone) cells which allow normal sight, the retina contains special cells, intrinsically photosensitive retinal ganglion cells (ipRGCs). ipRGCs produce a photopigment, melanopsin, which transmits signals to the SCN. These signals enable light resetting (entrainment) of the circadian clock to adjust it to the solar cycle, and to synchronise individual cell clocks. Therefore, light exposure is widely accepted as the major time cue, or 'zeitgeber', to synchronise the circadian system.[6] Melatonin is a key hormone linked with the 24-hour light-dark cycle. It is produced by the pituitary gland of the brain in conditions of darkness to regulate sleep-wake patterns. Melatonin is believed to influence regulation of several physiological functions, including glucose homeostasis, insulin secretion and energy metabolism,[7] and to inhibit breast cancer development.[8] In the complete absence of light, circadian clocks run slightly longer than 24 hours a day, which causes a daily slight delay in waking and sleeping.[9] A consistent pattern of light and dark acts as a zeitgeber to enable synchronisation of circadian clocks to the solar day so that waking and sleeping can occur at consistent times.[10]

Providing daylight in buildings can help to regulate circadian rhythms, resulting in improved sleep, mood, and overall health.[2,11,12] Compared to many electric light sources, daylight is relatively rich in blue wavelengths (as shown in Figure 1). ipRGCs are most sensitive to light at 460 to 480 nm, whilst melatonin suppression occurs most strongly between 446 and 477 nm,[13] and these wavelength ranges are in the blue light area of the spectrum. Thus, daylight can be particularly effective as a means of regulating circadian rhythms. Additionally, exposure to daylight has been shown to decrease subjective sleepiness and increase alertness[14,15] and to reduce production of the stress hormone cortisol.[16,17]

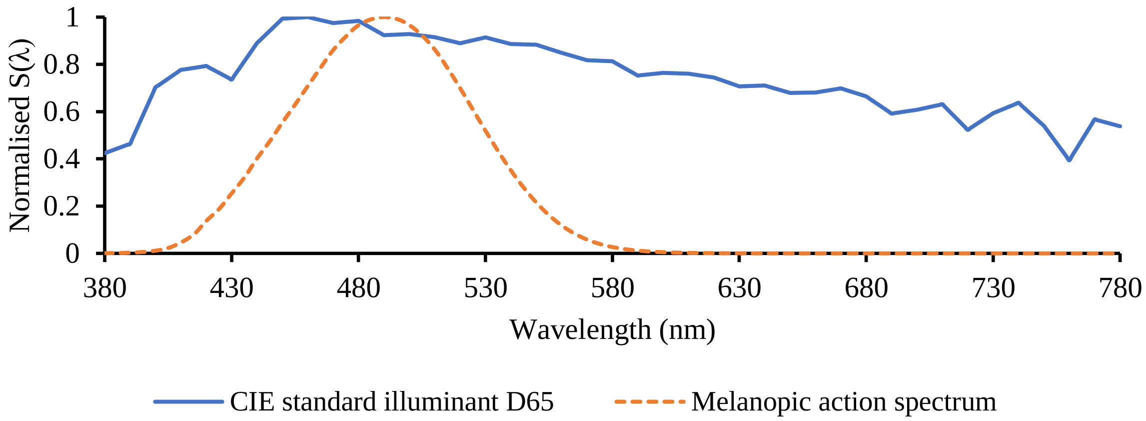

Figure 1. Normalised spectral power distribution of the CIE standard illuminant D65 (6500K daylight) based on ISO/CIE 11664-2:2022 ‘Colorimetry – Part 2: CIE standard illuminants’[18] and melanopic action spectrum based on CIE S 026 Toolbox.[19]

Boubekri et al[20] found that occupants of windowless indoor spaces receive less light overall and report a lower amount and quality of sleep compared with occupants of daylit spaces. Studying young adults in a school in North Carolina, Figueiro and Rea[21] determined that the onset of melatonin can be delayed by removing short-wavelength light during the morning. Delayed melatonin onset can reduce the sleep amount in adolescents that need to wake up early for a fixed school schedule, which in turn may lead to poorer academic performance.

The daylight available to occupants of typical buildings may not be sufficient for circadian stimulation and can vary significantly during annual occupancy hours in terms of both the amount and spectral characteristics. A study by Acosta et al[22] showed how the level of biological stimulation for occupants can be impacted by daylight penetration into single aspect, deep plan spaces. The study confirmed that circadian stimulation levels are highest in areas near the windows and decrease progressively away from the windows. In a study on people working in a three-storey office building designed for daylight maximisation, Figueiro and Rea[23] found that individual light exposure and circadian stimulation were higher during the summer and during the working day, which coincided with significant increases in sleep quantity and quality during those periods.

1.1. Metrics for circadian effects of light

Over the last decade or so, various sets of metrics have been proposed by researchers to address the response of the human circadian system to light. Quantitative measures have been developed to represent the effective circadian stimulus.

Researchers at the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute have proposed circadian stimulus (CS) to quantify the effectiveness of circadian light, or the spectrally weighted irradiance at the cornea specific to the human circadian system as opposed to the visual system, as measured by acute melatonin suppression after a one-hour exposure.[24] Rea[25] also proposed replacing the photopic spectral luminous efficiency function V(λ) with the universal luminous efficiency function U(λ), which is a broader luminous efficiency function meant to represent the full range of retinal sensitivity to electromagnetic radiation associated with all photoreceptor types in the retina (S-cones, M-cones, L-cones, rods, and ipRGCs).

Lucas et al.[26] developed a weighting function (action spectrum) for the ipRGCs and a tool for light measurement that uses photoreceptor sensitivity weighted illuminances expressed in α-opic lux such as, for example, equivalent melanopic lux (EML) for the melanopsin containing ipRGCs. In order to accord with SI units, the CIE standard S 026/E[27] introduced an α-opic metrology based on spectral sensitivity functions for each of the five types of retinal photoreceptor that can contribute to the non-visual effects of light. Based on a review of laboratory studies using subjects with dilated and undilated pupils[28], which indicated that non-visual responses are mostly due to melanopsin-based photoreception and that melanopic illuminance could be an acceptable predictor for circadian effects, the CIE[29] recommended the use of melanopic irradiance or melanopic equivalent daylight illuminance (EDI), expressed in lux. This is the illuminance from daylight that produces a melanopic irradiance, or a circadian stimulation, equivalent to that of the light source considered. Additionally, the CIE[29] also defined the corresponding melanopic D65 efficacy ratio (DER) as the ratio of melanopic efficacy of luminous radiation of a light source to melanopic efficacy of luminous radiation for the CIE standard illuminant D65. Various quantities and ratios of the α-opic metrology defined in CIE S 026/E can be derived from measurement results or pre-defined illuminants using the CIE α-opic toolbox.[19] Melanopic DER can be used to evaluate the potential of a light source to stimulate the circadian system via the melanopsin-containing ipRGCs (the higher the value, the higher the circadian stimulation potential) and to determine melanopic EDI through multiplication by photopic illuminance. Based on the definitions of EML[26] and melanopic EDI[27], it can be easily determined mathematically that melanopic EDI = 0.9058 x EML. It then results that melanopic DER = 0.9058 x M/P, where M/P is the melanopic to photopic ratio, a measure comparing the amount of light that stimulates the melanopsin-containing ipRGCs to the amount of light that stimulates the photoreceptors responsible for visual perception under photopic conditions.

Standards such as the WELL Building Standard[30] or the German standard DIN SPEC 67600[31] recognised the circadian effects of light. The WELL Building Standard initially adopted the approach of Lucas et al.[26] and gave recommendations in EML, but later also added recommendations in melanopic EDI. The current WELL version recommends at least 150 EML, or 136 lux melanopic EDI, for electric lighting alone, and for maximum credits 275 EML, or 250 lux melanopic EDI; if sufficient levels of daylight are achieved (as per separate criteria), the recommended value for electric lighting drops to 120 EML, or 109 lux melanopic EDI, and for maximum credits 180 EML, or 163 lux melanopic EDI. The recommended values should be achieved for at least four hours (beginning by noon at the latest) at a height of around 45cm above the working plane for all workstations in regularly occupied spaces. The WELL Building Standard also gives guidance on calculating EML values for different spectral power distributions. For daylight from a sample of overcast sky, a M/P ratio of 1.128 can be calculated (thus 100 photopic lux of daylight equals approximately 113 EML). However, in practice this would vary with the spectrum of daylight, which could depend on time of day, the amount of sunlight in the space, weather conditions, pollution, reflection from other objects like buildings outside, and the glazing type. The German standard DIN SPEC 67600[31] also gives specific design recommendations for biologically effective electric lighting that mimics the natural changes in daylight. It recommends a vertical photopic illuminance at the eye of at least 250 lux at a colour temperature of 8000K for several hours (preferably in the morning), and at most 50 lux at no more than 2700K in the evening. DIN SPEC 5031-100[32] gives guidance on calculating the melanopic action factor of light sources with different spectral power distributions and adjusting illuminance values accordingly. For the CIE standard illuminant D65 (6500K daylight), a value of 239 lux corresponds to 250 lux at 8000K; this is defined by the German standard as melanopic daylight equivalent illuminance.

The latest recommendations for daytime, evening, and night-time light exposure to best support optimal non-visual effects of light[33] use melanopic EDI as recommended by CIE S 026/E[27]. At least 250 lux melanopic EDI at eye level (1.2m above the floor) are recommended during daytime and preferably from daylight, whereas evening and night-time values at eye level are limited to maximum 10 lux melanopic EDI (three hours before bedtime) and 1 lux melanopic EDI (in the sleep environment), respectively. These recommendations are based on laboratory research showing that melanopic EDI can be used to approximate the influence of light exposure on spectral sensitivity of circadian and neuroendocrine responses[28,34] and, in some cases, that melanopic EDI is a better metric than others.[35,36] Additionally, these recommendations were supported by field evaluations of the impact of environmental lighting in schools and work environments. This was achieved by comparing the results from previous field research and transforming the data into melanopic EDI. For example, a recent meta-analysis[37] is quoted that outlines a significant subjective alerting effect of bright white light (melanopic EDI over 250 lux) compared to dim light (melanopic EDI below 50 lux) in around 80% of the reviewed studies. In schools, the settings reporting higher melanopic outputs (melanopic EDI over 500 lux) led to improvements in concentration and reading comprehension compared to what it is required in conventional lighting standards and codes centred upon lower values of vertical illuminance that are recommended to meet visual (non-circadian) needs (melanopic EDI below 200 lux).

The aim of the latest recommendations is to maximise daytime and minimise evening and night-time exposure to reduce any negative impacts on sleep, alertness, and the circadian system. The authors[33] also suggest that increasing melanopic light exposure during daytime could benefit alertness, performance, and sleep in real-world settings. However, no recommendation is given on the duration of exposure to 250 lux melanopic EDI during daytime to enable circadian entrainment. This may be thought as a minimum light level to be achieved either across an entire day (although this may not be easily achievable from daylight alone) or for a specific number of hours (similar to the approach adopted by the WELL Building Standard[30]). Nevertheless, attention should be paid to any negative effects that this could have, for example in terms of glare, visual discomfort, or increased energy use.

All the above metrics for circadian lighting are based on the vertical light level at the front of the eye i.e., at the cornea and, while there is generally no distinction between daylight and artificial light as the source of the light stimulus, Brown et al.[33] suggest daylight should be prioritised. In an electrically lit space with ceiling lighting, this vertical illuminance is normally significantly lower than the horizontal illuminance on the working plane. In a daylit space with side windows, the ratio of vertical to horizontal illuminance is generally closer to unity, although it depends significantly on which way people are facing. If someone is facing a window the vertical illuminance at their eyes may be greater than the horizontal illuminance on the desk. If they are facing away from the window, or towards a side wall, it will generally be lower. Such metrics present a clear practical advantage as they are relatively easy to measure, but they only offer an approximate quantification of the impacts on the biological processes involved in the non-visual effects of light. Newer metrics are still to be developed that factor in the influence of other aspects such as pupil size and how it affects retinal irradiance,[28,38] spatial distribution of radiance in the visual field relative to spatial distribution of ipRGCs,[39,40] photic history,[41] or individual sensitivity related to different factors such as age.[42]

1.2. Current daylighting metrics

Although daylight is very important for regulating circadian rhythms, existing daylighting metrics and design guidance do not address this issue. In climates with predominantly cloudy sky conditions, traditional methods of daylight design[43-44] used to rely on the daylight factor. This is the ratio of the daylight illuminance indoors to that on an unobstructed horizontal plane outdoors, under a standard overcast sky. The daylight factor is easy to calculate, and it is a constant which depends only on the design of the building and surrounding obstruction to skylight. This makes it easy to use and apply as a design criterion. However, it is independent of orientation and local climate characteristics, and it is not clear how to relate it to the circadian effects of daylight.

Climate-based daylight modelling (CBDM) represents a more sophisticated method to predict daylight provision and lighting use. A key concept is daylight autonomy,[45] which is the proportion of annual occupancy hours for which daylight illuminance exceeds a particular value. Spatial daylight autonomy has also been defined as the percentage area of a space which meets a minimum daylight illuminance for a specified fraction of operating hours.[46] Daylight autonomy has the advantage that it is directly linked to the savings that can be achieved from automatic daylight linked controls, and it includes the effects of orientation and departures from a standard overcast sky distribution. However, daylight autonomy is of limited value for assessing the impact of daylight on circadian rhythms. This is because it does not differentiate between daylight at different times of day and year. In a location close to the equator, day length varies little with time of day and year, and a 50% daylight autonomy may mean that on nearly every day daylight exceeds the criterion illuminance for a significant length of time. Nearer the poles however, day length and daylight availability vary considerably with season, and the 50% of the year for which daylight exceeds the criterion illuminance will tend to be clustered in the summer months, with long periods in winter having insufficient daylight. This is known to lead to circadian disruption and, in some people, seasonal affective disorder.[47]

There is a related issue where daylight autonomy is defined in terms of percentage of daylight hours, as it is in the European standard on daylight in buildings EN17037.[48] At high latitudes, contributions to daylight autonomy could in principle occur very early in the morning or late in the evening, which could lead to circadian disruption. Other definitions of daylight autonomy, based on a proportion of a particular working day[46] or school day[49] are better in this respect.

A related metric is useful daylight illuminance (UDI)[50-52] which is the proportion of annual occupancy hours for which daylight illuminance falls within a 'useful' range. Most commonly, UDI comprises four different sub-metrics, each describing the operating hours during which the illuminance E is in a particular range: UDI-f (UDI 'fell-short') $E < 100$ lux; UDI-s (UDI 'supplementary') 100 lux $< E <$ 300 lux; UDI-a (UDI 'autonomous') 300 lux $< E <$ 3000 lux; and UDI-e (UDI 'exceeded') $E > 3000$ lux.[52] UDI-a could be viewed as the 'ideal' range for daylighting purposes. UDI-s could be viewed as the range where daylight makes some, but not a full, contribution. UDI-f can be thought of as the range when daylight illuminances are too low, and UDI-e when daylight illuminances are too high. The UDI metric is not particularly suitable for assessing circadian impacts, because it rules out the high illuminances which are particularly effective at resetting circadian rhythms.

The European standard on daylight in buildings EN17037[48] (which replaced BS 8206-2[43] in the UK) gives recommendations for daylight provision to achieve an adequate subjective impression of lightness indoors by means of daylight. It also covers provision of direct sunlight and view out as well as protection against glare from daylight. Daylight provision is quantified through targets for daylight illuminance (using a form of spatial daylight autonomy) or equivalent daylight factor for certain percentage areas of the horizontal working plane. For vertical and inclined windows, the standard gives a minimum target of 300 lux to achieve over at least half of annual daylight hours over at least 50% of the working plane in a space, together with a minimum illuminance of 100 lux over 95% of the working plane. A medium target is 500 lux over 50% of the working plane with 300 lux over 95% of the working plane for at least half of annual daylight hours. A high target is 750 lux over 50% of the working plane with 500 lux over 95% of the working plane for at least half of annual daylight hours. Half of annual daylight hours is a total of 2190 hours throughout the year. For horizontal daylight openings the minimum, medium and high targets are 300 lux, 500 lux and 750 lux over 95% of the working plane for at least half of annual daylight hours. Equivalent median daylight factor targets are given for a range of European cities.

The above targets may be difficult to meet in typical buildings, particularly residential, and there appears to be inconsistency between the two calculation methods (daylight illuminance and equivalent daylight factor) with some spaces meeting one target but not the other. Bournas[53] found that of the residential rooms they studied the vast majority did not meet the daylight factor based recommendations, which they concluded are significantly harder to meet than the daylight illuminance based recommendations. Conclusions of a recent BRE study for CIBSE[54] are similar, in that the two methods in the European standard can lead to different results. Given that the daylight illuminance based method overcomes the inherent limitations associated with the daylight factor as it uses weather data specific to the site locality and takes into account both orientation and location, thus reflecting the real site characteristics more accurately, the BRE study's recommendations for daylighting practitioners included undertaking daylight provision calculations using the daylight illuminance based method. However, regardless of the method used, the recommendations in the main standard were substantially difficult to meet for the residential rooms analysed in the BRE study. In the UK, a National Annex to EN17037[48] provides alternative lower targets for residential properties, namely 100 lux for bedrooms, 150 lux for living rooms and 200 lux for kitchens. These should be achieved over at least 50% of the working plane for at least half of annual daylight hours. However, these are seen as minimum targets for dwellings, as they were designed for hard to light places, and therefore would not be suitable as best practice targets.

All existing daylighting metrics are based on levels of daylight on the horizontal working plane. However, they fail to characterise the amount and spectrum of light reaching the eye which are required to be known when assessing the non-visual effects of light. Nor do they characterise the amount of light falling on other surfaces such as walls and ceilings and therefore they cannot give an indication of the lit appearance of a space, which has been recently suggested to correlate with the retinal response to light.[55] Newly proposed metrics such as mean room surface exitance[56] or mean indirect cubic illuminance[57] may be able to provide a better understanding of the lit appearance of a space and provide a link to metrics characterising non-visual effects of light. However, such metrics are in their infancy and require more research to better understand their impacts and establish appropriate levels for non-visual effects in typical daylit spaces.

Therefore, there is a case for developing a new type of daylighting metric which can address the effect of daylight on circadian rhythms. This paper evaluates the extent to which current daylighting metrics could be used to inform assessments of the effect of indoor natural light on circadian rhythms using examples of an office environment. More specifically, the aim of this paper is to assess whether office spaces that meet the minimum or high levels of recommendation for daylight provision in EN17037 would also provide adequate conditions for meeting the latest recommendation for daytime light exposure to best support optimal non-visual effects of light.

2. Using measured data to derive a 'melanopic daylighting metric'

There are some variations in the guidelines contained in the above documents, with the latest recommendations[33] requiring a higher melanopic light level during the day but being vaguer about when it should be supplied. However, the principle is to have a period of time each day when a minimum melanopically active amount of light is provided.

Aiming to define a realistic exposure duration when a minimum melanopic EDI value should be achieved, this paper assesses the amount of daylight typically available using data recorded in 1992 at Garston, near Watford, England, some 30km north-west of central London (51.71°N, 0.37°W). This formed part of the International Daylight Measurement Programme (IDMP). The data included global and diffuse horizontal illuminance as well as a range of other illuminance, luminance, and irradiance parameters. Careful quality control was carried out on the data using the IDMP protocols. There were some limited periods of missing data; in the current study, data from adjacent recordings were substituted for the missing data, to avoid seasonal bias in the results. Diffuse illuminance was measured using a photocell with a shadow-band; a correction was made for the effect of the shadow-band in blocking some diffuse light.

Hourly average data were used in the analysis. Daylight data at a shorter time step are difficult to obtain, and most dynamic analyses use daylight data derived from an hourly weather tape. Clock time, which from April-October incorporated daylight saving time (BST), was used for the analysis.

The analysis uses external unobstructed illuminance data. The critical days for circadian rhythms are likely to be dull overcast ones, and therefore a reasonable first approximation for internal illuminance could be assumed by multiplying these external illuminances by a daylight factor.

The daylight data were first analysed against the principle of having four hours (beginning by noon at the latest as used in the WELL Building Standard[30]) equalling or exceeding a particular external horizontal illuminance. Four hours between 0900 and 1300 were chosen for this analysis as an example, and the results are shown in Table 1 and Figure 2. This gives the number of days in the year for which a particular hourly average illuminance was equalled or exceeded for all of the four hours between 0900 and 1300. 1992 was a leap year, so the total number of days was 366.

For days with very low illuminances, the results are similar for both global and diffuse illuminances. These days would be expected to be heavily overcast. At higher illuminances there is more difference between the global and diffuse data, because of the effect of direct sunlight.

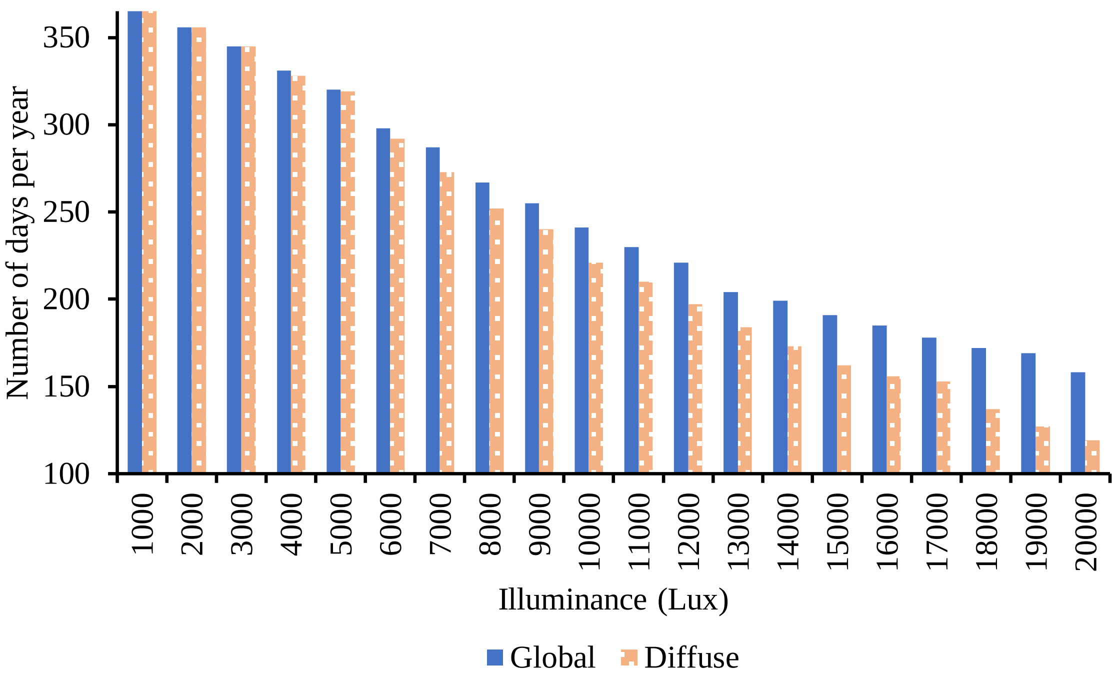

Figure 2. Number of days per year for which a particular hourly average external horizontal illuminance was equalled or exceeded for all four hours between 0900 and 1300.

The results show that in the Watford area there are some days with very low daylight illuminances. On the dullest day, 3 December 1992, an hourly average external illuminance of 1128 lux (global) and 1098 lux (diffuse) was recorded at 0900. Because the recommendations require a particular light level (250 lux melanopic EDI, equivalent to 250 photopic lux for the CIE standard illuminant D65) for a specific time period every day of the year, the contribution of daylight is effectively assessed on this worst-case day. To meet the daytime recommendation using daylight D65 alone in the Watford area would require a vertical daylight factor of at least 250 / 1098 x 100% = 22.8% at all workstations in a regularly occupied space as recommended in the WELL Building Standard.[30] This is not practicable except in a greenhouse or outdoor space.

The WELL Building Standard[30] also has a lower tier criterion of 136 lux melanopic EDI using electric lighting alone or, if sufficient levels of daylight are achieved (as per separate criteria), the recommended value for electric lighting drops to 109 lux melanopic EDI. Effectively this means that, unless daylight D65 can provide 27 lux melanopic EDI on the dullest day of the year, it is not worth including in the calculation. A value of 27 lux melanopic EDI corresponds to 27 photopic lux for the CIE standard illuminant D65, which would require a vertical daylight factor of 27 / 1098 x 100% =

2.5%. Though this is possible for someone facing a window and relatively close to it, it would be difficult to achieve in a space with typical depth and multiple workstations.

The German standard DIN SPEC 67600[31] has a more flexible approach, recommending a vertical illuminance at the eye of at least 250 lux at a colour temperature of 8000K for several hours, preferably in the morning. This corresponds to 239 lux from daylight with a colour temperature of 6500K. One way to assess this would be to find the number of days with four hours of daylight above a particular illuminance at any time in the period 0800-1500. This formulation would require at least one hour of daylight before noon and thus reduce the potential for exposure to higher light levels later in the afternoon. The results are given in Table 1 and Figure 3.

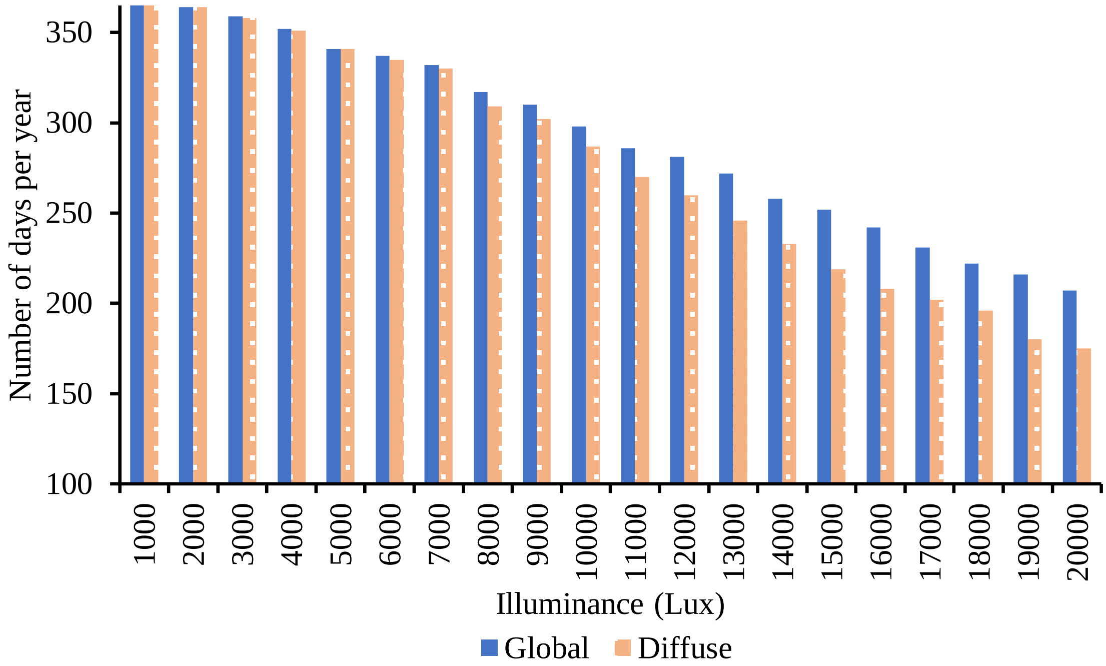

Figure 3. Number of days per year for which a particular hourly average external horizontal illuminance was equalled or exceeded for any four hours between 0800 and 1500.

This only helps a little, because on another very dull day, 18 December 1992, only 1798 lux (diffuse) was exceeded for four hours of the day (from 0800-1000 and 1100-1300). Thus, to meet the German standard of 239 lux on every day of the year using daylight D65 alone would require a vertical daylight factor of 239 / 1798 x 100% = 13.3%. By applying the same approach but using the latest recommendation of 250 lux melanopic EDI, which corresponds to 250 lux from daylight D65, the vertical daylight factor target would be 250 / 1798 x 100% = 13.9%. Neither of the above vertical daylight factor values are readily achievable in a normal workspace.

One way round this would be to recommend four hours of a particular illuminance on a (sizeable) proportion of days in the year. After all, many people occasionally spend a day with relatively little light exposure, for example in a conference or windowless meeting room, without significant circadian disruption. Also, there may be a few days in a year with very low levels of daylight due to heavily overcast sky conditions; for example, outdoor illuminance measurements at the same site in Garston on 6 August 1981 found values of horizontal unobstructed daylight illuminance as low as 89±7 lux just after 1100, whilst between 1100 and 1200 the unobstructed horizontal illuminance did not exceed 1000 lux.[58]

For example, a criterion for a particular light level to be achieved for four hours between 0800 and 1500 on 90% of days throughout the year, would correspond to an external diffuse illuminance of 7000 lux. The recommendation of 250 lux melanopic EDI (250 photopic lux for daylight D65) could be achieved with a vertical daylight factor of 3.6%, and daylight could start to make a minimal contribution according to the WELL Building Standard (more than 27 lux melanopic EDI or 27 photopic lux for daylight D65) at vertical daylight factors as low as 0.4%. Basing a criterion on 90% of days over the year need not lead to lengthy periods of inadequate daylight. Of the 36 days in the BRE dataset without four hours of diffuse illuminance above 7000 lux, most occurred in ones and twos. The longest run of days without four hours above 7000 lux occurred from 14 December 1992 to 19 December 1992, a run of six days. There were also three consecutive days from 14 to 16 January.

Based on the above analysis, this paper evaluates a 'melanopic daylighting metric' of achieving four hours with 250 lux melanopic EDI on 90% of annual days.

3. Assessing the 'melanopic daylighting metric' against EN17037 recommendations

Computer modelling based analysis was undertaken to evaluate whether, and if so to what extent, an office space meeting the minimum and the high levels of recommendation for daylight provision as per EN17037[48] would also provide adequate conditions for meeting the latest recommendation for daytime light exposure to best support optimal non-visual effects of light.[33]

The analysis employed office space models selected from those used in a recent BRE study.[54] Two types of office space were selected, one with one glazed wall (space type 1) and the other with two adjacent glazed walls (space type 2), each space being chosen such that the minimum (labelled A) and the high (labelled B) levels of recommendation in EN17037[48] were met. Numbers 1 and 2 indicate the number of glazed walls in the space (one and two adjacent, respectively), whilst letters A and B indicate the level of recommendation in EN17037 the space meets (minimum and high, respectively). The calculation model (Figure 4) included a range of external obstructions of different sizes at various distances opposite and to the side of the analysed spaces. The office space models included a 0.8m wide brise-soleil along the building perimeter, placed at 0.2m above window head height, as well as realistic window frames and typical reflectances and transmittances for internal and external surfaces and glazed areas, respectively. The calculation model was rotated 90°, 180° and 270° clockwise to allow for site orientation towards each main cardinal direction. In this way, each office space included in the analysis had the (main) window wall facing each main cardinal direction. Space characteristics are summarised in Table 2, and available in detail from the BRE study report.[54]

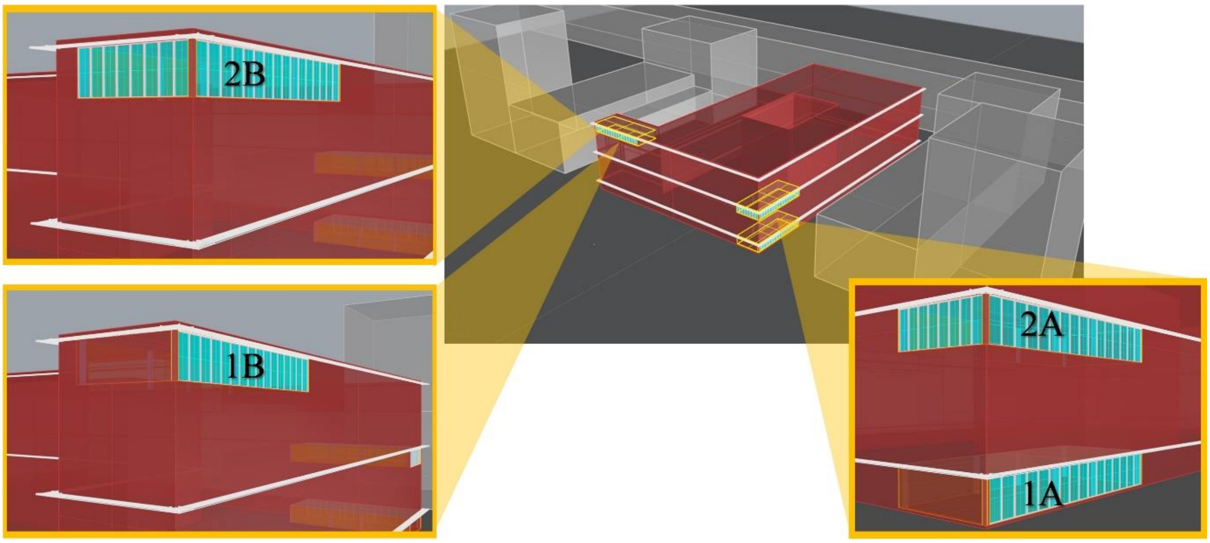

Figure 4. Views of the calculation model showing the office spaces used in the analysis that meet the *minimum* (rooms 1A and 2A) and *high* (rooms 1B and 2B) levels of recommendation in EN17037. Rooms 1B and 2B are situated in the same position within the model.

Metrics such as the vertical sky component (VSC) can be used to describe the level of external obstruction for the four office space models used in the analysis. VSC is a measure of the amount of light reaching a window. It is the ratio (expressed as a percentage) of illuminance at a point (usually the centre of a window) on a given vertical plane (the outside of a window wall) received directly from a CIE standard overcast sky, to illuminance on an external horizontal plane due to an unobstructed hemisphere of this sky. The VSC does not include reflected light, either from the ground or from other buildings. The maximum theoretical value of the VSC for a fully unobstructed vertical window is almost 40%, whilst a VSC value of at least 27% shows good potential for adequate daylight with conventional window design.[59] Table 3 shows the VSC results for the glazed walls in each room model used in the current study. Although some glazed walls do not face any external obstructions (W1 in room 1B, W2 in room 2A, and W1 in room 2B), the corresponding VSC values are affected by the presence of the brise-soleil, yet on average exceed 27%. The other glazed walls have lower VSC values, with wall W1 in room 1A being the most obstructed.

Daylight provision calculations had been previously[54] carried out for all rooms and site orientations using ClimateStudio.[60] This software calculates diffuse and reflected light using a 145-patch sky dome, but it samples the direct sunlight contribution based on explicit solar positions similar to the 5-phase method.[61,62] It uses a progressive path tracing approach combined with hardware acceleration where, instead of tracing all possible light paths before computing a result, a few paths are traced at a time whilst the result is constantly updated. The ClimateStudio settings used in the previous BRE study[54] were –ab 7 –lw 0.01 –ad 1 with 20 passes and 64 rays per pass, and the calculations were carried out using a 0.3m grid (targeted) with a 0.3m wall offset, placed at 0.85m above the floor. For the example discussed in this paper, a similar calculation grid was used but at 1.2m above the floor (typical eye level of a seated occupant) in each of the four room types described above (1A, 1B, 2A and 2B), and for each grid point vertical illuminance calculation planes were placed to face each main wall in the space. Using this arrangement, annual vertical illuminance was calculated at each grid point (four values per point, corresponding to the four wall directions) at hourly steps throughout a typical year (8760 hours). The ClimateStudio settings used for the vertical illuminance calculations were –ab 7 –lw 0.01 –ad 1024 with 100 passes and 100 rays per pass. Similar to the previous BRE study,[54] a ground plane 500m x 500m in size was placed in the calculation model so that its geometric centre coincided with the geometric centre of the building containing the rooms used in the analysis, and the calculations were carried out using the Climate One Building weather dataset for London Heathrow Airport.

Additional calculations were carried out for all four office spaces and site orientations using ALFA (Adaptive Lighting for Alertness).[63] ALFA is a Radiance based multi-spectral simulation tool,[64] developed to predict the amount of light absorbed by the ipRGCs depending on the observers' location in the room and view direction. It provides predictions for equivalent melanopic lux (EML) using high resolution spectral simulations.[63] ALFA performs simulation on 81-colour channels, and the outputs include the average spectral irradiance at 5nm intervals between 380nm and 780nm. In the current example, ALFA calculations were carried out using a 0.5m calculation grid with a 0.5m wall offset, in the same four wall directions at a height of 1.2m above the floor (typical eye level of a seated occupant). The location used was London, England, with a uniform ground spectrum and an albedo of 0.15. The calculation settings in ALFA were –ab 7 –lw 0.01 with 100 passes for increased accuracy. Electric light sources were not considered in this example; therefore, the ALFA calculations did not include luminaires but only the contribution from daylight through the window glazing. Surface materials in ALFA were selected so that their photopic reflectances and transmittance matched as closely as possible the characteristics of internal and external surfaces used in the previous BRE study[54] (see Table 4).

It is not possible to run annual calculations in ALFA. This tool can only be used to determine melanopic and photopic illuminances and the melanopic to photopic ratio at a specific point in time (i.e., time and date) for a certain site location and sky condition (clear, hazy, overcast, or heavy rain cloud). For this exercise, point-in-time calculations were run for 21st March, 21st June and 21st December as representative equinox and solstice days at 0900, 1200, 1500 and 1800 (for June only), using clear and overcast sky conditions and London as the site location (51.51°N, 0.13°W). For each office space in each site orientation, the M/P ratio at each grid point in each view direction was used to further determine the corresponding melanopic DER. The expression melanopic DER = 0.9058 x M/P was the basis for deriving melanopic DER from the M/P values obtained through the ALFA calculations in this study.

Using this methodology, melanopic DER was calculated at each grid point in each view direction for each office space analysed and site orientation, assuming both clear and overcast sky conditions. Hazy and heavy rain cloud conditions were not included in the analysis since the normalised spectral power distribution of outdoor daylight in these scenarios (as derived from the ALFA graphical user interface) did not differ significantly from that corresponding to an overcast sky and the aim of this exercise was to determine melanopic DER only, which is a relative measure of efficacy, and not absolute values of irradiance or illuminance. Statistical analysis results indicate strong correlations in melanopic DER for each room and site orientation between the different date, time and sky type scenarios, except for cases with a higher potential for direct low-angle sun (e.g., 21st June 1800 clear sky in a West facing space with no external obstructions). Median correlation coefficients for the different melanopic DER datasets were in the range 0.91-0.99 for room type 1 (single aspect) and in the range 0.90-0.99 for room type 2 (dual aspect), whilst mean correlation coefficients were in the range 0.73-0.99 for room type 1 (single aspect) and in the range 0.80-0.95 for room type 2 (dual aspect); all these results are representative of strong correlations.

Figure 5 and Table 5 show melanopic DER values averaged across all grid points in each view direction and over all dates and times considered, and between clear and overcast sky conditions, for each room type and site orientation. Overall, standard deviation of melanopic DER values in each scenario considered was in the range 0.01-0.12, indicating only a small variation from the mean in all cases. Table 6 presents standard deviation ranges for each view direction and over all date, time and sky type scenarios considered.

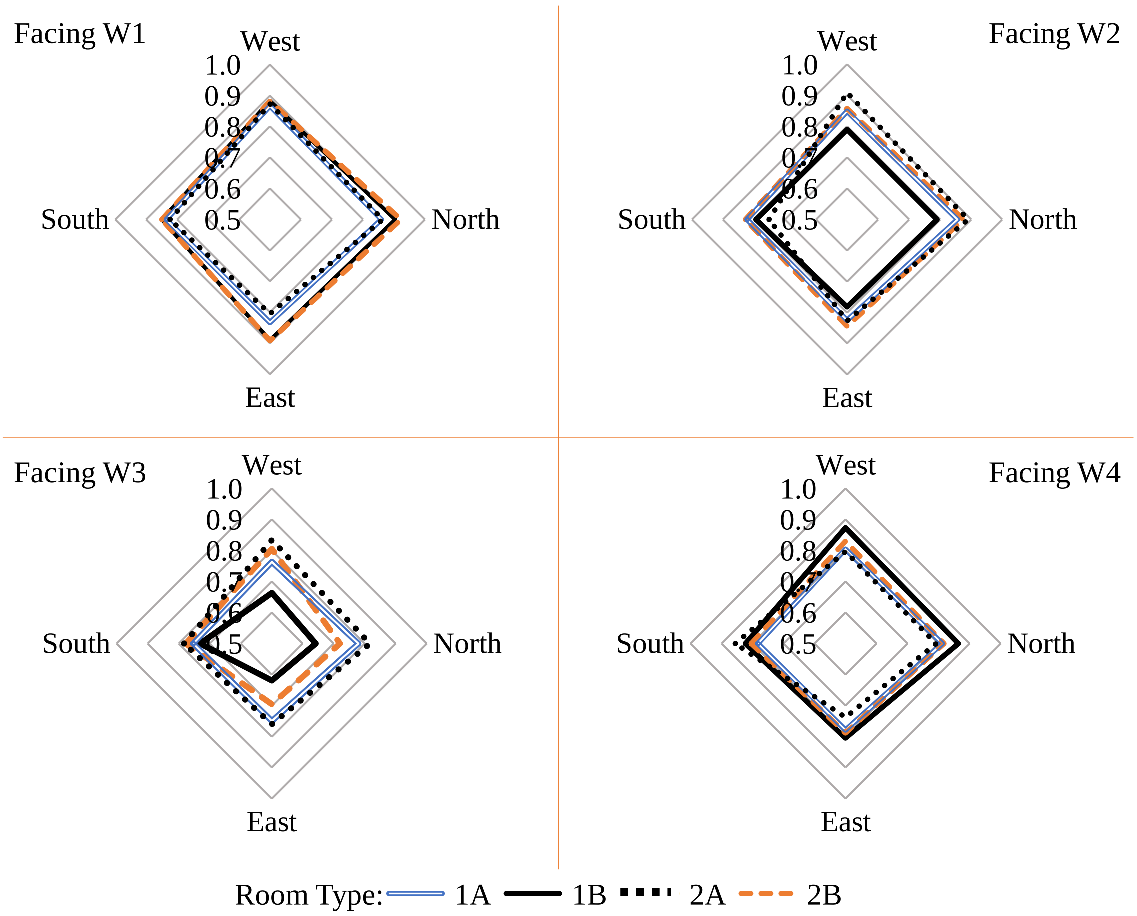

Figure 5. Melanopic DER values averaged across all grid points in each view direction for each type of room and site orientation. Values are averaged over all dates and times considered and between clear and overcast sky conditions. W1 to W4 indicate the four walls in each room, as described in Table 2. Room types indicate: 1A – single aspect, minimum level EN17037; 1B – single aspect, high level EN17037; 2A – dual aspect, minimum level EN17037; 2B – dual aspect, high level EN17037. Cardinal directions labelled indicate the orientation of wall W1, which is the window wall in room type 1 and the large window wall in room type 2.

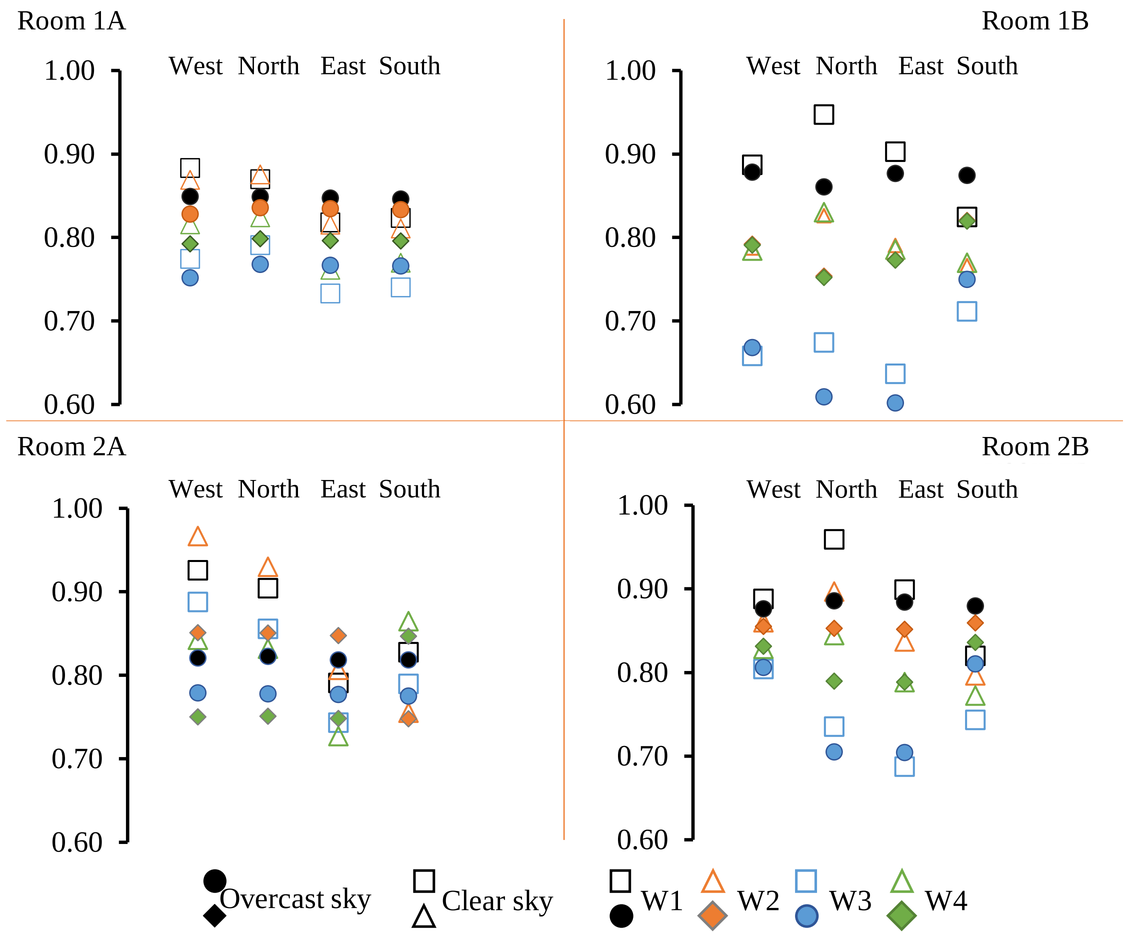

Figure 6. Melanopic DER values averaged across all grid points in each view direction and over all dates and times considered, for each type of room and site orientation, broken down by clear and overcast sky conditions. W1 to W4 indicate a view direction towards the four walls in each room, as described in Table 2. Room types indicate: 1A – single aspect, minimum level EN17037; 1B – single aspect, high level EN17037; 2A – dual aspect, minimum level EN17037; 2B – dual aspect, high level EN17037. Cardinal directions labelled indicate the orientation of wall W1, which is the window wall in room type 1 and the large window wall in room type 2.

By multiplying the vertical photopic illuminance (Ev) results obtained in separate ClimateStudio simulations (based on the settings discussed above) by the corresponding mean melanopic DER values presented in Table 5, melanopic EDI was calculated for each grid point and view direction in each office space and site orientation at hourly steps throughout a typical year (8760 hours). The next step was to determine for each room type and site orientation the percentage room area (based on grid point numbers) meeting 250 lux melanopic EDI over four hours on 90% of days throughout the year. This was completed for any four hours between 0800 and 1800 (see Figure 7 and Table 7), as well as for all four hours between 0800 and 1200 (see Figure 8 and Table 8).

The hours of 0800 to 1800 were selected as a representative sample of typical working hours for an office. Although later hours, say after 1500, are not as valuable as morning hours from a circadian entrainment perspective because morning light exposure is preferable, there may be certain cases, particularly for west facing spaces and longer days in the year, when daylight levels may be higher towards the end of the working day. The analysis aimed to capture such cases too. An alternative approach could have been to only assess the hours between 0800 and 1500 as in the previous section, yet this would have only shown compliance with the minimum light level recommendation during those hours leaving out potential late hours with an increased light exposure which would not benefit the body clock.

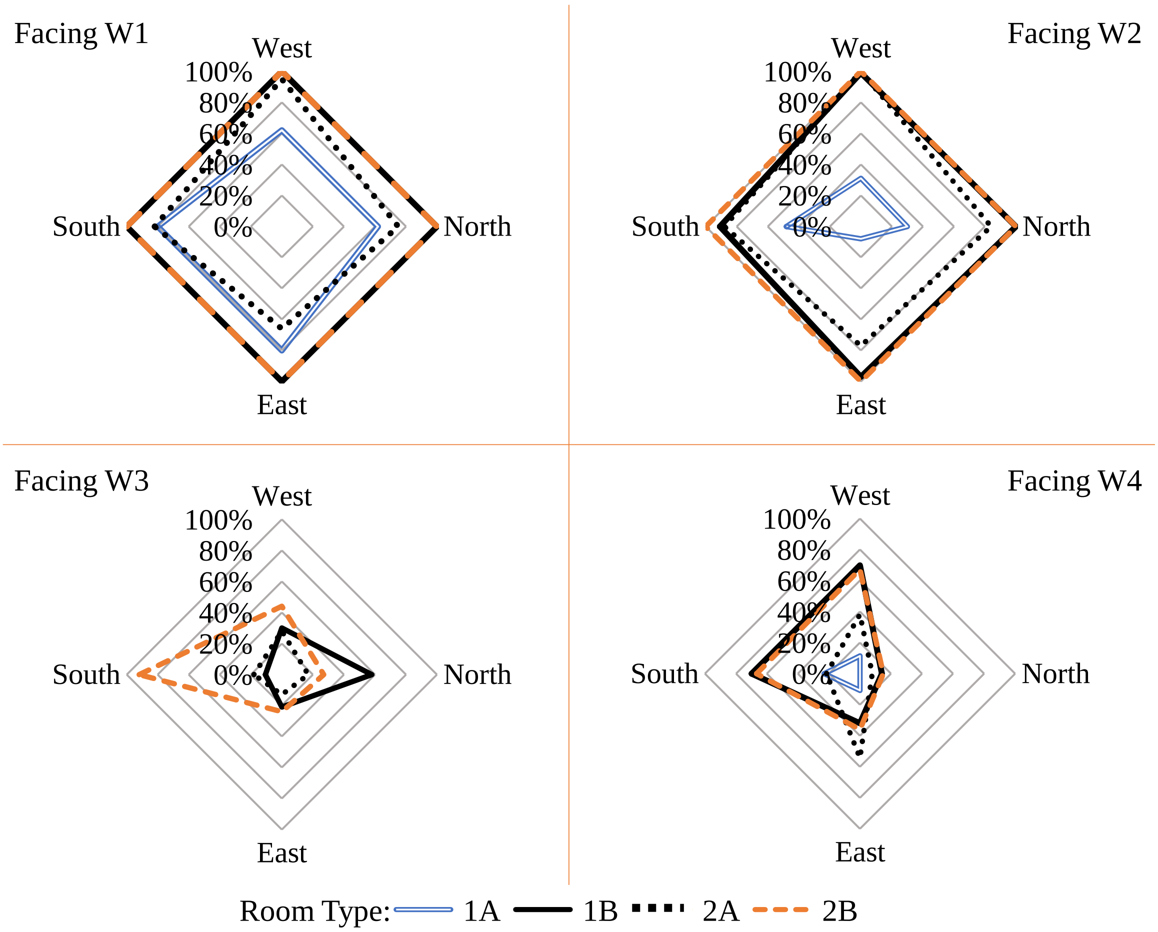

Figure 7. Percentage of room area where 250 lux melanopic EDI is met over any four hours between 0800 and 1800 for 90% of annual days in each view direction for each type of room and site orientation. Cardinal directions labelled indicate the orientation of wall W1, which is the window wall in room type 1 and the large window wall in room type 2.

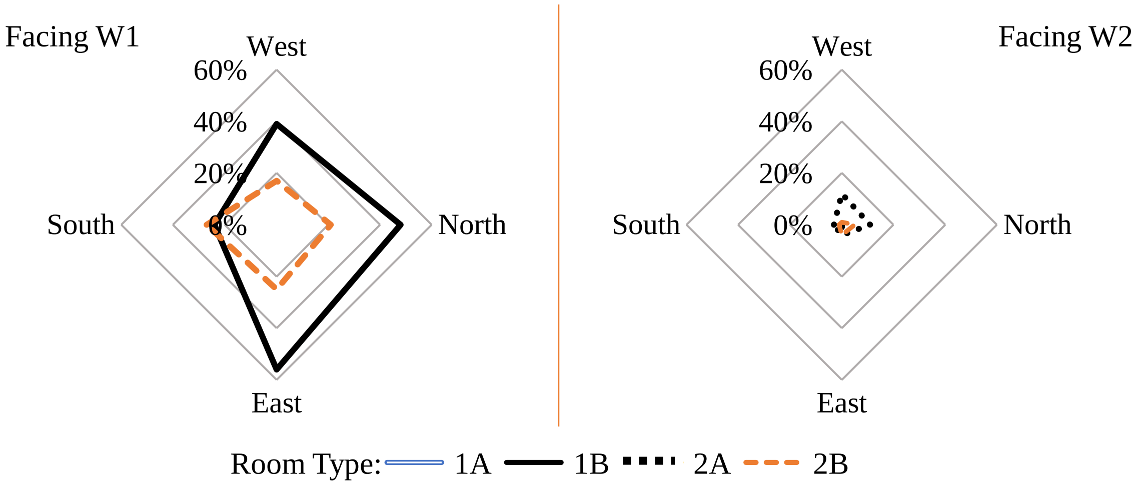

Figure 8. Percentage of room area where 250 lux melanopic EDI is met over all four hours between 0800 and 1200 for 90% of annual days for each type of room and site orientation if facing walls W1 and W2 as defined in Table 2. Values for the other view directions are null. Cardinal directions labelled indicate the orientation of wall W1, which is the window wall in room type 1 and the large window wall in room type 2.

The analysis results indicate that the target of 250 lux melanopic EDI over any four hours between 0800 and 1800 on 90% of days throughout the year can be achieved in the entirety of a space that meets the high level of recommendation in EN17037 and for a view direction facing a window wall. This was the case for both spaces considered. Other view directions in such a space offer some potential for the melanopic EDI target to be also met, yet to a varying degree depending on internal surface reflectances; in general, the percentage of room area where the target is met increases with internal surface reflectances. Because the small window wall in room 2B faced external obstructions, as shown in Figure 4, and glazing reflectance is inherently much lower than wall reflectance, there was less reflected light in room 2B compared with room 1B despite an overall larger glazed area. This caused the percentage room area in room 1B when facing the wall to the left of the window wall to be higher than that for the corresponding view direction in room 2B (facing wall opposite small window wall) for cases where higher surface reflectances were used. This demonstrates the importance of sufficiently high surface reflectances in addition to glazed areas in helping to achieve melanopic EDI targets.

The same target of 250 lux melanopic EDI over any four hours between 0800 and 1800 on 90% of days throughout the year cannot be generally achieved throughout an entire space that only meets the minimum level of recommendation in EN17037, not even if facing a large window wall. In the analysis considered, there was just one case where the entire room offered the potential for the target to be achieved; this was when facing the small (unobstructed) window in a dual aspect space with the large, glazed wall facing west. In a space with glazing on a single façade that only meets the minimum level of recommendation in EN17037, the above target cannot be met at any location in the space if facing the wall opposite the window wall.

As regards achieving 250 lux melanopic EDI over all four hours between 0800 and 1200 on 90% of days throughout the year, this could not be achieved across the entire room area in any of the spaces and scenarios considered, even if facing a window wall. The best result was observed in a space with unobstructed glazing on a single façade (facing east) meeting the high level of recommendation in EN17037; just over half of the area in this space achieved the target. For this type of space, the percentage room areas were lower when the window wall was facing the other directions, which could be explained by higher light levels being expected in an east facing room during morning hours. The result for the south orientation is significantly lower than those for the other orientations given the lower surface reflectances used in the modelling of that scenario. A similar trend could be observed for the space with windows on two adjacent façades that met the high level of recommendation in EN17037. However, the compliant room area was lower in this type of space than the other above given the effect of the external obstructions in combination with a lower surface reflectance for the glazing compared with the internal walls. Overall, unless facing a window wall in which case the target could be met over a proportion of the space dependant on the level of external obstructions and internal reflectances, the target of 250 lux melanopic EDI over all four hours between 0800 and 1200 on 90% of days throughout the year could not be met at any location in the spaces considered in this exercise.

Nevertheless, the likelihood to meet the melanopic EDI target is highest for occupants facing a window wall and relatively close to it. However, seating locations facing a glazed wall, particularly in the case of floor-to-ceiling curtains walls, are generally prone to glare from daylight. To assess the potential for daylight glare, additional calculations were carried out in ClimateStudio using the same calculation grid as that used for vertical photopic illuminances as described above (1.2m above the floor, 0.3m spacing with a 0.3m wall offset, four view directions facing walls W1 to W4) and the same Climate One Building weather dataset for London Heathrow Airport. The ClimateStudio settings used for the glare calculations were –ab 7 –lw 0.01 –ad 1024 with 100 passes and 100 rays per pass. The glare assessment used daylight glare probability (DGP), which is the metric used in EN17037[48] to evaluate glare from daylight in internal spaces and has been rated as a reliable metric for daylight glare evaluation in a variety of office situations.[65,66] DGP takes into account the luminance distribution in the visual field and the size, intensity and location of the glare source(s) relative to the observer's line of sight. As such, it depends on the vertical illuminance on the observer's eyes, the luminance of the glare source, its angular size and its position relative to the observer's line of sight. For a minimum level of glare protection, EN17037[48] recommends that DGP for the occupied space does not exceed a value of 0.45 over more than 5% of the occupancy hours. Occupancy hours were considered to be 0800-1800 every day throughout the year. Figure 9 gives an overview of the glare assessment results, which indicate an increased likelihood of glare particularly in south facing spaces and when facing a window wall.

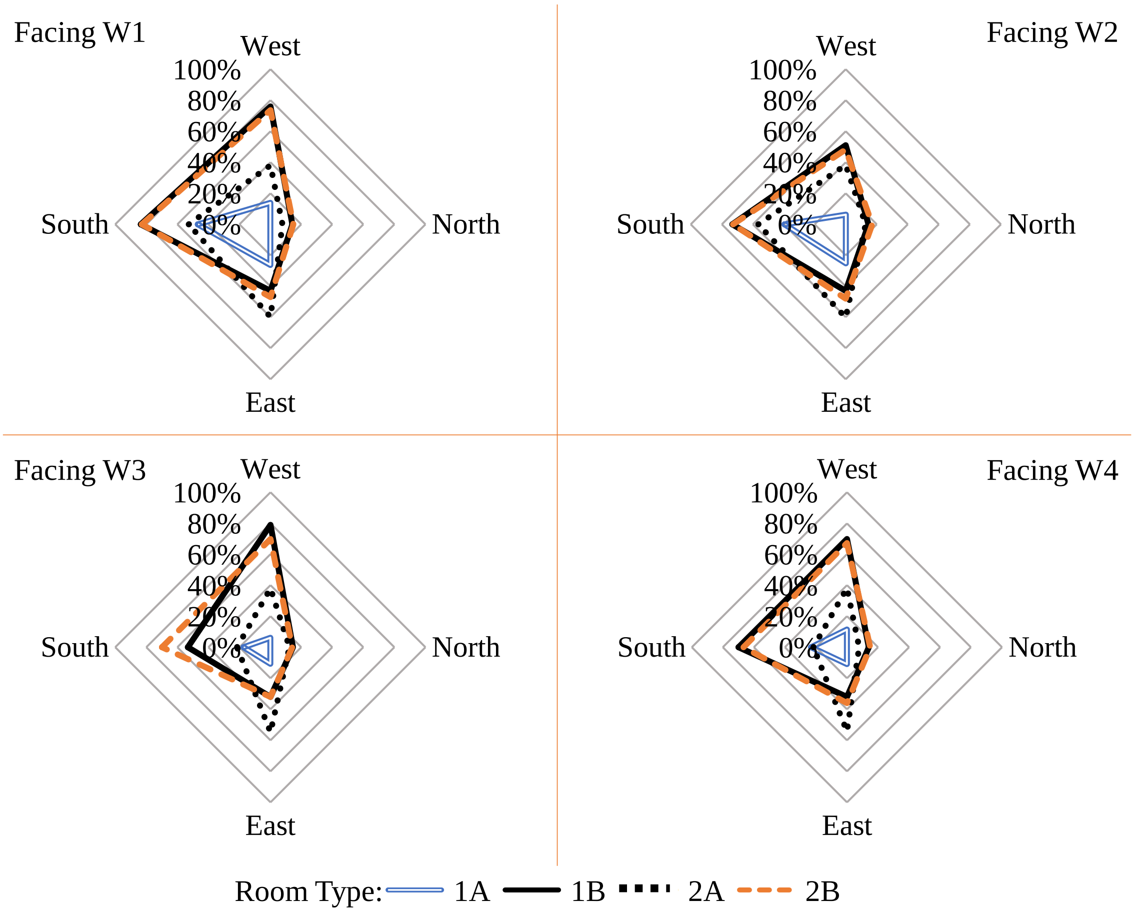

Figure 9. Percentage of room area where glare is predicted to be *intolerable* (DGP exceeds 0.45 over more than 5% of the occupancy hours 0800-1800) in each view direction for each type of room and site orientation. Cardinal directions labelled indicate the orientation of wall W1, which is the window wall in room type 1 and the large window wall in room type 2.

4. Discussion

Exposure to daylight is important in maintaining circadian rhythms. New metrics such as EML and melanopic EDI have been developed to assess the circadian effects of light, and recommendations for daytime light exposure are currently available using these metrics based on a number of hours per day above a certain value. However, the daylight available to occupants of typical buildings may not be sufficient for circadian stimulation and can vary significantly during annual occupancy hours in terms of both the amount and spectral characteristics.

This paper has compared the daytime light exposure recommendations to measured daylight data for Watford in Southern England. Nearer the equator, or in locations with fewer cloudy skies, different results would be expected. However, in a cloudy, variable, climate such as that of the UK, it is inappropriate to use a worst-case criterion which requires a given level of daylight on every day. The calculation then becomes dominated by an extreme condition which rarely happens. This is highly dependent on the dataset used. Our analysis used hourly average illuminances, but an evaluation based on a shorter time step may well have resulted in significantly lower daylight illuminances as light levels dipped below the average. As very dull days sometimes occur, this type of criterion substantially undervalues the contribution daylight can bring. An alternative approach can be based on requiring a given illuminance due to daylight for a set number of hours per day on a given proportion of days of the year. This paper suggests a metric based on four hours of daylight on 90% of days throughout the year. However other durations and proportions may be appropriate for other climate types and requirements.

Additionally, the photopic lux values in the examples used to derive the 'melanopic daylighting metric' are based on the spectral power distribution of the CIE standard illuminant D65. In practice the outdoor daylight spectrum varies with factors such as time of day, weather conditions, atmospheric pollution, or reflection from surfaces in the external context, occasionally with significant deviations from the CIE standard illuminant D65. In addition, there may be further spectral variation in indoor daylight due to glazing characteristics, the amount of sunlight entering the space, and the spectral properties of internal surface materials. A more detailed analysis is required to assess the potential for circadian stimulation of indoor daylight levels by taking into consideration the above factors.

Current metrics to assess daylight provision to a space are based on daylight factor and CBDM. The European standard on daylight in buildings EN17037 gives recommendations for daylight provision based on areas of a horizontal plane that meet illuminance (or daylight factor) targets for at least half of annual daylight hours. CBDM annual metrics are less appropriate for assessing the impact of daylight on circadian rhythms because they do not differentiate between daylight at different times of day and year.

Research using laboratory and field measurements, as well as computer modelling, has investigated the potential of both electric lighting and daylight to contribute to non-visual effects.[67-77] The focus has been to test variables that could impact the provision of daylight in a space to meet the minimum non-visual effect requirements, assess the beneficial characteristics of electric lighting for non-visual effects, or evaluate the energy consumption required to meet non-visual effect recommendations. Findings suggest that effective circadian stimulus can typically be achieved only for view directions facing the windows or at positions near the windows where daylight levels are higher.[67] However, daylight may not always be sufficient for circadian entrainment, particularly under overcast sky conditions or when shading devices are deployed to control glare.[68,69] While increased use of electric lighting would be needed in areas away from windows[67] and at times when daylight is insufficient, typical electric lighting is designed to meet target illuminances on the horizontal working plane rather than vertically at the eyes,[68,69,71] or may have reduced output in short wavelengths, contributing to reduced circadian entrainment effects.[68,70] This leads to an increased energy demand for achieving the required light dose,[69,71] even double according to some researchers,[71] compared to a baseline condition where visual target requirements are met. Nevertheless, using lighting richer in short wavelengths for non-visual effects can lower energy demand. For instance, some researchers found that 5500K lighting can save up to 20% of annual lighting energy use compared to 4000K lighting.[72] However, the use of artificial lighting with a high correlated colour temperature should be limited to the first part of the day to avoid detrimental effects. Spectrally tuneable, dimmable lighting could be used to supplement daylight and provide integrative lighting solutions capable of satisfying both visual and non-visual requirements.[73-77]

This paper presents a computer modelling based exercise to evaluate whether example office spaces which meet the minimum or high levels of recommendation for daylight provision in EN17037 would also provide adequate conditions for meeting the latest recommendation for daytime light exposure to best support optimal non-visual effects of light. The computer modelling involved calculations of vertical photopic illuminance from daylight at the eye in four main view directions at hourly steps throughout the year, in combination with mean melanopic DER for each view direction averaged across dates, times, and sky types, in order to derive the corresponding melanopic EDI values. The office spaces considered faced all four cardinal directions and different degrees of external obstruction.

When calculating melanopic EDI, the most accurate approach would have been to multiply each Ev result from ClimateStudio simulations by the corresponding individual melanopic DER value determined through ALFA simulations for that specific point in each type of space and site orientation not only for each view direction but also for each date and time and actual sky condition as deducted from the weather file used in the simulations. However, this would have necessitated substantial computing effort, and it was decided to use the melanopic DER values averaged across all grid points in each view direction and over all dates and times considered, for each room type and site orientation. This was because individual melanopic DER values did not vary substantially and there was a strong correlation between the different datasets as discussed above.

As would be expected, melanopic DER values in each case were highest when facing the main window wall and in general slightly higher for a clear sky compared to an overcast sky. Overall, the relative difference between clear and overcast sky results was within up to ±12% depending on the site orientation, although by averaging the results for all site orientations, this relative difference was within up to ±5%. Generally, melanopic DER values tended to be higher for the rooms meeting the high level of recommendation in EN17037, and lowest when facing the wall opposite the main window wall in all rooms considered. The overall conclusion from the melanopic DER calculation is that the higher the level of direct daylight with a spectral content richer in blue wavelengths (such as in the case of a clear sky), the higher the melanopic DER value. Nevertheless, melanopic DER of indoor daylight is influenced by the spectral properties of the window glazing and room surface finishes. The latter would have a stronger effect for points and view directions receiving less direct daylight such as if a window is not in the field of view. The combination of room models and surface characteristics used in this analysis led to some occurrences of melanopic DER values above 1, but in most cases and on average melanopic DER values are lower than 1. The maximum mean melanopic DER calculated was around 0.9, and in general melanopic DER was higher for a view direction facing a window wall and north, which can be explained by the north skylight spectrum matching more closely the D65 spectrum compared with other occurrences of natural light that include more direct sunlight. The results indicate that melanopic effects arising from indoor daylight in the spaces considered would be weaker than those of the CIE standard illuminant D65.

Furthermore, the analysis results indicate that it is very difficult to achieve 250 lux melanopic EDI from daylight alone over all four morning hours 0800-1200 on 90% of days throughout the year, even in a space that meets the high level of recommendation in EN17037 and has large, unobstructed windows and high internal reflectances. In fact, this target could not be achieved across the entire room area in any of the spaces and scenarios considered. Spreading the four hours of 250 lux melanopic EDI throughout the day would make it easier to achieve the target, although this comes with a potentially higher risk of insufficient circadian synchronisation or even detrimental effects since morning light exposure is preferable for body clock resetting. In this study, the target of 250 lux melanopic EDI over any four hours between 0800 and 1800 on 90% of days throughout the year can be achieved in the entirety of a space for any site orientation if the space meets the high level of recommendation in EN 17037 and for a view direction facing an unobstructed, main window wall. Other view directions in such a space offer some potential for meeting the melanopic EDI target but to a varying degree which would depend on internal surface reflectances. In the analysis considered, there was just one case where the entire room offered the potential for the above melanopic EDI target to be achieved when the minimum level of recommendation in EN17037 was met. It should be noted that the spaces included in this analysis were modelled as empty with no pieces of furniture or other items indoors, whereas in real-world settings the presence of objects would likely make it more difficult to achieve the targets due to obstructing effects.

Overall, a target of any four hours of 250 lux melanopic EDI throughout the day is therefore easier to achieve. However, since morning light exposure is preferable for body clock resetting, this comes with a potentially higher risk of insufficient circadian synchronisation, or even detrimental effects in the case of exposure to increased light levels later in the day. Even when considering total occupancy hours throughout the day, spaces meeting the minimum level of recommendation in EN17037 only provide limited potential for achieving the melanopic EDI target.

The results of the current study align with previous research findings[22,67] that circadian stimulation levels in daylit spaces are highest in areas near the windows and decrease progressively away from the windows. Additionally, the current study shows that the melanopic EDI recommendation is most likely to be met in very well daylit spaces (which meet the high level of recommendation in EN17037) if facing an unobstructed main window wall, whereas other view directions in such spaces present a varying degree of likelihood to meet the melanopic EDI target depending on internal surface reflectances. However, facing large areas of glazing has the potential for glare from daylight. An additional DGP assessment using the example office spaces considered in this paper found that there would be the potential for large proportions of some rooms at certain orientations where glare would be predicted to be 'intolerable' (as defined in EN17037). To protect themselves against glare from daylight, occupants would be likely to close the blinds if they are provided with this option. However, this may result in lower daylight levels throughout the space and thus reduce the potential for achieving the minimum targets for both daylight provision and non-visual effects, as also demonstrated in other studies.[68,69] As such, it is difficult to achieve all targets – namely daylight provision, melanopic EDI, and glare protection – in a daylit space; the layout and surface characteristics of both internal spaces and the external site context must be carefully considered to attain a balanced outcome in the daylighting design process.

In general, daylighting analysis would need to consider the use of blinds. However, this study aimed to determine if a space that meets the EN17037 daylight provision recommendations would also comply with the latest daytime light exposure guidelines for melanopic effects. The modelled spaces used in this study had been previously assessed for EN17037 compliance in another study[54] which did not include blinds due to the focus on aperture design. Although excluding blinds is a simplification, the goal of this study was to evaluate the potential of daylight apertures to help meet recommendations as part of an envelope design strategy. Including blinds in the models would inherently limit achievable daylight levels throughout the year, making it even more challenging to meet both EN17037 and daytime light exposure recommendations.

5. Conclusion

Daylight exposure is essential for maintaining circadian rhythms. New metrics like EML and melanopic EDI have been proposed to assess light's circadian effects, with specific recommendations for daytime exposure. However, typical buildings may not provide sufficient daylight for circadian stimulation, and levels vary throughout the year. This study compared daylight exposure recommendations to actual data from Watford, Southern England. In cloudy climates like the UK, using a worst-case criterion is impractical. Instead, a metric based on achieving a certain light level for a set number of hours on most days is suggested, proposing four hours of daylight on 90% of days annually.

The spectral characteristics of daylight vary due to factors like time of day and weather, affecting its circadian impact. Research indicates that effective circadian stimulus is typically achieved near windows, but daylight alone may not suffice, especially under overcast conditions. Electric lighting, particularly with higher short-wavelength content, can supplement daylight but increases energy demand. Spectrally tuneable, dimmable lighting could provide integrative solutions for both visual and non-visual needs. The study used computer modelling of daylight in example office spaces to verify whether, and to what extent, compliance with daylight provision recommendations in EN17037 can help to meet the latest recommendation for daytime light exposure for circadian stimulation.

The analysis in this paper suggests that achieving daylight provision targets in EN17037 as well as daylight levels for circadian stimulation as per the latest industry recommendations while limiting the potential for glare from daylight is a difficult balancing act. In fact, achieving the necessary circadian entrainment stimulus in typical daylit spaces using only daylight may be challenging, particularly under overcast sky conditions. Clear sky conditions are more favourable for this purpose. Nevertheless, supplementary artificial lighting may be required, especially in predominantly cloudy climates, although this would come at the expense of increased electricity consumption.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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TABLES

Table 1. Number of days per year for which a particular hourly average external horizontal illuminance was equalled or exceeded for different hour periods.

Illuminance (lx)	All four hours between 0900 and 1300		Any four hours between 0800 and 1500	
	Global	**Diffuse**	**Global**	**Diffuse**
1000	366	366	366	366
2000	356	356	364	364
3000	345	345	359	358
4000	331	328	352	351
5000	320	319	341	341
6000	298	292	337	335
7000	287	273	332	330
8000	267	252	317	309
9000	255	240	310	302
10000	241	221	298	287
11000	230	210	286	270
12000	221	197	281	260
13000	204	184	272	246
14000	199	173	258	233
15000	191	162	252	219
16000	185	156	242	208
17000	178	153	231	202
18000	172	137	222	196
19000	169	127	216	180
20000	158	119	207	175

Table 2. Space types used in the analysis.

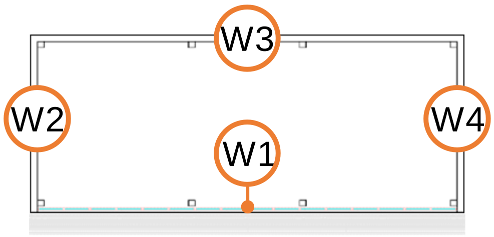
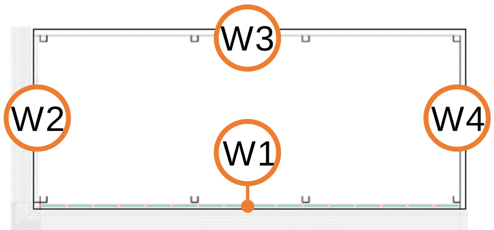
Type	Space type	Space layout	Space dimensions	Opening dimensions
1	Office (one window wall; fully glazed curtain wall)	 W1 – window wall; W2 – wall to the right of window wall*; W3 – wall opposite window wall; W4 – wall to the left of window wall*. * Terms 'right' and 'left' apply to an observer looking at the window wall W1.	20m x 8m x 3m	1 curtain wall (W1) 20m x 3m (floor to ceiling) 16 windowpanes 1.15m x 2.90m each
2	Office (two adjacent window walls; fully glazed curtain walls)	 W1 – large window wall; W2 – small window wall; W3 – wall opposite large window wall; W4 – wall opposite small window wall.	20m x 8m x 3m	1st curtain wall (W1) 20m x 3m (floor to ceiling) 16 windowpanes 1.15m x 2.90m each 2nd curtain wall (W2) 8m x 3m (floor to ceiling) 8 windowpanes 0.90m x 2.90m each

Table 3. VSC values corresponding to the glazed walls in each room model used in the study.

Room	Glazed wall (as labelled in Table 2)	VSC range (for all windowpanes in each glazed wall)	Mean VSC (for each glazed wall)
1A	W1	7.1% to 15.7%	10.6%
1B	W1	28.1% to 28.4%	28.2%
2A	W1	15.2% to 19.9%	17.1%
	W2	27.7% to 28.1%	28.0%
2B	W1	28.1% to 28.4%	28.2%
	W2	22.4% to 23.2%	22.8%

Table 4. Characteristics of internal and external surfaces as used in the analysis.

Object / surface	ClimateStudio	ALFA	
	Reflectance	**Photopic reflectance**	**Melanopic reflectance**
Internal walls style 1	0.50	0.51	0.52
Internal walls style 2	0.70	0.70	0.50
Pillars	0.50	0.51	0.52
Internal floors style 1	0.20	0.20	0.20
Internal floors style 2	0.40	0.42	0.38
Internal ceilings style 1	0.70	0.70	0.50
Internal ceilings style 2	0.80	0.81	0.80
Frame	0.50	0.51	0.52
Brise soleil	0.50	0.51	0.52

NOTE. Rooms 2B facing West and North, and rooms 1B facing West and East used higher reflectances for internal walls and ceiling as per style 2 for each material. Room 1B facing North used higher reflectances for internal walls, ceiling, and floor as per style 2 for each material.

Table 5. Melanopic DER values averaged across all grid points in each view direction for each type of room and site orientation. Values are averaged over all dates and times considered and between clear and overcast sky conditions.

Room type		View direction	Main window orientation			
			West	**North**	**East**	**South**
1	A	Facing window wall [a]	0.866	0.859	0.833	0.835
		Facing wall to the right of window wall	0.849	0.856	0.825	0.822
		Facing wall opposite window wall	0.763	0.779	0.750	0.753
		Facing wall to the left of window wall	0.804	0.811	0.779	0.783
	B	Facing window wall [b]	0.883	0.904	0.890	0.850
		Facing wall to the right of window wall	0.790	0.790	0.782	0.793
		Facing wall opposite window wall	0.663	0.642	0.619	0.731
		Facing wall to the left of window wall	0.788	0.791	0.779	0.795
2	A	Facing large window wall [c]	0.873	0.864	0.805	0.823
		Facing small window wall [d]	0.909	0.890	0.827	0.752
		Facing wall opposite large window wall	0.834	0.817	0.760	0.783
		Facing wall opposite small window wall	0.796	0.792	0.738	0.856
	B	Facing large window wall [e]	0.882	0.922	0.891	0.850
		Facing small window wall [f]	0.857	0.875	0.844	0.828
		Facing wall opposite large window wall	0.805	0.720	0.696	0.777
		Facing wall opposite small window wall	0.830	0.817	0.788	0.804

Symbols indicate: [a] obstructed, ground floor; [b] unobstructed, top floor; [c] obstructed, middle floor; [d] unobstructed, middle floor; [e] unobstructed, top floor; [f] obstructed, top floor.

Table 6. Standard deviation ranges for melanopic DER values in each view direction for each type of room and site orientation. Ranges cover all date, time and sky type scenarios considered.

Room type		View direction	Main window orientation			
			West	North	East	South
1	A	Facing window wall [a]	0.02 - 0.07	0.02 - 0.07	0.03 - 0.09	0.03 - 0.09
		Facing wall to the right of window wall	0.02 - 0.10	0.02 - 0.07	0.02 - 0.08	0.02 - 0.07
		Facing wall opposite window wall	0.03 - 0.07	0.03 - 0.07	0.03 - 0.06	0.03 - 0.05
		Facing wall to the left of window wall	0.03 - 0.08	0.03 - 0.08	0.03 - 0.07	0.02 - 0.07
	B	Facing window wall [b]	0.02 - 0.10	0.02 - 0.05	0.02 - 0.11	0.01 - 0.10
		Facing wall to the right of window wall	0.05 - 0.11	0.06 - 0.11	0.06 - 0.11	0.01 - 0.10
		Facing wall opposite window wall	0.03 - 0.06	0.03 - 0.09	0.02 - 0.07	0.03 - 0.08
		Facing wall to the left of window wall	0.06 - 0.08	0.06 - 0.12	0.06 - 0.12	0.01 - 0.07
2	A	Facing large window wall [c]	0.02 - 0.06	0.02 - 0.05	0.02 - 0.11	0.02 - 0.07
		Facing small window wall [d]	0.02 - 0.08	0.02 - 0.06	0.02 - 0.11	0.02 - 0.09
		Facing wall opposite large window wall	0.04 - 0.11	0.03 - 0.08	0.03 - 0.07	0.03 - 0.11
		Facing wall opposite small window wall	0.03 - 0.06	0.04 - 0.05	0.03 - 0.05	0.03 - 0.05
	B	Facing large window wall [e]	0.01 - 0.10	0.01 - 0.05	0.01 - 0.08	0.01 - 0.09
		Facing small window wall [f]	0.02 - 0.05	0.03 - 0.11	0.03 - 0.12	0.02 - 0.07
		Facing wall opposite large window wall	0.04 - 0.07	0.05 - 0.07	0.05 - 0.08	0.04 - 0.06
		Facing wall opposite small window wall	0.01 - 0.10	0.06 - 0.09	0.06 - 0.09	0.02 - 0.09

Symbols indicate: [a] obstructed, ground floor; [b] unobstructed, top floor; [c] obstructed, middle floor; [d] unobstructed, middle floor; [e] unobstructed, top floor; [f] obstructed, top floor.

Table 7. Percentage of room area where 250 lux melanopic EDI is met over any four hours between 0800 and 1800 for 90% of annual days in each view direction for each type of room and site orientation.

Room type		View direction	Main window orientation			
			West	North	East	South
1	A	Facing window wall [a]	62%	62%	80%	80%
		Facing wall to the right of window wall	31%	30%	8%	48%
		Facing wall opposite window wall	0%	0%	0%	0%
		Facing wall to the left of window wall	10%	6%	44%	16%
	B	Facing window wall [b]	100%	100%	100%	100%
		Facing wall to the right of window wall	99%	100%	97%	91%
		Facing wall opposite window wall	30%	58%	21%	11%
		Facing wall to the left of window wall	100%	100%	100%	91%
2	A	Facing large window wall [c]	95%	75%	66%	82%
		Facing small window wall [d]	100%	84%	77%	88%
		Facing wall opposite large window wall	28%	17%	13%	18%
		Facing wall opposite small window wall	4%	0%	0%	2%
	B	Facing large window wall [e]	100%	100%	100%	100%
		Facing small window wall [f]	100%	100%	100%	100%
		Facing wall opposite large window wall	44%	27%	24%	92%
		Facing wall opposite small window wall	89%	79%	71%	100%

Symbols indicate: [a] obstructed, ground floor; [b] unobstructed, top floor; [c] obstructed, middle floor; [d] unobstructed, middle floor; [e] unobstructed, top floor; [f] obstructed, top floor.

Table 8. Percentage of room area where 250 lux melanopic EDI is met over all four hours between 0800 and 1200 for 90% of annual days in each view direction for each type of room and site orientation.

Room type		View direction	Main window orientation			
			West	North	East	South
1	A	Facing window wall [a]	0%	0%	0%	0%
		Facing wall to the right of window wall	0%	0%	0%	0%
		Facing wall opposite window wall	0%	0%	0%	0%
		Facing wall to the left of window wall	0%	0%	0%	0%
	B	Facing window wall [b]	39%	48%	56%	24%
		Facing wall to the right of window wall	0%	0%	1%	0%
		Facing wall opposite window wall	0%	0%	0%	0%
		Facing wall to the left of window wall	0%	0%	0%	0%
2	A	Facing large window wall [c]	0%	0%	0%	0%
		Facing small window wall [d]	12%	11%	4%	3%
		Facing wall opposite large window wall	0%	0%	0%	0%
		Facing wall opposite small window wall	0%	0%	0%	0%
	B	Facing large window wall [e]	17%	21%	25%	27%
		Facing small window wall [f]	1%	5%	4%	1%
		Facing wall opposite large window wall	0%	0%	0%	0%
		Facing wall opposite small window wall	0%	0%	0%	0%

Symbols indicate: [a] obstructed, ground floor; [b] unobstructed, top floor; [c] obstructed, middle floor; [d] unobstructed, middle floor; [e] unobstructed, top floor; [f] obstructed, top floor.