CLEAR AS DAYLIGHT

All lighting designers appreciate the importance of maximising the benefits of daylight within an interior space. But accurately describing and representing daylight within a space remains challenging. **Dr Jemima Unwin** and **Longyu Guan** explore some of the latest, and changing, thinking around daylight metrics

The benefits of daylight have been advocated for centuries, as we see in an ancient limestone relief that shows the Egyptian Queen Nefertiti holding up her daughters to the rays of the sun [1] (Figure 1, below). More recently, the writer and playwright George Bernard Shaw

Figure 1 (above). Nefertiti limestone relief
Figure 1a (below). Shaw's revolving shed

(Figure 1a) used a revolving shed to optimise his daylit working conditions [1].

As electrical lighting increasingly replaced daylight in buildings, the effect of light on wellbeing was largely forgotten until the discovery of the intrinsically photoreceptive retinal ganglion cells (ipRGCs) which influence circadian, hormonal and behavioural systems [2].

The role of light as a stimulus for these systems is unquestioned, however whether ipRGC activation should be maximised or minimised in buildings is unknown [3]. Despite this, the advantages of daylight are unquestioned as it provides high retinal illuminance and information about the external environment. This is why daylight propagation in spaces where people spend most of their time is an important area of exploration.

'Daylight factor' is the ratio of interior to exterior illuminance over a horizontal plane, and has been the dominant metric for daylight design for over 50 years. Whilst the metric has remained the same, working environments have evolved. Figure 2, for example, compares a typical office in the 1970s with one of the present day.

From the image of the 1970s, it is clear the desk top (in other words the horizontal working plane) is the most important task area. However, in working environments today, people find that the horizontal desk plane is no longer the only important task area.

The most task-intensive planes are, arguably, computer screens on which good visual performance is easy to achieve (by 'zooming in' for example). As the use of computers means that people can work from anywhere, the main reason to attend a workplace is to communicate with colleagues, which involves looking at their faces. Therefore, it could also be argued that facial communication is also an important task.

To summarise, the emphasis of lighting design has moved away from the lighting of horizontal working planes. Whilst task illuminance is still in use, there is now more emphasis on the appearance of the room and the people in them.

Figure 2. Offices from the 1970s (right) and the present day (left)

Therefore, it is worth questioning whether the traditional daylight factor approach meets the needs of modern daylight design and whether there is any scope for metrics which consider daylight propagation in the whole volume occupied by people.

A STEP TOWARDS VOLUMETRIC LIGHTING

Electrical lighting standards have moved a step forward from the lighting of the horizontal plane. In 2002, the European electrical lighting standard EN 12464-1 removed the term 'working plane', and instead recommended illuminance levels on 'task areas' (which may or maybe not be on a horizontal plane) and on 'major room surfaces' (wall/ceiling/floor) [8].

In the 2011 revision, the standard introduced 'cylindrical illuminance'. Cylindrical illuminance measures the illuminance on the curved surface of a small cylinder centred at the reference point. To ensure good visual communication and adequate illumination in the volume of space, EN 12464-1 recommends a minimum mean cylindrical illuminance of 50 lux evaluated 1.2m above the floor for sitting people, and 1.6m for standing people [9].

Another metric that can be useful to describe lighting in the volume of occupied space is 'cubic illuminance'. In this concept, developed by Cuttle [10], the calculation point is a tiny cube on which illuminance is measured on all six faces.

From these values the illuminance vector of the calculation point can be deduced. Figure 3 (below right) shows illuminance vectors of multiple calculation points in a daylit room. Drawing the illuminance vectors reveals the indoor 'daylight flow' and the spatial distribution of illumination. This can be a useful tool for advanced daylight designs, such as daylighting for a sculpture gallery.

However, due to its complexity, cubic illuminance is hardly used in general practice. Even though it is useful for the derivation of other metrics, such as cylindrical illuminance and hemispherical illuminance, cubic illuminance contains too much information which makes it uneconomical to calculate. Then the question becomes: 'Is there a simpler volumetric lighting metric?', 'Can we make it more approachable for daylighting?'. The answer may lie within the concepts of 'exitance' and 'indirect illuminance'.

EXITANCE AND INDIRECT ILLUMINANCE

Exitance is the luminous flux reflected by a surface per unit area (as shown in Figure 4 below). Therefore, it equals the illuminance of the surface (E) multiplied by the surface reflectance (R).

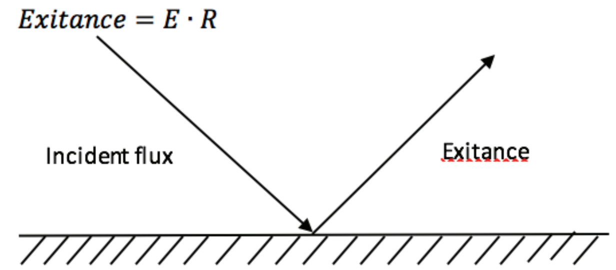


Figure 4. Incident flux and exitance

For example, if one wall inside a room was lit to 100 lux and the wall has a reflectance value of 0.8, then there will be 80 lux of exitance reflected back to the space. If exitance is calculated for all major room surfaces, an average exitance value can be obtained to summarise the diffused light in the room. This average exitance value is called Mean Room Surface Exitance (MRSE).

$$MRSE = \frac{\sum E_S \cdot R_S \cdot A_S}{A_T}$$

This term 'MRSE' might be new (proposed by Cuttle [11]), however its underlying concepts are not. Essentially, it is a way of describing

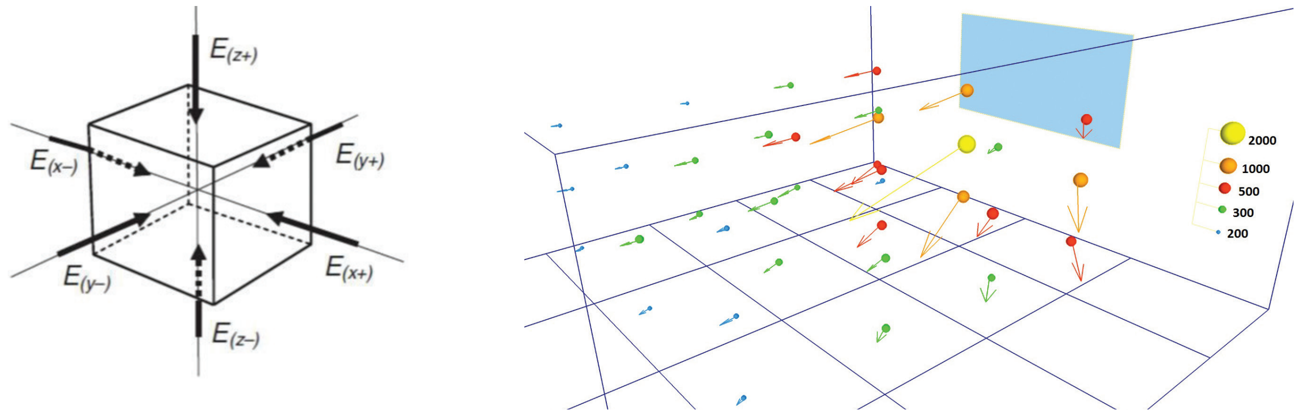


Figure 3. Cubic illuminance (left) and illuminance vectors in a daylit room (right)

the indoor inter-reflection of light. The same concept is used to calculate the internal reflected component of daylight factor (for example, Hopkinson's split flux method [12]).

MRSE as a daylight metric has some user-friendly traits. Firstly, it is a single number and is easy to calculate to a first approximation using Sumpner's principle (in any closed system the flux emitted must equal the flux absorbed [13]).

The components needed to calculate MRSE are only the total flux entering the window (Φ), the room surface area (A_r) and surface reflectance (R). Secondly, it correlates very well with the electrical lighting standards. The lighting standard EN 12464-1 recommends illuminances on major room surfaces, and this, coupled with guidance on surface finish reflectance, already effectively forces a minimum MRSE.

In addition, MRSE may be related to the biological effects of light. Given that ipRGCs are distributed across the retina [3], a good candidate for driving the response is likely to be illuminance in the plane of the pupil. Moreover, as aversion of gaze is the natural reaction to a direct view of a light source, it is quite likely that the best metric to describe any possible response is indirect pupil plane illuminance. This suggests that MRSE might be a good way of describing the potential of a daylighting design to impact on people's endocrine systems.

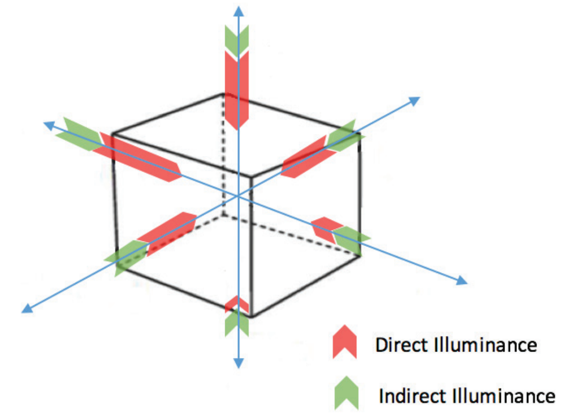
While MRSE might look promising in theory, it faces problems in practice. The biggest flaw of the exitance approach is that it does not work so well when a building is open-planned and geometrically complex. Exitance is the flux intensity being bounced back to the space from room surfaces, and MRSE measures the average exitance in the enclosure.

However, what if the room is not a closed system? What if there is no ceiling, or one or more internal walls is missing? Open spaces and voids are very common in modern architecture. In a workplace such as that shown in Figure 5 (below right), it is only possible to calculate the exitance from the highlighted surfaces.

However, what about the light being reflected from the far back corner of the building, and what about the flux 'loss' to the ground floor due to the huge void on the first floor? MRSE works perfectly for a simple 'box-like' room geometry, but it cannot be sub-sampled or calculated for open spaces or complicated spaces.

A solution to this limitation of MRSE is to use indirect illuminance. The total illuminance of any location facing any direction consists of direct and indirect illuminance (Figure 6). The indirect illuminance is the illuminance produced by one or multiple reflections from internal surfaces. It is a very similar concept to exitance, as both describe the flux intensity through reflections. In fact, the essence of MRSE can be considered to be the average indirect illuminance value of the entire room.

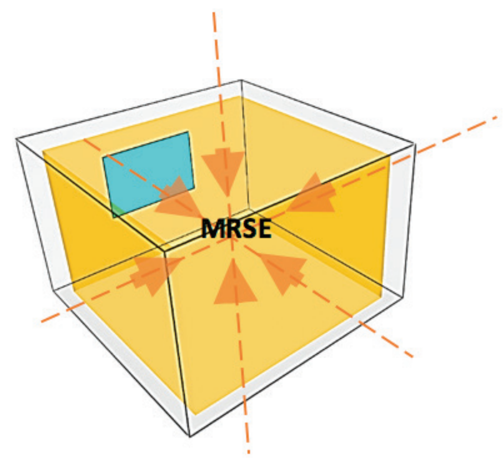
Figure 6. Example of direct and indirect illuminance (on a cube), assuming the window is on the distant left wall



Unlike exitance, which emphasises room surfaces, indirect illuminance can be calculated for any given point of the space (thanks to modern computation). Therefore, it is possible to calculate the indirect illuminance at multiple locations facing different directions, just like calculating cubic illuminance. However, unlike cubic illuminance, where the total illuminance of some directions might be significantly greater than others due to facing the light source, the indirect illuminance values on the other hand are very close on different faces .

This means the indirect illuminance values of all faces can be averaged to give the 'Average Indirect Illuminance of the calculation point'. If multiple calculation points are assigned in the space, the average indirect illuminance at each point can be measured (Figure 7 below right) and from this, a value of 'Average Indirect Illuminance of the space' can be calculated.

As MRSE, the Average Indirect Illuminance (AIE) of the space describes the overall inter-reflection within the room space. The more calculation points taken to calculate AIE, the closer the result will be to MRSE. However, AIE could be seen as an improvement because it overcomes the weakness of MRSE because it can be sub-sampled and can be calculated regardless of geometry complexities.



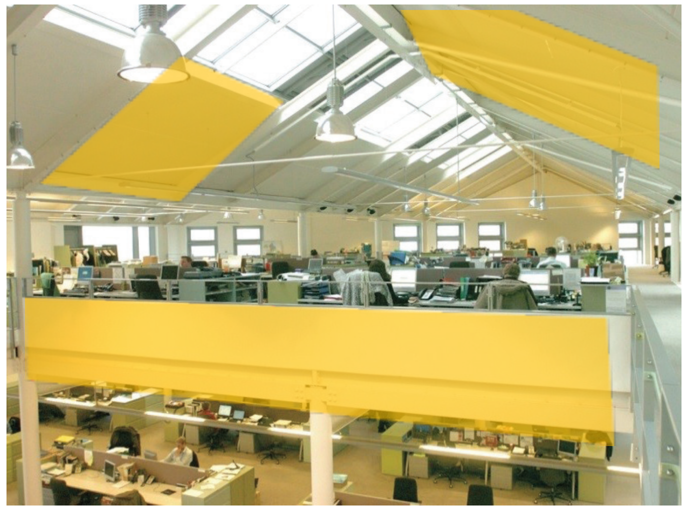


Figure 5. MRSE (left) and open space office (right)

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

Describing daylight in space is challenging. However, as daylight is likely to influence wellbeing, it is an important area of study that requires further research. Whilst this article has shown that there is good theoretical justification for the use of volumetric daylight metrics, this does not constitute grounds for widespread adoption until there is more evidence to show that such metrics correlate better with the needs of building users compared to traditional metrics.

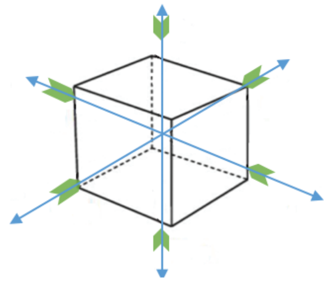


Figure 7. Indirect illuminance (left) and calculating average indirect illuminance of the space (above)

Testing the metric is the hardest part of developing new metrics. An initial pilot study which used data of people's perceptions of daylight, revealed that Average Indirect Illuminance better reflects people's perception of daylight adequacy.

In a study of three spaces it gave a higher value for a space that had a large window with a passive shading device, compared to daylight factor, and this was well correlated with office workers' self-reported preferences.

The metric will also encourage high-reflectance indoor surface materials. However, daylight metrics can only be reliably tested in a large number of real buildings. The link with people's perception of daylight is challenging, as impressions are affected by other factors (such as view, weather and so on).

Further research will conduct more real-life case studies and compare the performance of different daylight metrics. The incorporation of climate-based daylight modelling into the method will also be explored.

In conclusion, as a volumetric lighting metric for daylighting, Average Indirect Illuminance combines the advantages of both MRSE and cubic illuminance. It is one simple number which summarises the diffused daylight within the volume of space, yet it also can be sub-sampled and calculated anywhere in the space.

Unlike daylight factor, which only focuses on the working plane, Average Indirect Illuminance better represents daylight in the whole space. If this is found to also relate to how people perceive daylight, then its use may lead to spaces that have a positive influence on wellbeing.

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