A new metric to predict perceived adequacy of illumination

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Short title: A new metric for perceived adequacy of illumination

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Over recent years mean room surface exitance (MRSE) has gained acceptance as a predictor of perceived adequacy of illumination. However, it can be argued that MRSE either cannot be applied or has limited value in a number of practical situations. This paper proposes the use of a new metric, mean indirect cubic illuminance (MICI), to be used instead of MRSE in complex situations commonly found in practice. The paper also demonstrates that MRSE and average MICI have nearly the same numerical values.

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1. Introduction

Cuttle[1] introduced the concept of mean room surface exitance (MRSE) in 2010. He suggested that MRSE was correlated to the perceived adequacy of illumination (PAI) in a room. The concept has been tested in regular orthogonal (created from three pairs of parallel planes with each pair being orthogonal to the other pairs) spaces where from any point in the room an observer can see all of the room surfaces. In the tests run by Duff *et al*[2] a series of scenes was created using different lighting designs, and wall finishes. It was found that in the 27 conditions tested MRSE was a good predictor of PAI with about 50% of tests at a MRSE of 100 resulting in a perception of adequate illumination.

Thus MRSE could be considered as a metric for use in lighting design if the objective is to provide a perception of adequate illuminance. However, MRSE has always been considered in simple rooms with relatively uniform lighting and where at any point in the room it is possible to see all of the room surfaces. There is reason to believe that the relationship between MRSE and PAI may break down in more complex real environments. For example, consider an L shaped room (Figure 1). In this room an observer at point P cannot see the room surfaces between points A and B. Thus the surface exitance of the surfaces in this region can have no direct influence on the observer's perception of the adequacy of illumination.

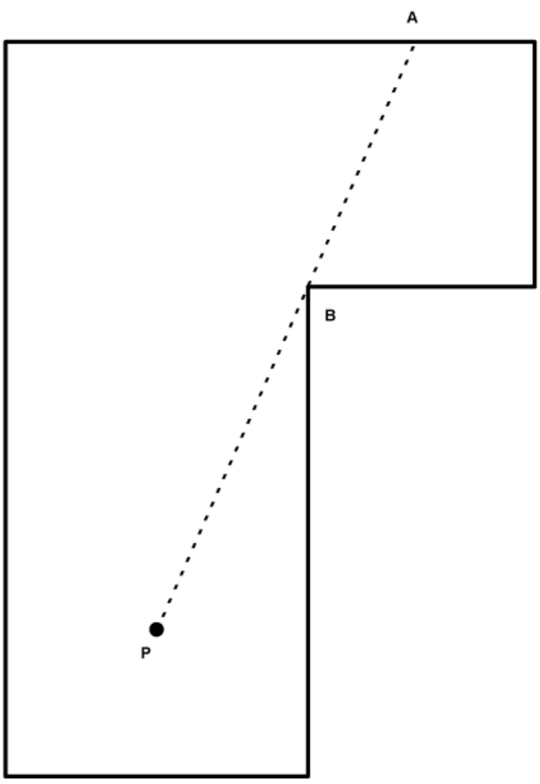

Figure 1. An L Shaped room in which it is not possible to see all the room surfaces from point P

A further problem with MRSE in real rooms is that it can be very complex to calculate. Consider a multi-storey building where the floors have been cut through to create a series of atria some of them are open and some are surrounded by glazing. Even if we could work out which surfaces may contribute to the perception of adequate illuminance at any given point or area in the building, calculating the precise areas of the surfaces and their exitance values would be quite complex.

Finally it is possible that a single value for MRSE in a room may not always be useful particularly where the lighting conditions vary dramatically across a room. Consider a deep plan office that is daylit from windows in one wall. In the absence of artificial lighting it is likely that the illuminance on the walls away from the windows will be less than one tenth of those close to them. Moreover, as any furniture in the room is likely to break up the space and hence disrupt any lightness constancy, it is possible to argue like Jay[3] that lightness constancy will not govern the perception of the space as a unified room and people close to the widow may judge the space adequately lit and those at the back of the room may not.

As MRSE has the above problems, it would be useful to have a new metric that could be more universally applied and at the same time had a similar relationship with perceive adequacy of illuminance. MRSE is described by Duff *et al*[2] as "*the measure of overall density of reflected (excluding direct) luminous flux within a space*". It is thus possible to consider a metric that describes the density of inter reflected light at a point within the space and by assessing the metric at a number of locations within the space derive a metric that describes the overall density of reflected lighting in the whole room or area.

A good starting point for this is cubic illuminance. Cubic illuminance as a concept was described by Cuttle[4], "*Cubic illumination specifies the spatial distribution of illumination about a point in terms of the illuminances on six faces of a small cube centred at the point*". Cuttle also described a number of methods of working with cubic illuminance at a point and used the values to describe lighting vectors and derive a number of other lighting metrics such as cylindrical and semi cylindrical illuminance. To solve the issues with MRSE we propose the use of mean indirect cubic illuminance (MICI). This metric is the average of the 6 indirect illuminances received on the faces of a cube.

In the case when all the room surfaces have the same exitance it is possible to demonstrate that MICI at all points in the volume of the space will be the same as the MRSE of the room. It can be shown that under a uniform luminance field the illuminance at point will be equal to π times the luminance[5]. Given that the exitance of a Lambertian diffuser is also π times the luminance then MICI and MRSE will always be equal.

The situation in real rooms is more complex and it is not possible to demonstrate the mathematical relationship between MICI and MRSE in a general mathematical sense. However, the authors hypothesised that the average MICI of all points in the volume of the space should be same as MRSE and to test this they calculated and compared the MRSE and MICI in a wide range of rooms for which MRSE is a valid measure.

2. Method

To test the relationship between MRSE and MICI, 10,000 separate rooms were considered. The length, width and height of the rooms were all set separately to random values in the range shown in Table 1. The values were based on room dimensions that are likely to be found in practice. All of the room surfaces were individually assigned a random luminance in the range 0 to 80 cdm^{-2}, this corresponds to exitances of up to just over 251 lumens per square metre. The luminance of each of the surface was uniform.

In each room a number of calculation points was selected such that the distance between any two points in any direction was less than 1m. The MRSE in each room was calculated from the areas of the six surfaces and the luminance of each of the surfaces and the result multiplied by π to convert the luminance into exitance. The indirect illuminance at each calculation point on each of the six faces of a nominal cube was calculated by subdividing the room surfaces into small patches with their maximum dimension less than one tenth of the distance of the calculation point to the surface. The areas were then treated as point sources with their luminous intensity being calculated from the projected area of the surface toward the calculation point and the surface luminance. The six illuminance values were then averaged to create the mean indirect cubic illuminance for the point and then all of point values were averaged to create an average MICI for the whole room.

3. Results

The calculated values of MRSE and average MICI for each of the 10,000 rooms are plotted in Figure 2. This shows that MRSE is closely correlated with average MICI with a R^2 value greater than 0.999.

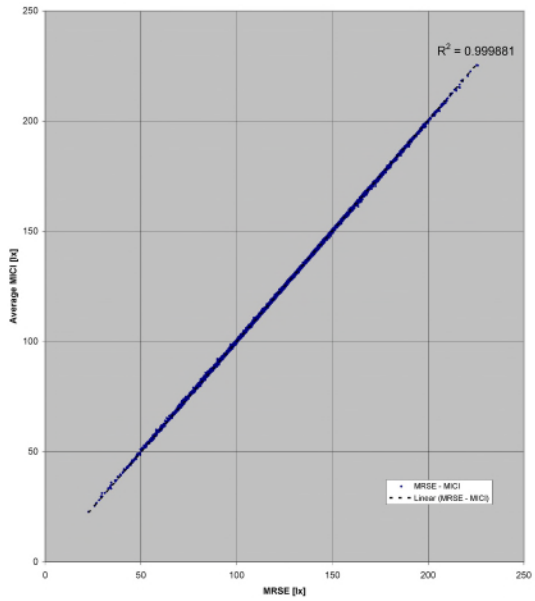

Figure 2. A plot of MRSE against average MICI

The ratio of MRSE to average MICI was calculated for each room and the mean of all of the values was 0.999 indicating that average MICI is very close to MRSE. The number of values in narrow ranges (±0.005) about a centre value were plotted (see Figure 3) and it is clear that distribution of results may be considered to be Gaussian.

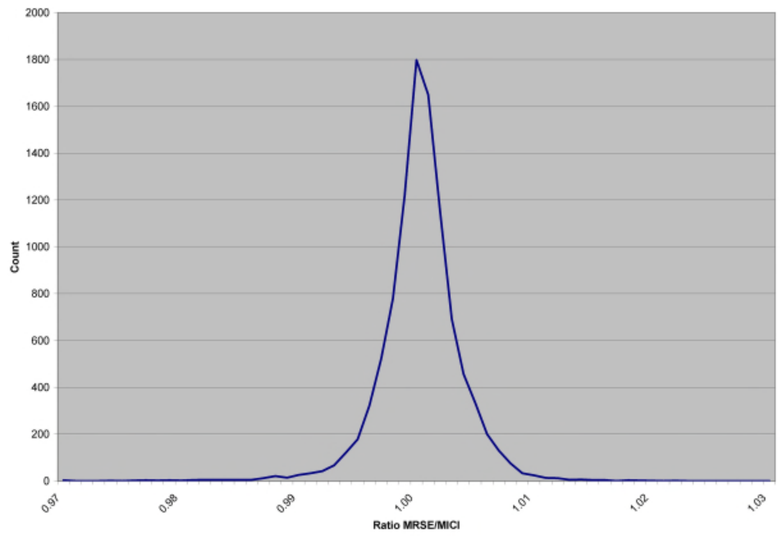

Figure 3. Distribution of values of the ratio MRSE / average MICI

Given that the distribution is normal it was possible to calculate the standard deviation of the ratios and it was found to be 0.0035. Given that the average ratio of MRSE to average MICI is close to unity then using the language of CIE 198[6] it would be possible to describe the MICI calculation predicting MRSE with an uncertainty of 0.35%.

4. Discussion

Conceptually MRSE and MICI are different. MRSE describes the average inter-reflected flux density within a room, and is independent of location within the room as well as view direction. MICI describes the inter-reflected flux density at a point in the room and thus is a function of position within the room but is independent of view direction. For a range of rooms this paper has shown that the average value of MICI is the same as MRSE, however, MICI has the advantage that it can be computed in complex rooms, where not all of the room surfaces can be seen from all points in the room. Moreover, MICI may also be useful in a room where the lighting is very non uniform.

Consider a room that is 10 m long and 5m wide and 2.4 m high. In one of the short walls there is a window 4m by 1m with a transmittance of 0.7. The bottom of the window is 0.8m above the floor, the ceiling has a reflectance of 0.7, the walls 0.5

and the floor 0.2. Calculations were made for the room under an overcast sky that created an external illuminance of 14,100 lux. This value was chosen as it is the median external illuminance for London[7]. From the calculated illuminance for each of the room surfaces it was found that the room had a MRSE value 80.7 lx. The results of the calculation of MICI at a height of 1.2 m above the floor are shown in Figure 4. Whilst the average of all MICI values at 1.2 m above the floor is 77.5 lx the figure shows that there is a significant variation across the room. Whilst about one third of the room close to the window has MICI values in excess of 100, the region of the room close to the rear wall has MICI values that are below 40. This wide difference in MICI is likely to result in the rear part of the room being regarded as being too dark whilst the side of the room close to the window has adequate illumination.

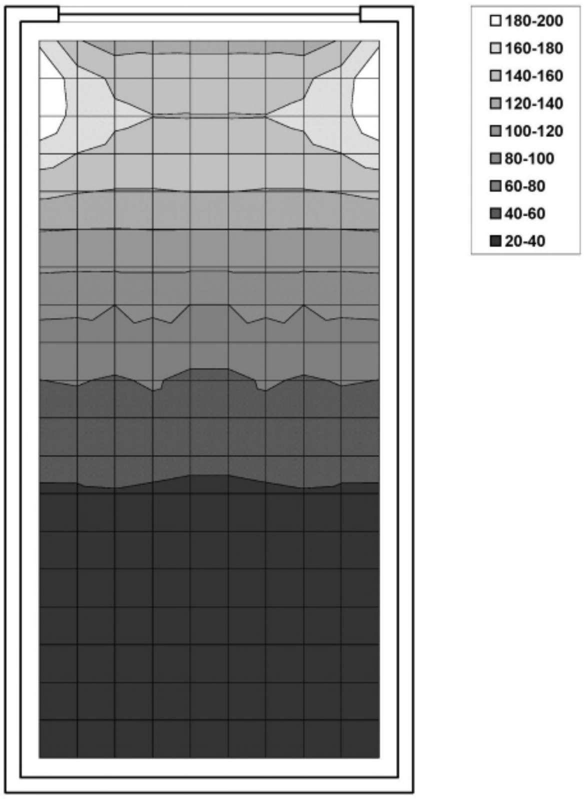

Figure 4. Plot of the distribution of MICI [lx] in a room with non-uniform lighting

This finding is no surprise and there is a test in BS 8206-2[8] for rooms that are lit by windows in only one wall to determine if the lighting is uniform.

The test is given in equation (1)

$$\frac{L}{W}+\frac{L}{H}\leq\frac{2}{1-R_b} \quad (1)$$

where:

L	is the depth of the room [m]
W	is the width of the room [m]
H	is the height of the room [m]
R_b	is the area weighted average reflectance of the room surfaces

The room clearly fails this test and its length would need to be reduced to 6.15m for it to pass the test. In this room the MRSE value of 80.7 lux would indicate that room is likely to be regarded as being slightly under lit. However, would people working at different places in the room characterise their perception of the adequacy of illumination the same or would people at the back of the space consider the room darker than those close to the window?

5. Conclusion

It has been shown that in a variety of regular rooms the average value of mean indirect cubic illuminance is very nearly equal to the mean room surface exitance. Thus, it can be assumed that perceived adequacy of illumination can be predicted from average MICI. The limitation of this is that so far the connection between MRSE and PAI has only been established in uniformly lit spaces and there has been no attempt to see if PAI varies across rooms that are not uniformly lit. Moreover, the connection of MRSE to PAI has not been tested for daylit rooms and it quite possible that the luminance of surfaces outside the window may contribute to the perception of illuminance adequacy within the room. Thus, further research is needed to explore the relationship of MICI with PAI in rooms that are complex, daylit or both.

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Figure captions

Figure 5. An L Shaped room in which it is not possible to see all the room surfaces from point P

Figure 6. A plot of MRSE against average MICI

Figure 7. Distribution of values of the ratio MRSE / average MICI

Figure 8. Plot of the distribution of MICI [lx] in a room with non-uniform lighting

Table 1. Range of room dimensions

Room Dimension	Minimum Value [m]	Maximum Value [m]
Length	4	20
Width	2.5	16
Height	2.2	6