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Spatial Brightness, Horizontal Illuminance and Mean Room Surface Exitance in a Lighting Booth

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Spatial brightness, horizontal illuminance and mean room surface exitance in a lighting booth

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Short title: Spatial brightness, horizontal illuminance and MRSE

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This paper presents a pilot study that has investigated the suitability of mean room surface exitance as a predictor of spatial brightness and compared these results with how horizontal illuminance predicts spatial brightness under the same conditions. The experiment took a group of 26 participants and, using a scaled booth, exposed each participant to three levels of mean room surface exitance, each delivered with three different light distributions and three different surface reflectances, resulting in a total of 27 light scenes. Results demonstrated that, under the range of conditions to which participants were exposed, a systematic relationship existed between mean room surface exitance and spatial brightness, but not between horizontal illuminance and spatial brightness.

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1. Introduction

In recent years, indoor lighting standards and guidance documents have changed to allow designers the option to select the orientation of the working plane within a space, which may, or may not be, the horizontal plane. In addition, new metrics such as mean cylindrical illuminance, a modelling index and minimum quantities of illuminance on major room surfaces have been added.[1-2] Whilst these have been formally introduced into standards and guidance, for those working within the lighting industry, it can be observed that the most prominent lighting metric in practice remains the quantity of illuminance on the horizontal working plane. This observation is supported by Boyce who states; *"Despite the use of task plane rather than working plane in recent recommendations and the fulminating of various eminent personages, the fact is the horizontal working plane is still the plane of choice for simple lighting calculations"*.[3]

Over the past decade, Cuttle has been the prime advocate for reforming indoor lighting standards from their current state, to consider an alternative approach that he believes better relates to what we see.[4,5,6,7,8] Cuttle has suggested that mean room surface exitance (MRSE),5 being the measure of overall density of reflected (excluding direct) luminous flux within a space, is a metric that may correlate with the perceived brightness of a space, or in other words, the spatial brightness. Spatial brightness is a term that relates to the perceived quantity of light within a space, or the light that is influencing the appearance of a space rather than illuminating the tasks. Fotios *et al* provide a good review[9] and for reference, spatial brightness has previously been referred to as building lighting,[10] room brightness[11] and in some more recent studies, scene brightness.[12,13]

Cuttle proposes MRSE with the intention that it would be a proxy for the quantity of light arriving at the eye, which could also be represented by the indirect illuminance on a vertical plane at eye level. Many past studies have investigated the influence of spectral power distribution on spatial brightness,[9,14,15,16,17,18,19,20,21,22,23,24,25] whilst others have examined the influence of light on a horizontal or vertical plane[26] and within a defined field of view.[27,28] Rea *et al* found better correlations with brightness between illuminance measured on a vertical plane than with that measured on a horizontal plane.[26] In two separate studies, Loe *et al* found strong correlations between assessments of brightness and the illumination of a horisontal band 40° wide.[27,28]

Cuttle's ideas have generally been well received[29,30,31,32,33,34] and Boyce[3] even offers the procedure as one of three possible ways in which the gap between indifferent quality lighting and good quality lighting might be bridged in the future. However, before Cuttle's ideas can be considered for implementation, the relationship between MRSE and spatial brightness must be better understood. This paper investigates the relationship between MRSE and spatial brightness, and also compares the relative merits of MRSE and horizontal illuminance (E_h) as suitable predictors of spatial brightness. Whilst the spectral power distribution of a light source is very relevant to perceived spatial brightness, this study deals only with how the level of MRSE, the associated spatial distribution of the light and the space surface properties influence the perception of spatial brightness.

2. Method

A lighting booth was constructed from MDF and sealed for light tightness using silicone caulk (Figures 1 and 2). The booth was 860 mm high, 1500 mm long and 850 mm deep and contained multiple hatches spaced out in a regular grid on all sides of the booth. The smaller hatches were used solely for measurement. Two large hatches, one on each long elevation of the booth, facilitated viewing points, with volunteer participants pressing their faces against this to view the booth interior. The booth sat 750 mm above finish floor level on in-built legs. Luminance values were recorded through each of the measuring hatches and converted to MRSE using equations 1 and 2. Luminance values were recorded using an independently calibrated Konica Minolta LS-110. Reflectance values were calculated using luminance and illuminance measurements. Prior to beginning the each experiment, all lamps were run at full output for a sufficient length of time so that their output stabilised. This was verified with spot measurements taken at the start and end of each light scene.

For each surface within the booth, the mean exitance (M_S) of that surface is given by the product of the mean recorded luminance (L_S) and pi:

$$M_S = L_S\,\pi \tag{1}$$

The MRSE is then given by the sum of the product of the mean exitance (M_S) and area (A_S) for all surfaces, divided by the total room surface area:

$$MRSE = \frac{\sum M_S\,A_S}{\sum A_S} \tag{2}$$

Lighting in the booth was provided by pulse width modulation (PWM) dimmable 300 mm T5 fluorescent lamps, with two of each located inside custom aluminium housings. The lamps had a correlated colour temperature of 4000K and a colour rendering index of 80. Lamps were circuited, grouped (SC-1, SC-2, SC-3 in Figure 2) and dimmed together to produce uplight and downlight components. Light scenes were programmed using a DSI interface and a scene set panel.

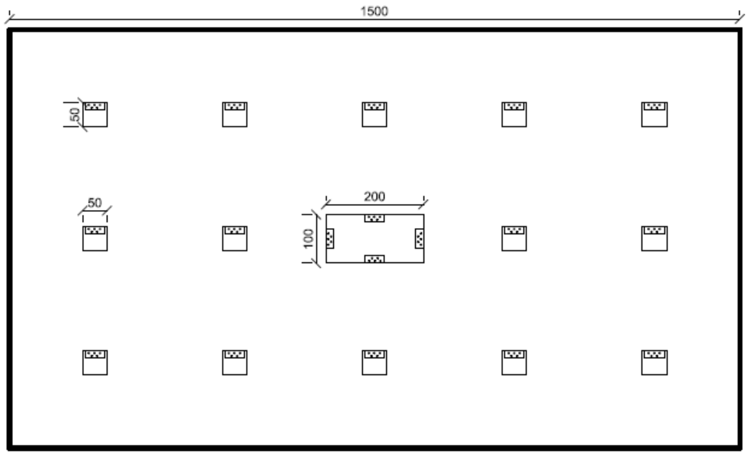

Figure 1. Front elevation of the lighting booth. Note the smaller measuring hatches and the larger central hatch for viewing. Measuring hatches, at similar spacing, were used on all sides of the booth, including the top and bottom surfaces.

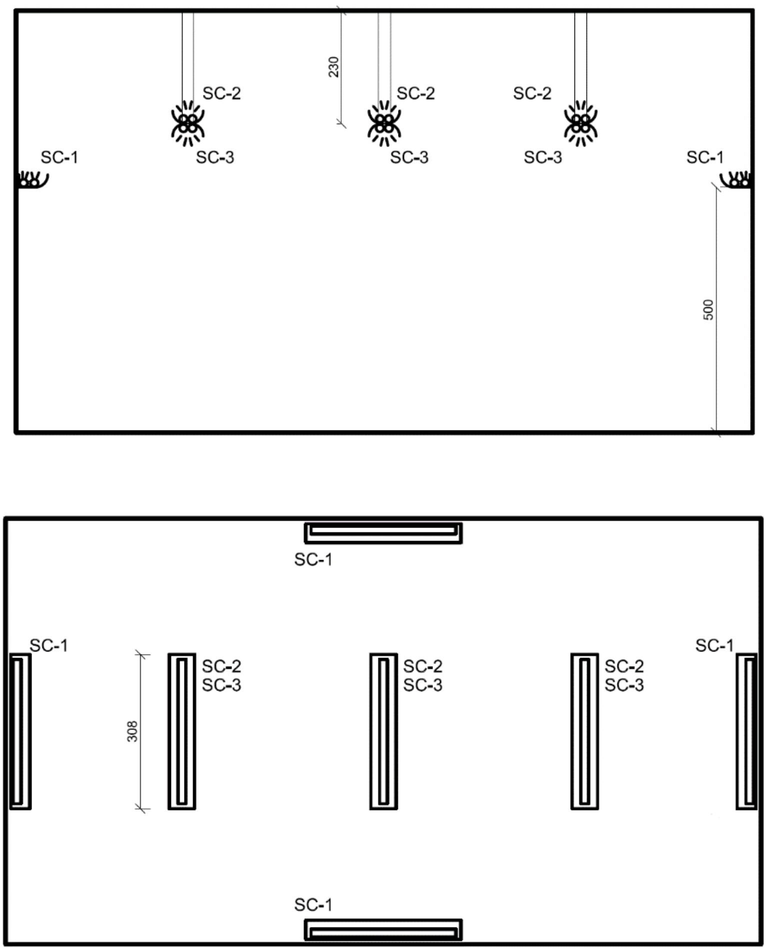

Figure 2. Elevation and plan sections of the lighting booth. Note the position of lamps and the switching circuits as described in Section 2.

The study examined the subjective response to the spatial brightness perception of 26 participants. Participants were between the ages of 18 and 25 years (mean=20.8 years, standard deviation=2.3 years) with no participant using corrective eyeware. In each experiment, participants viewed a range of light scenes. The experiment used groups of two participants and each participant completed three separate sittings. During each sitting, participants were exposed to nine different light scenes at varying levels of MRSE, with the corresponding level of E_h at booth floor level also recorded. Three levels of MRSE were set up; 25, 50 and 100 lm/m^2, along with three methods to achieve the distributions of each, these being *indirect*, *direct* and *mixed*. *Indirect* scenes were a combination of SC-1 and SC-2, *direct* scenes were solely SC-3 and the *mixed* scenes were a combination of all three switching circuits. The reflectance on the internal surfaces of the booth and within the interior of the experimental space were also varied to broadly represent *light*, *medium* and *dark* surface properties. Together, these combinations produced a total of 27 light scenes. A graphical breakdown of the light scenes is given in Figure 3 and further details about surface reflectances and luminance distributions are given in Table 1.

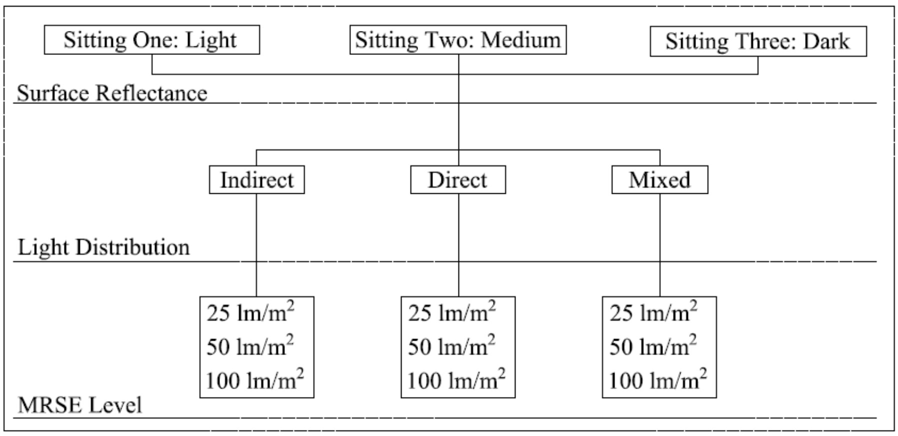

Figure 3. Graphical representation of each light scene programmed. Note that each sitting contained static surface reflectances, but varied levels of MRSE and light distribution.

The order of exposure to light scenes was randomised and three scenes were repeated to compare participant responses. The numbering of each light scene is given in Table 1. The repeated scenes were scene 7, scene 14 and scene 21 and were chosen to best include each of the variables; being one scene from each level of MRSE, one scene from each light distribution and one scene from each surface reflectance. Participants were exposed to each scene for two minutes and during each scene, answered one question that examined subjective spatial brightness levels on a seven point semantic differential scale. Question response polarity was varied at random to prevent directional bias.

Q1. On the scale below, please rate the brightness of the entire booth.

very dim	*dim*	*slightly dim*	*neither dim nor bright*	*slightly bright*	*bright*	*very bright*

Brightness scales were defined using the definition coined by Vrabel *et al*[35]; "*very bright is represented by the light in an outdoor sports area (when all the floodlights are on) and very dim is the level of an outdoor parking lot at night*". In addition to this, participants were reminded prior to each scene change that they should relate brightness to the entire booth, and not solely to their immediate field of view.

3. Results

Values of one to seven were assigned for responses from *very dim* to *very bright*, respectively. A full list of the mean spatial brightness response ratings, coupled with the associated standard deviations, for all light scenes is given in Table 1.

4. Data analysis

Using parametric statistical tests requires the data to be drawn from a normally distributed sample. Distribution of data was investigated using statistical and graphical methods available through SPSS, namely; measures of central tendency, skewness, frequency histogram, kurtosis, box and whisker plots and probability plots. These tests indicated that the data were not normally distributed and as such, non-parametric statistical tests have been applied.

4.1 Repeated scenes

Repeated scenes were introduced to ensure that the order of light scene exposure had no impact on subjective assessments. As stated previous, three scenes were repeated without participants knowledge; scene 7, scene 14 and scene 21, with the repeated scene being excluded from the final results. Scores produced from each of these scenes were examined using the Wilcoxon signed-rank test. All three repeated scenes produced no statistically significant differences between participants' first response and their second (scene 7, $Z = -0.933$, $p = 0.351$; scene 14, $Z = -1.155$, $p = 0.248$ and scene 21, $Z = -1.265$, $p = 0.206$). It can thus be concluded that the order of exposure had no significant impact on participants' assessments.

4.2 Mean room surface exitance and spatial brightness

Repeated measures analysis of variance (ANOVA) was used to investigate the influence of the different independent variables on spatial brightness assessments. To change the reflectance of the internal surfaces of the booth, they were repainted and as such, it could not be avoided that participants saw each surface reflectance in the same order, producing an associated order effect. For this reason, three separate two by three repeated measures ANOVA's were carried out, with level of MRSE (3) and light distribution (3) as the independent variables.

In sitting one, participants viewed scenes with *light* surface reflectances as given in Table 1. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 5.49$, $p = 0.064$, level of MRSE, $X^2(2) = 0.0256$, p =

0.987, and the interaction between level of MRSE and light distribution, $X^2(9) = 2.682$, $p = 0.976$. Within subjects effects then showed that the subjective assessment of spatial brightness was influenced by the level of MRSE, $F(2, 50) = 190.112$, $p < 0.001$, and also by light distribution, $F(2, 50) = 15.605$, $p < 0.001$. There was no significant interaction between level of MRSE and light distribution, $F(4, 100) = 0.182$, $p = 0.947$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was a significant difference between direct and indirect scenes ($p < 0.001$) and also between direct and mixed ($p < 0.001$). No statistically significant difference could be found between the mixed and indirect scenes. For level of MRSE, there was a statistically significant difference between each of the pairs of means ($p < 0.001$).

In sitting two, participants viewed scenes with *medium* surface reflectances as given in Table 1. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 2.314$, $p = 0.314$, and for the interaction between light distribution and level of MRSE, $X^2(9) = 13.629$, $p = 0.137$, but not for level of MRSE, $X^2(2) = 12.954$, $p = 0.002$. For level of MRSE, *F* values are reported using degrees of freedom corrected with the Greenhouse-Geisser factor ($\varepsilon = 0.706$). Within subjects effects showed that subjective assessment of spatial brightness was influenced by level of MRSE, $F(1.41, 35.3) = 145.958$, $p < 0.001$, and also by light distribution, $F(2, 50) = 13.474$, $p < 0.001$. There was also a significant interaction between level of MRSE and light distribution, $F(4,100) = 4.698$, $p = 0.002$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was again a significant difference between direct and indirect scenes ($p < 0.001$) and also between direct and mixed ($p < 0.001$), but with no statistically significant difference being concluded between the mixed and indirect scenes. For level of MRSE, there was again a statistically significant difference between each of the pairs of means ($p < 0.001$).

In sitting three, participants viewed scenes with *dark* surface reflectances as given in Table 1. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 1.38$, $p = 0.502$, level of MRSE, $X^2(2) = 3.353$, $p = 0.187$, and the interaction between level of MRSE and light distribution, $X^2(9) = 10.598$, $p = 0.305$. Within subjects effects then showed that subjective assessment of brightness was influenced by level of MRSE, $F(2, 50) = 223.244$, $p < 0.001$, and also by light distribution, $F(2, 50) = 11.520$, $p < 0.001$. There was also a significant interaction between level of MRSE and light distribution, $F(4, 100) = 2.722$, $p = 0.002$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was again a significant difference between direct and indirect scenes ($p = 0.001$) and also between direct and mixed ($p < 0.001$). No statistically significant difference could be concluded between the mixed and indirect scenes. For level of MRSE, there was a statistically significant difference between each of the pairs of means ($p < 0.001$).

4.3 Mean room surface exitance and mean horizontal illuminance

Graphing the mean spatial brightness response of each light scene visually indicates the difference in relationship between MRSE and spatial brightness, compared with horizontal illuminance ($E_{h)}$ and spatial brightness (Figure 4 and 5). Applying a linear regression to MRSE and spatial brightness produces a strong relationship between the two items ($R^2=0.89$). Within this experiment, horizontal illuminance was not explicitly controlled as an independent variable and in addition, participants viewed values of it within a small range, generally between 50 lux and 250 lux. However, applying a linear regression model to E_h and spatial brightness serves as a pragmatic backward inference as to the relationship experienced between the two items. Considering the entire dataset as a whole, no predictable relationship could be found. Visually examining Figure 5 shows that three outlying points strongly influence the regression line. Applying a linear regression that excludes these points improves the relationship experienced ($R^2=0.46$), but not to the level where it could be considered strong.

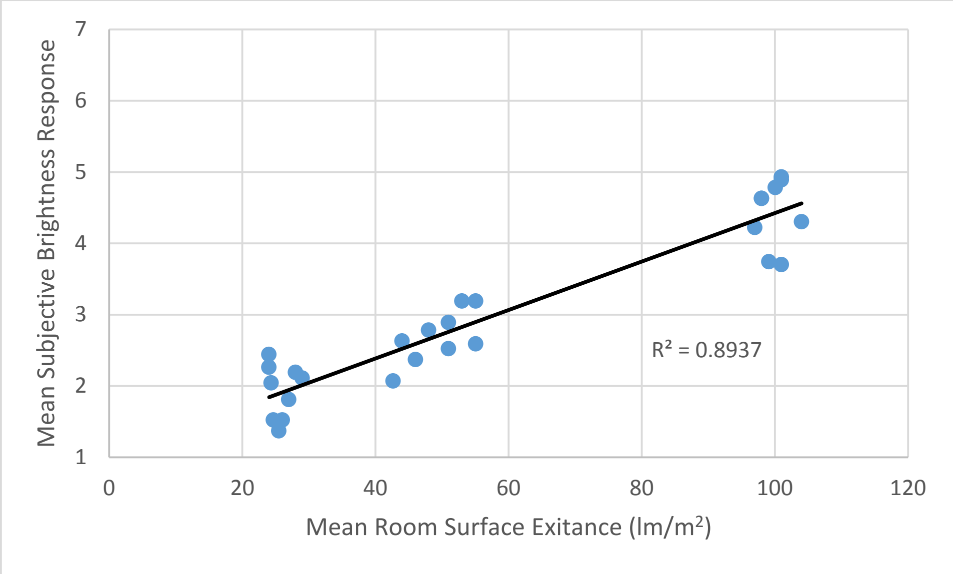

Figure 4. The mean spatial brightness rating plotted against the mean room surface exitance for each light scene presented.

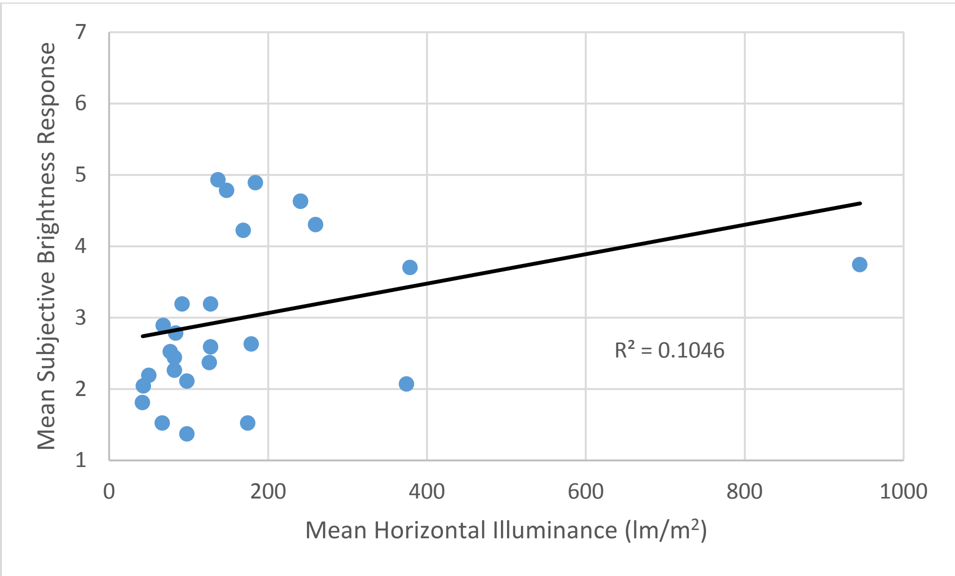

Figure 5. The mean spatial brightness rating plotted against the horizontal illuminance for each light scene presented.

5. Discussion

Analysis of the results has shown that regardless of light distribution or surface reflectance, in the light scenes presented, the level of MRSE had a significant impact on subjective assessment of spatial brightness. In addition, whilst participants were exposed to two independent variables during each sitting, MRSE and light distribution, analysis demonstrated that level of MRSE had a stronger impact on assessment of spatial brightness than light distribution.

The relationship between luminance and brightness has previously been shown to be logarithmic,[36,37,38,39,40] but the upper levels of luminance used in these studies reached values far in excess of what the participants were exposed to in this experiment. Participants viewed scenes between 25 lm/m^2 and 100 lm/m^2, with the maximum recorded luminance being 86 cd/m^2. The results in this study demonstrated a strong linear relationship between MRSE and spatial brightness. Remembering that values one to seven were assigned to each response category from *very dim* to *very bright*, the relationship between spatial brightness (*B*) and MRSE experienced in this study can be approximately given by:

$$B = 1 + \frac{MRSE}{30} \quad (3)$$

Again, it should be noted that the maximum value of MRSE used in this study was $100lm/m^2$. It is envisaged that as levels of MRSE increase above this value, ratings of brightness may plateau. Verifying and further understanding this relationship will be a focus for future work.

From the linear regression analysis, and visually from Figures 4 and 5, it can be seen that for the light scenes used in this study, MRSE was a superior predictor of spatial brightness when compared with E_h. Logically, increasing or decreasing the luminance of the surfaces within a space will have an impact on how dim or bright it appears, but the illumination engineering metrics used to control this phenomena are not yet widely understood. Loe *et al* investigated subjective response to brightness using the average luminance and the luminance distribution standard deviation within a horizontal band 40° wide.[27] The authors here did not record luminance values within the horizontal band 40° wide, but did record luminance values on all booth surfaces. Using the premise that the mean luminance of the booth walls is approximately equivalent to that of the 40° wide horizontal band, correlations can be drawn between mean wall luminance and MRSE (*r = 0.95*) and also between mean wall luminance and E_h (*r = 0.69*). This serves to highlight that if controlling luminance in the field of view is of importance, then for the scenes used in this study, even with a wide range of light distributions and surface reflectances, MRSE did a better job than E_h.

In two separate studies, Loe *et al*[27,28] found that firstly, for a room to appear "*light*", it needed to have an average luminance within the horizontal band 40° wide of at least 30 cd/m^2 and secondly, that for a space to "*begin to appear bright*", luminance levels within the horizontal band 40° wide need to be approximately 40 cd/m^2. The results found in this study show substantial agreement with these findings.

6. Limitations

The definition of brightness given to study participants should be considered. This was taken from previous work by Vrabel *et al*[35] and it informed participants to relate very bright to "*the light in an outdoor sports area (when all the floodlights are on)*" and relate very dim to the brightness "*of an outdoor parking lot at night*". Whilst defining the ends of the semantic scale has benefits, in this case, the chosen definition caused scale compression. None of the light scenes that participants viewed approached a brightness close to the level of an outdoor sports area, nor did they come close to the dimness of an outdoor parking lot at night. Defining these extremes may have ultimately suggested to participants that they should not choose towards the outer ends of the scale and results of this are evident in Figure 4, where few scenes were scored towards the upper end of the brightness scale.

A range of surface reflectances was presented, but due to the nature of changing reflectance properties, participants experienced these in a fixed order, producing an associated order effect. As such, results across each of the surfaces reflectances could not be compared in an ideal manner.

While this research has examined a range of light distributions, it has not explored very extreme distributions. Truly non-uniform distributions were not investigated and it still remains unclear how participants will react to these.

Many past studies have investigated how the spectral power distribution of the lighting affects the perceived brightness of a space and this work is still on-going. The work presented in this paper did not vary spectral power distribution, with each of the sources used having a CCT of 4000K and a CRI of 80.

7. Conclusion

This paper presents a pilot study conducted as part of on-going research. It used a lighting booth to investigate the relationship between MRSE and spatial brightness under varying surface properties and light distributions, but with static source spectral power distributions. It then compared this relationship to the relationship between E_h and spatial brightness under the same conditions. From the data collected and considering the limitations discussed, the key findings of this work have been:

- A simple linear relationship was found to exist between MRSE and spatial brightness.
- A broadly unpredictable relationship was found to exist between E_h and spatial brightness.

These conclusions are drawn within the limitations discussed and in the knowledge that the experiment presented is a preliminary study. Further work is underway to continue investigating the topic.

Funding

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Figure captions

Figure Error! Main Document Only.**.** Front elevation of the lighting booth. Note the smaller measuring hatches and the larger central hatch for viewing. Measuring hatches, at similar spacing, were used on all sides of the booth, including the top and bottom surfaces.

Figure 2. Elevation and plan sections of the lighting booth. Note the position of lamps and the switching circuits as described in Section 2.

Figure 3. Graphical representation of each light scene programmed. Note that each sitting contained static surface reflectances, but varied levels of MRSE and light distribution.

Figure 4. The mean spatial brightness rating plotted against the mean room surface exitance for each light scene presented.

Figure 5. The mean spatial brightness rating plotted against the horizontal illuminance for each light scene presented.

Table Error! Main Document Only.. Properties of the 27 lights scenes programmed. Also indicated is the mean subjective spatial brightness rating for each light scene.

Light Scene	Target MRSE (lm/m^2)	Surface Reflectance (Ceiling/ Wall/ Floor)	Light Distribution	Recorded MRSE (lm/m^2)	Recorded Horizontal Illuminance (lm/m^2)	Mean Recorded Luminance (cd/m^2)				Mean Spatial Brightness Rating (SD)
						Floor	Ceiling	Long Wall	Short Wall	
1	25	Sitting 1 88/83/27	Indirect	29	67	3	16	10	8	2.08 (0.92)
2	25		Direct	26	98	6	7	10	9	1.54 (0.57)
3	25		Mixed	28	50	4	12	10	9	2.19 (0.68)
4	50		Indirect	51	68	5	28	17	15	2.96 (1.32)
5	50		Direct	46	126	11	13	16	16	2.38 (0.74)
6	50		Mixed	53	92	8	23	19	16	3.19 (0.83)
7	100		Indirect	101	137	9	56	34	30	4.96 (1.16)
8	100		Direct	104	260	22	28	40	34	4.31 (1.29)
9	100		Mixed	101	184	16	42	36	31	4.92 (0.92)
10	25	Sitting 2 73/64/27	Indirect	27	42	3	19	9	7	1.85 (0.77)
11	25		Direct	26	98	8	7	10	8	1.38 (0.56)
12	25		Mixed	24	82	4	13	9	7	2.27 (0.65)
13	50		Indirect	51	77	5	36	16	13	2.58 (0.84)
14	50		Direct	44	179	15	12	15	15	2.65 (0.68)
15	50		Mixed	55	128	10	28	19	15	2.62 (0.62)
16	100		Indirect	100	148	9	70	32	24	4.81 (1.14)
17	100		Direct	101	379	29	25	39	33	3.73(1.16)
18	100		Mixed	98	241	19	46	33	27	4.65 (1.04)
19	25	Sitting 3 48/44/13	Indirect	24	43	2	21	7	5	1.58 (0.78)

20	25		Direct	25	175	9	5	9	8	1.27 (0.52)
21	25		Mixed	24	82	4	13	9	7	2.15 (0.57)
22	50		Indirect	48	84	3	43	14	9	2.42 (0.99)
23	50		Direct	43	374	17	10	14	15	1.96 (0.72)
24	50		Mixed	55	128	10	28	19	15	2.54 (0.96)
25	100		Indirect	97	169	7	86	28	18	5.08 (1.00)
26	100		Direct	99	945	50	29	45	45	4.08 (0.94)
27	100		Mixed	98	241	19	46	33	27	4.38 (1.09)