Lighting for Subsidiary Streets: Investigation of lamps of different SPD. Part 2 - Brightness

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Abstract

British Standard BS5489-1: 2003 permits a trade-off between colour rendering and illuminance for lighting in subsidiary streets – if lamps of high colour rendering index are used, such as metal halide instead of low- and high-pressure sodium, a lower illuminance can be used. A series of tests were carried out to validate the trade-off and this article reports on the new brightness data from these tests. The experimental results support the trade-off but it is suggested that its application may depend on the stage of chromatic adaptation at which the assessment of brightness is made. The experimental results were compared with predictions made by four models of mesopic photometry.

1. Introduction

In the UK, where lighting in subsidiary streets is designed for the demands of the pedestrian, the design illuminance is specified through two documents. BS EN 13201-2:2003[1] specifies the minimum maintained average horizontal photopic illuminance for six lighting classes, the S-series, ranging from S6 = 2.0 lux to S1 = 15.0 lux. Surrounded by surfaces of low reflectance, e.g. r = 0.07, typical of asphalt, these illuminances imply photopic luminances in the range 0.04 to 0.33 cd/m^2, which means the pedestrian's visual system will usually be operating in the mesopic state.

BS5489-1:2003[2] identifies the selection of a lighting class according to crime rate and traffic flow and furthermore permits a reduction of one S class (i.e. a reduced illuminance) if lamps of General Colour Rendering Index (CRI) $R_a \geq 60$ are used. CRI is an unreliable metric upon which to base such a trade-off, giving a limited description of one aspect of a complex spectral power distribution and making no reference to the appearance of the light. However, for the range of lamps currently in common usage in the UK for exterior lighting, it appears to give suitable guidance as to which lamps the trade off is intended to apply. Of the five million street lighting luminaires in the UK, the majority use High Pressure Sodium (HPS) or Low Pressure Sodium (LPS) lamps, as was recommended in the previous issue of BS5489[3] for their high luminous efficacy and long life despite poor colour rendering performance. The trade-off is used to support the installation of lamps such as Metal Halide (MH) which have a higher colour rendering index than sodium lamps but a lower luminous efficacy[†] - the illuminance reduction offsets the lower efficacy and hence offsets an increase in overall energy consumption.

The decision to permit a reduction of one S-class in illuminance was drawn from the professional judgement of practising lighting engineers. To encourage widespread use of the trade-off there is a need to determine whether it is supported by research evidence. A recent review[4] concluded that further evidence is required as to how lamps of different spectral power distribution (SPD) affect brightness and on-axis visual performance. Experimental work has been carried out to fill these gaps. The current paper discusses the results and implications of brightness assessments. A second paper[5] discusses the results of visual performance tests.

When lighting for pedestrians is being considered, brightness is likely to matter because it is a fundamental visual perception that experience tells us is related to the amount of light present, and that in turn is related to how well we can see where we are going and what is happening around us. An area that is brightly lit after dark is perceived to provide good visibility and that, in

[†] HPS lamps tend to have a higher luminous efficacy than MH lamps, although this depends on the particular type of lamp (e.g. SON or SON Plus) and wattage.

the public mind, is likely to be more interesting and safer.[6] There is evidence that increasing the light level in an area from a low level will reduce the fear of crime, even if its effect on actual crime is dependent on other factors.[7] Light sources that provide a perception of greater brightness than others at the same photopic luminance are likely to be perceived as producing a safer environment. Alternatively, light sources that maintain the same level of brightness and perceived safety but at a reduced illuminance may lead to reductions in energy consumption.

A review[4] of laboratory and field studies of brightness using lamps that tend to be used for street lighting revealed a confusing picture. There is some evidence that different SPDs do produce different brightness perceptions at the same photopic luminances in mesopic conditions but there are also studies that have failed to reveal any consistent effects of SPD. The two studies considered to be the most reliable, and which have compared HPS and MH lamps, are by Rea[8] , who suggests that MH and HPS are differently bright at the same photopic illuminance, and by Boyce & Bruno[9], who suggest the difference would be small if any. Models of mesopic photometry tend to suggest that there would be a difference in brightness at equal photopic illuminance.[4]

This paper reports on new investigations of brightness carried out using three techniques of assessment – semantic rating, side-by-side ranking, and side-by-side matching. Every method of judging brightness has its particular limitations and thus two or more techniques should be employed to compare the same stimuli - if these separately point towards the same conclusion then this promotes greater confidence of the robustness of the results. Two of the methods employ side-by-side presentation of two stimuli, giving mixed chromatic adaptation, exaggerating any differences between the two stimuli, and this is expected to show a strong effect of SPD on brightness if such an effect exists. The semantic rating method uses the test lamps individually, allowing more complete chromatic adaptation to each, and this is expected to reveal a weaker effect of SPD on brightness. In real situations, pedestrians may evaluate lighting under various states of chromatic adaptation and therefore both presentation methods are of practical interest.

Three questions are addressed:

1. Do lamps of different SPD produce lighting which appears differently bright? This is examined by validation of the trade-off between lamp type and illuminance specified in BS5489-1:2003.[2]
2. Is the assessment of brightness consistent when using different experimental techniques?
3. Can the results be predicted by proposed models of mesopic photometry?

2. Brightness Rating

The laboratory shown in Figure 1, of dimensions 10.5m x 6.1m x 5.7m high, was lit by one of the five types of light sources described in Table 1. These lamps were used because they are commonly used for street lighting in the UK. HPS and LPS lamps were recommended in the 1992 issue of BS5489[3] and are hence in widespread use. The current issue of BS5489[2] recommends a CRI of R_a>20 for urban and residential roads which means LPS lamps are no longer installed for these roads in the UK. The CFL and MH lamps are those that could take advantage of the S-class illuminance trade-off, having R_a>60. In following discussions, the CFL, MH1 and MH2 lamps are collectively referred to as the *white* lamps.

The lamps were installed in identical luminaires (URBIS FV3 symmetrical tunnel) to project similar spatial distributions of luminance from all five lamps. There were two identical clusters of luminaires, mounted 1.5m below the ceiling and facing downwards. Both clusters contained all five types of lamp. A translucent diffuser of opal white Perspex was fixed to the underside of the luminaires to assist in balancing the spatial distribution and shield the lamps from direct view. Measurements confirmed an approximately neutral spectral transmission. Opaque masking tape was fixed to the translucent diffuser to dim the light from each type of lamp to the higher reference illuminance of 15.0 lux. Moveable neutral density filters were placed between the lamps and the diffusing filter, and were pulled into place to enable dimming from the higher reference illuminance of 15.0 lux to the lower reference illuminance of 2.0 lux. These were mean illuminances on the floor, and are the lower and upper limits of the S-series.[1]

The room surfaces were painted matt grey, with few chromatic surfaces, and unused apparatus was covered with black cloth. Mean surface luminances were in the range 0.11 cd/m^2 to 1.03 cd/m^2 and it was confirmed that there was a similar spatial distribution of light under each light source. The vertical illuminances at the observer's eye when making the appearance judgements are shown in Table 2.

Test participants were initially dark adapted for 20 minutes in an adjacent side room. The laboratory was lit by one of the five sources to one of the two standard illuminances. After the participant entered the laboratory a period of 5 minutes was allowed for chromatic adaptation before the participant judged the appearance of the room using semantic rating. Eight rating items were addressed: bright, dim, dark, clear, hazy, pleasant, warm and cool. These were rated along an 8-point scale with end points labelled "very much so" and "not at all so". Forty-seven participants were used (18 older subjects aged 60+ with an approximate mean of 69 years; 29 younger subjects with an approximate mean age of 33 years; 31 were female) and each rated all ten lamp and illuminance combinations. All participants were confirmed colour-normal using the Ishihara test. The order of presentation of the ten lamp type and illuminance combinations, and the order in which the eight rating items were addressed, were randomised.

Mean values of the semantic ratings reported by the 47 participants are shown in Figure 2. Analysis of the individual rating items using the Friedman test suggests that lamp type has a significant effect ($p<0.001$) except for the pleasantness ratings which show no significant difference between the different types of lamp. Friedman analysis was used because the results are not normally distributed: analysis using ANOVA confirms these conclusions but also suggests that lamp type does affect the pleasantness ratings ($p<0.01$). Repeated application of the Wilcoxon Signed Ranks test (and confirmed by the *t*-test) suggests that the white lamps (MH1, MH2, CFL) produce an environment which is significantly brighter and clearer than the HPS ($p<0.05$), which is in turn brighter ($p<0.01$) and clearer ($p<0.001$ at 15.0 lux; not significant at 2.0 lux) than the LPS. There is a hint that the MH2 is brighter and clearer than the MH1 and CFL which are rated equal. Only the 'bright' rating was significantly affected by age, with the older age group rating all the white lamps to be less bright than did the younger age group (Mann-Whitney test, $p<0.05$).

The mean floor illuminances were aimed at two levels, 2.0 lux and 15 lux. The different types of lamp gave approximately, but not exactly, these illuminances. It is thus possible that illuminance differences could explain the different ratings applied to each lamp. Figure 3 compares mean ratings for the item *bright* with actual mean illuminance. Although the ratings made at around 15.0 lux are rated brighter than the ratings made at around 2.0 lux, there is no clear trend between brightness ratings and actual illuminance within these two groups. A similar conclusion can be drawn for the other rating items. Hence it is concluded that, within the separate upper and lower illuminance groups, the actual illuminance under each lamp type did not affect the ratings.

3. Side-by-Side Brightness Ranking

Two juxtaposed booths, as shown in Figure 4, were simultaneously illuminated by separate light sources (Table 1). The viewing chamber of each booth was of approximate dimensions 575mm deep x 680mm wide x 660mm high, hence each booth presents a visual field of 38^{O} wide by 37^{O} high from the seated viewing distance of one metre in front of the central partition. This size is close to the horizontal band of 40^{O} suggested to be the primary field of view.[10] The interior surfaces were painted matt grey and contained coloured objects, these being four pyramids 60mm high, one each made from red, green, yellow and blue card. The test lamps were fitted behind the booths, the light being directed to the top of the booth through a light pipe into which an iris damper was inserted to permit mechanical dimming. An integrating chamber at the top of the booths ensured that changes in the type of light source and position of the iris damper did not cause significant differences in luminance distribution.

The HPS lamp was used as the reference source, against which light from the CFL, MH1 and MH2 lamps were individually compared, the task being to report which booth appeared brighter. The HPS was presented at one of three illuminances, 2.0 lux, 7.5 lux and 15.0 lux, as measured in the centre of the floor of the booth, and this gave luminances in the range of 0.09 cd/m^2 to 0.66 cd/m^2 on the rear wall of the booth. The white light sources were presented at equal illuminance and at illuminances equivalent to three S-class steps below and one step above the HPS as shown in Table 3. This presentation offers two conditions either side of the expected equal brightness condition and thus counterbalances a potential stimulus frequency bias.[11-13] Comparison illuminances above 15.0 lux and below 2.0 lux were defined by extrapolation of the S-series. Light source location was counterbalanced between the LHS and RHS booths. Twenty-one participants were used (age range 18 years to 54 years, approximate mean 31 years; 14 female subjects), confirmed to have normal colour vision using the Ishihara test, and each saw each lamp and illuminance condition once. Prior to commencement of the series of tests the participants were dark adapted for 20 minutes.

Table 3 shows the results. These are the percentage of votes for the booth lit by the white lamp to be brighter than the booth lit by the HPS lamp. In this table a vote of approximately 50% suggests the booths were equally bright, and votes of approximately 100% and 0% suggest that the white lighting and HPS lighting respectively appeared brighter. The data were analysed using Dunn-Rankin Variance Stable Rank Sums[14] as has been previously used to analyse similar data.[15]

To employ Variance Stable Rank Sums a minimum of three stimuli need to be arranged in all possible pairs. The current experimental work was limited to comparison of the white sources against the HPS, rather than comparisons between the white sources, and furthermore the HPS was presented at three distinct illuminances. Therefore three combinations of light source and illuminance were compared each time, these comprising the HPS at one of three reference illuminances, the white source at equal illuminance, and the white source at a lower illuminance. Consider comparison of the HPS lamp at 15 lux against the MH1 lamp, the three combinations were:

1) HPS, 15 lux vs. MH1, 15 lux
2) HPS, 15 lux vs. MH1, 10 lux
3) MH1, 15 lux vs. MH1, 10 lux

Hence the analysis was repeatedly applied to the individual lamp type and illuminance triads. Of the three combinations, 1) and 2) were tested directly in the current experiments whilst the third combination was not tested and it was assumed that the booth of higher illuminance would be voted as brighter. This assumption was considered to be acceptable because the stimuli are identical other than the difference of illuminance, and by definition higher illuminance yields higher brightness when there are no differences in SPD or other parameters. Furthermore, null condition testing (section 4) using HPS and CFL lamps revealed that with stimuli of identical SPD, differing in illuminance by an amount equal to a single class of the S-series, the vote of brighter booth was given to the stimulus of higher illuminance in 100% of observations.

To statistically analyse all four lamp pairs with illuminance trade-offs of one and two classes of the S-series requires 18 sets of comparisons. With repeated application of a statistical test to the same set of experimental results there is an increased risk of committing a Type I error – identifying a chance result as being significant**.** Two methods for countering this risk are (1) by adopting a lower critical p value, and (2) by interpreting the overall pattern of results rather than attaching undue significance to any individual result. Using the Bonferroni correction[16] to set the cumulative criterion for significance at $p \leq 0.05$ suggests a criterion of $p \leq 0.0028$ (i.e. 0.05/18). Critical values for variance stable rank sums are presented for the $p=0.01$ and $p=0.001$ levels.[14] Adopting $p = 0.001$, which is more conservative than the Bonferroni corrected value, would increase the risk of committing a Type II error – that of retaining the null hypothesis when the alternative hypothesis is in fact correct. Hence in this analysis the critical value of $p=0.01$ was chosen whilst also interpreting the overall pattern of results rather than attaching undue significance to any individual result.

It was found that when presented at equal illuminance the booth when lit by the white lamps (MH2, MH1, CFL) is significantly brighter than the booth when lit by HPS ($p<0.01$). This pattern is consistent for all three lamp pairs and for all three test illuminances. When the white lamps were presented at one S-series illuminance lower than the HPS the two booths appear equally bright – any differences are not significant.

The trade-off of one class of the S-series appears to be a choice of convenience. Hence the data were used to test a trade-off of two classes of the S-series, e.g. is there a difference in brightness between HPS at 15 lux and MH at 7.5 lux? It can be seen in Table 3 that the HPS is now nominated as the brighter source more frequently than the white lamps. Applying variance stable rank sums reveals that the HPS is significantly brighter ($p<0.01$) in 6 cases (MH1 and MH2 at 15.0 vs. 7.5 lux and 7.5 vs. 3.0 lux; CFL at 7.5 vs. 3.0 lux and 2.0 vs. 1.0 lux). The three remaining cases do not find the HPS to be brighter at the $p = 0.01$ level, but in one case it is brighter at p<0.05 and the other two cases are close to p = 0.05. The overall pattern therefore suggests that HPS lighting is significantly brighter than white lighting presented at a lower illuminance by two classes of the S-series.

4. Brightness Ranking Null-Condition

Null-condition tests were carried out with 18 participants (aged 18-54 years, of which only 1 was over 44 years old, and 11 were female) using the same type of lamp to illuminate both booths. Three reference illuminances were used (2.0 lux, 7.5 lux and 15.0 lux) against which the test booth was presented at three levels: equal illuminance and illuminances one S-class above and below. At each illuminance comparison, each participant provided four brightness assessments to counterbalance (i) presentation in the left-hand and right-hand booths and (ii) which lamp was nominated as the test or reference source, the difference being the range of illuminance at which the lamp was presented. Hence there were 72 observations at each condition and the test was carried out by all participants under both HPS and CFL lamps.

The results shown in Table 4 identify the percentage vote for which booth was brighter. With a two-alternative forced choice a frequency of 50% would indicate no significant difference in brightness. The results presented in Table 4 are only those where the illuminances of the two side-by-side booths were equal. When the illuminances were not equal there was a 100% vote for the booth of higher illuminance to be noted as brighter. The results are presented in two formats, to enable comparison of different possible experimental bias. The test booth versus reference booth analysis, where the result shows percentage frequency of observation in which the test booth was reported to be brighter, lies within the range 47% to 57% and displays no obvious trends. The left-hand booth versus right-hand booth analysis, where the results show the percentage frequency by which the left-hand booth was reported to be brighter, displays mean results in the range 51% to 63%. This suggests the left-hand booth appeared brighter more frequently than did the right-hand booth. Analysis using Dunn-Rankin variance stable rank sums identifies no significant difference between the test and reference booths or the left and right booths, suggesting that any unintentional differences between the two booths were negligible.

5. Side-by-Side Brightness Matching

Brightness matching was also carried out using the side-by-side booths (Figure 4), in which the three white sources (MH1, MH2, CFL) were matched against the HPS. One booth was presented at one of three reference illuminances and the illuminance of the comparison booth was adjusted by the participant until the two sides appeared, as near as possible, equally bright. For every combination of lamp and illuminance, each participant provided four matches, counterbalancing both the initial illuminance of the comparator (set by the experimenter to an illuminance clearly higher or lower than the reference) and application of dimming to both sources.

When the HPS lamp was used as the reference the three reference illuminances were 2.0 lux, 7.5 lux and 15.0 lux, these being the bottom, middle and top of the S-series. However, when the white lamps were used as the reference, the three reference illuminances were 1.4 lux, 5.0 lux and 10.0 lux. These are a reduction of illuminance by one S-series step which, according to the brightness ranking results, should present an approximately equally bright reference stimulus as the HPS. By this method the brightness matches would be made with the visual system at the same adaptation level regardless of whether the HPS or white lamps were used as reference source.

The brightness matching tests were carried out concurrently with the brightness ranking tests (section 3 above) hence using the same 21 observers. The results are summarised in Table 5, and these show that on average the white lamps were set to a lower illuminance than HPS for equal brightness. The data were confirmed as being drawn from a normally distributed population using several graphical and statistical tests of normality (Histogram, box-plot, skewness, kurtosis, Kolmogorov-Smirnov test and & Shapiro-Wilks test). According to the one-sample *t*-test these mean illuminance ratios are significantly lower than unity ($p<0.01$).

Results for the CFL/HPS and MH2/HPS lamp combinations suggest a trend for the mean illuminance ratio to decrease slightly further from unity as illuminance decreases. Comparison of illuminance ratios using one-way ANOVA suggests the reference illuminance (i.e. reference set to 2.0 lux, 7.5 lux or 15 lux) does not significantly affect the illuminance ratio, although for the MH2/HPS lamp combination the effect is close to significance ($p=0.067$). Combining data within each lamp combinations from the three reference illuminances gives mean illuminance ratios as shown in Table 5.

6. Brightness Matching Null-Condition

Null-condition brightness matching tests were carried out by 18 participants (aged 18-54 years with only one participant aged above 44 years old; 13 females) with HPS lamps in both booths. At each of three reference illuminances (2.0 lux, 7.5 lux and 15.0 lux) eight matches were given in order to counterbalance positional bias (allocation of the adjusted lamp between the left-hand and right-hand booths) and dimming bias (setting the illuminance of the adjusted lamp to an initial level higher or lower than the reference illuminance, and applying the dimming to both sets of HPS lamps). A mean illuminance ratio of unity would confirm that there is no unintended experimental bias.

Table 6 shows the illuminance ratio of the left-hand to right-hand booths at equal brightness. At all three illuminances the *t*-test suggests there is no significant departure from unity, a result which indicates negligible bias between the left-hand and right-hand booths.

Table 6 also shows the null condition results in the form test/reference illuminance ratio. The mean illuminance ratios depart from unity, being greater than unity at 2.0 lux but less than unity at 15.0 lux – these differences are small but statistically significant (p<0.01). At the middle reference illuminance of 7.5 lux, the test/reference illuminance ratio does not depart significantly from unity. Analysis of the data suggests this is evidence of a response contraction bias.[17] These mean illuminance ratios were used to correct the main brightness matching results: at 2.0 lux, the illuminance of the adjusted booth was divided by 1.05, and at 15.0 lux it was divided by 0.97. Data recorded at the 7.5 lux standard illuminance were not corrected. The results in Table 5 include this correction: due to counterbalancing in the experimental procedure, this correction has a negligible effect on the mean values.[17]

In the null-conditions tests, the booth to which dimming was applied was set by the experimenter to an initial illuminance either higher or lower than that of the reference booth, and this was counterbalanced throughout the test. Table 7 shows the test/reference illuminance ratio broken down according to whether the adjusted booth was set initially to the higher or lower illuminance. If the initial illuminance caused a significant effect these two sets of mean illuminance would be different. There is trend for the illuminance ratio to be higher when the adjusted lamp starts from the higher illuminance, but application of the two-sample *t*-test suggests the difference is significant only at 2.0 lux (p<0.01). A possible reason for this is that the initial starting illuminances were chosen to be approximately two S-classes above or below the reference, but at 2.0 lux the *lower* starting illuminance was the lamp almost completely dimmed. In any case, the higher or lower initial illuminance was counterbalanced and is not considered to significantly affect the main results.

The null-condition data brightness matching data reveal only one potential bias, that of the response contraction bias. The data have been corrected for this bias but it does not significantly affect the results. This is because the bias is small compared to the main results and the application of dimming control was counterbalanced to both the HPS and the white lamps. Furthermore the data are supported by the brightness ranking results, which suggest that at one S-class trade-off, an illuminance ratio of approximately 0.7, booths lit by the white and HPS lamps are equally bright.

7. Models of Mesopic Photometry

Four previously proposed models of mesopic photometry were applied to see whether they would predict the results of the current brightness matching data. The SPD of the lamps used in the current work were measured using a Minolta CS1000a spectroradiometer. These measurements were made from the view point of the test participants and are hence the SPD experienced by the observer, being the SPD of the lamps as subsequently modified by surface reflectances and transmittance of the diffuser. These SPD are presented in the companion article.[5]

Palmer,[18] Kokoschka & Bodmann[19] and Sagawa[20] developed models to fit data from heterochromatic brightness matching studies. These used on-axis fields of size 3 degrees to 64 degrees, at mesopic luminances, and matched monochromatic lights from across the range of the visible spectrum to a single reference source. The input data for Palmer's model are 10 degree photopic luminance as characterised by $V_{10}(\lambda)$ and scotopic luminance as characterised by $V'(\lambda)$. The input parameters for Kokoschka & Bodmann's model are 10 degree photopic luminance, scotopic luminance and the 10° tristimulus values (X_{10}, Y_{10}, Z_{10}); the coefficients are determined by light level, and at 0.1 cd/m^2 these are $F_x = -0.276$, $F_y = 1.17$, $F_z = 0.0501$ and $F_s = 0.175$.The input parameters for Sagawa's model are photopic luminance as characterised by $V(\lambda)$, scotopic luminance and two-degree x-y chromaticities.

A model of mesopic photometry has been developed by Rea *et al*[21] to fit reaction time data. An outcome of the current move toward establishing a system of mesopic photometry may be that a system is promoted that is based on visual performance data, and it is therefore important to be aware of how well other responses such as brightness are predicted by such a model. Hence this model also was used to predict the current brightness matching data. The input parameters are photopic luminance as characterised by $V(\lambda)$ and scotopic luminance in proportions defined by the adaptation level and the light source S/P (scotopic/photopic) ratio.

The SPD were weighted to give the mean illuminance ratios of the three lamp pairs collated across the three reference illuminances as shown in Table 5. The models were used to determine the equivalent luminance of the lamps at the photopic luminance suggested by the current results to yield equal brightness, with the HPS photopic luminance set to 0.1 cd/m^2. A model yielding an accurate prediction of the current data would thus yield unity ratios of equivalent luminance (white/HPS). The results are shown in Table 8. The table shows the root mean square (RMS) error (departure from unity), hence a smaller RMS value identifies a model that better fits the current data. Sagawa's model gives the best fit, slightly better than that offered by Palmer's model and Kokoschka & Bodmann's model. The model from Rea *et al* gives the least accurate fit to the current data, generating an RMS error larger than that obtained by using the Photopic Observer V(λ) to predict mesopic brightness.

Table 9 shows the ratio of photopic illuminances that would be needed for equal mesopic illuminance according to predictions made by the four models. If these models successfully predict the relative brightness of different lamps at mesopic levels, these predicted ratios would match the mean illuminance ratios found in the brightness matching tests. In consideration of sampling error within the brightness matching data, an accurate prediction is considered as one which lies within the 99.9% confidence interval of the mean. Sagawa's model gives an accurate prediction of two lamp pairs (CFL/HPS, MH2/HPS) and is close to giving an accurate prediction for the remaining pair (MH1/HPS). The models from Palmer, and Kokoschka & Bodmann, give an accurate prediction of the CFL/HPS result, a prediction close to accurate for the MH1/HPS and a less accurate prediction for the MH2/HPS. The model[21] based on visual performance data does not give an accurate prediction for any of the lamp pairs. Applying this model to identify illuminances for the white lamps would produce environments significantly less bright than under HPS lighting.

There are two reasons why the three brightness models are not expected to predict the current brightness matching results. Firstly is the type of light source - all three brightness models used monochromatic lights rather than practical sources having a broadband SPD as were used in the brightness matching tests. The second reason is the stimulus size. The current work used a field of size 37 degrees high and 71 degrees wide. Sagawa's data were from brightness matching using a 10 degree field, whereas Palmer and Kokoschka & Bodmann used larger fields of up to 45 degrees and 64 degrees respectively. The model based on visual performance data was not expected to predict the current brightness data because it was developed to fit a different type of visual response. However, if this model is adopted by CIE or other standards organisations, then the limitations of its application need to be clearly understood. Similarly, a model of mesopic photometry based upon a brightness response may be inadequate for predicting visual performance.

8. Discussion

The brightness of lamps of different SPD were compared using three different techniques of assessment. Both of the methods employing side-by-side presentation, the matching and ranking tasks, found that lamps of different SPD do appear differently bright. When presented at equal illuminance, the ranking data shows that booths lit by the white lamps are significantly brighter than when lit by the HPS lamp. The ranking data suggests the white lamps and HPS lamps are equally bright when the white lamps are presented at an illuminance one S-class lower than the

HPS, an illuminance ratio of approximately 0.7 (white/HPS). The brightness matching data suggests a similar illuminance ratio (white/HPS) of approximately 0.72 at equal brightness. The rating data, in which lamps were presented individually to enable chromatic adaptation to the single SPD, also found that at equal illuminance the room when lit by the white lamps is significantly brighter than when lit by the HPS. This is a similar result to that found in the side-by-side ranking tests. What is not known is the strength of the SPD effect on brightness in the semantic rating tests, for example the illuminance ratio at equal brightness.

Two previous studies have examined brightness at mesopic levels using HPS and MH lamps. Rea[8] had subjects view a coloured diorama of a landscape and used a moveable mirror to switch quickly between MH and HPS lighting. The photopic luminance of the background of the diorama provided by the MH was set to one of three levels, 0.01 cd/m^2, 0.10 cd/m^2 and 1.00 cd/m^2. At each luminance, sixteen subjects were asked to adjust the amount of light from the HPS source until the diorama looked equally bright when alternately lit by the two light sources. The mean photopic luminance ratios for equal brightness (MH/HPS) were 0.71, 0.71 and 0.48 at 1.00 cd/m^2, 0.10 cd/m^2, 0.01 cd/m^2, respectively. The current brightness matching tests used mean background luminances in the range 0.1 cd/m^2 to 1.0 cd/m^2, the upper two levels of Rea's tests, and the mean illuminance ratio (MH/HPS) at equal brightness of approximately 0.72 is in good agreement with Rea.

In contrast, results from Boyce & Bruno[9] suggest that any effect of SPD on the brightness-illuminance relationship is small if it exists at all. Their study employed semantic rating applied to HPS and MH lighting observed separately in a car park, the perception measures being recorded towards the end of each 15 minute trial. They used illuminances in the range 29 lux to 49 lux, with lamps being compared on the basis of wattage rather than illuminance, and the stimuli were observed through a vehicle windscreen by subjects either wearing or not wearing glasses of transmittance 0.1.

The results from Boyce & Bruno disagree with the results from the current semantic rating tests which found significant differences in ratings of brightness given to lighting from HPS and MH lamps. There are several differences between the current study and the Boyce & Bruno study. Some of these differences are expected to have a small effect, if any. There may be differences in the SPD of the particular lamps used, although this is expected to be a small effect compared to the typical differences in SPD between MH and HPS lamps. Boyce & Bruno's tests were carried out at a higher range of illuminances than the current work, although the reported range of mean luminances (0.07 cd/m^2 to 1.49 cd/m^2) is similar to the range in the current study (0.11 cd/m^2 to 1.03 cd/m^2). Boyce & Bruno's tests were carried out in a real outdoor situation rather than in a laboratory, and whilst laboratory based work tends to enables better control of extraneous variables there are obvious differences in realism, such as the proximity of boundary vertical surfaces. Both studies employed full-field vision. They did not relocate the three different lamps between the three different test bays, and thus differences in the environment may have confounded differences between the lamps, for example different levels of oil staining on, or wear of, the floor and hence surface reflectance. Boyce & Bruno compared the lamps MH and HPS on the basis of wattage and hence there were two independent stimulus variables, SPD and illuminance; assuming SPD and illuminance interact to affect brightness, the absence of comparisons at equal illuminance confound the conclusions for SPD alone.

There are two reasons by which Boyce & Bruno's study is suspected to have failed to yield a significant difference in brightness, if one exists. Firstly, their brightness assessments were made after a longer period of exposure, approximately 10 to 15 minutes, which may have permitted a greater degree of chromatic adaptation than in the current work, which permitted only five minutes before the ratings were made. With increased chromatic adaptation, a chromatic contribution to brightness diminishes, and the brightness difference between lamps of different SPD decreases. Results from colour appearance judgements made at photopic levels suggest that chromatic adaptation is complete after approximately two minutes exposure.[22] It is not known whether this applies to colour appearance judgements made at mesopic levels, or to brightness judgements made at any level, and thus whether differences are expected between brightness judgements made at five minutes and 10 to 15 minutes.

Secondly, Boyce & Bruno's study may have unintentionally contained response range bias. They used a seven-point response range and the presence of a middle value tends to contract the response range;[13] ratings of the brightness of brighter stimuli tend to be decreased toward the middle value whilst ratings of the dimmer stimuli tend to be elevated toward the middle value, and therefore this decreases the range between different stimulus conditions. The current study used an eight-point response range.

Boyce & Bruno did not use pre-experimental standards to demonstrate the ends of their rating scale and this can lead to response contraction bias.[13] Linking the ends of the rating scale to the ends of the stimulus range encourages use of the full range of ratings, thus reducing the response contraction bias, and the test is more sensitive to differences between the stimuli. Without such instruction each subject must develop their own internal criteria as to what denotes the upper and lower limits of the rating scale, decisions which are difficult to make, particularly early in an experiment, when they have not yet seen the range of possibilities. Pre-experimental standards have the potential to reduce the variance in the data, or at least to increase the internal consistency of each subject. In the current work, the ends of the brightness rating were demonstrated to observers at the start of the test sequence.

It is therefore suggested that the difference between the current work, which found a significant difference in ratings of brightness for MH and HPS lamps, and Boyce & Bruno's work, which did not find a significant difference in ratings of brightness, is that response contraction bias in Boyce & Bruno's study did not enable discrimination between the different lamps. This may have been enhanced by an increase in the degree of chromatic adaptation to the individual sources.

9 Conclusion

The current experimental results confirm that lamps of different SPD will appear differently bright at mesopic levels, however the strength of the effect depends on the chromatic adaptation of the observer and hence the situations in which the judgement is made.

Consider incomplete chromatic adaptation, which might be judgements of brightness made on immediate exposure to the lighting. Results of the studies employing side-by-side presentation and hence incomplete chromatic adaptation to a particular SPD suggest that S-series trade-off between CRI and illuminance is valid. For the lamps tested, a reduction of one class in the S-series is an appropriate trade-off between lamp type and illuminance, thus supporting the guidance given in BS5489-1:2003.[2]

Secondly consider complete chromatic adaptation to a single type of lamp, which might be judgements of brightness made after several minutes exposure to the lighting. Lamps of different SPD may still appear differently bright but the effect may be weaker than with incomplete chromatic adaptation. In the current semantic rating tests, which allowed five minutes for chromatic adaptation, MH lighting was rated significantly brighter than HPS lighting. Boyce & Bruno[9] allowed 10 to 15 minutes for chromatic adaptation and found no significant difference in brightness between MH and HPS lighting, but this may be attributed to experimental bias rather than to chromatic adaptation.

Further work is needed to extend the analysis of lamp SPD and brightness:

1. The brightness of lamps of different SPD should be assessed in real (outdoor) situations to determine the validity of extending laboratory data. This is currently being addressed using questionnaires to survey household residents before and after their street lighting is changed.
2. This study has compared relative values, i.e. a comparison of brightness at different illuminances. It does not reveal whether those illuminances are appropriate for the purpose

for which the lighting was installed. Further work is needed to investigate whether the absolute illuminances used in designing pedestrian lighting are appropriate, and initially this demands identification of the tasks that are important to pedestrians.

3. BS5489-1:2003[2] uses CRI to identify the lamps to which the illuminance trade-off is applicable. The spectrally enhanced brightness from white light sources is believed to be some combination of activity from the chromatic systems and the rod systems. Rod activity is not predicted by CRI, and it has been demonstrated[23] that CRI alone can fail to predict the perception of lighting of different SPD at photopic levels. Further work is needed to determine an appropriate metric(s) for the trade-off, which ideally would be an already well-established unit.

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Lamp type		CCT (K)	CRI (R_a)
LPS	35W SOX	-	-
HPS	70W SON-T	2000	25
CFL	55W PL-L	3000	82
MH1	70W CDO-TT	2800	83
MH2	70W CDM-T	4200	92

Table 1

Description of the lamps used in brightness assessments. The CCT and CRI are as reported in manufacturers literature.

Lamp	Angle between observation direction and plane parallel to length of room (degrees)						
	-90 left	-60	-30	0 centre	30	60	90 right
				Vertical illuminance (lux)			
Mean floor illuminance = 15 lux							
LPS	3.55	8.61	12.22	12.83	10.35	6.01	3.50
HPS	2.41	6.90	11.36	13.10	11.72	7.85	4.16
CFL	1.98	5.18	10.26	13.19	13.00	9.97	5.64
MH1	2.55	6.60	10.93	12.72	11.50	7.91	4.50
MH2	3.87	8.37	11.57	11.97	9.58	5.68	3.64
Mean floor illuminance = 2 lux							
LPS	0.46	0.99	1.38	1.43	1.17	0.70	0.44
HPS	0.24	0.61	0.98	1.13	1.03	0.71	0.42
CFL	0.19	0.42	0.81	1.06	1.10	0.89	0.59
MH1	0.25	0.55	0.89	1.04	0.96	0.69	0.45
MH2	0.54	0.96	1.24	1.25	1.00	0.63	0.48

Table 2

Vertical illuminance at observer’s eye. Measurements taken with Minolta T-10M illuminance meter, with sensor at 1.5m above floor level.

White lamp	HPS booth @ 2.0 lux					HPS booth @ 7.5 lux					HPS booth @ 15.0 lux				
	Illuminance of white lamp booth (lux)					Illuminance of white lamp booth (lux)					Illuminance of white lamp booth (lux)				
	0.6	1.0	1.4	2.0	3.0	2.0	3.0	5.0	7.5	10.0	5.0	7.5	10.0	15.0	22.0
	S-class relative to HPS					S-class relative to HPS					S-class relative to HPS				
	-3	-2	-1	0	+1	-3	-2	-1	0	+1	-3	-2	-1	0	+1
CFL	*0*	*0*	*48*	*95*	*100*	*0*	*5*	*71*	*100*	*100*	*0*	*14*	*52*	*100*	*100*
MH1	*0*	*10*	*67*	*100*	*100*	*0*	*0*	*38*	*100*	*100*	*0*	*5*	*52*	*100*	*100*
MH2	*0*	*19*	*52*	*95*	*100*	*0*	*0*	*57*	*95*	*100*	*0*	*5*	*57*	*95*	*100*

Table 3

Percentage of observations in which white lighting (CFL, MH1, MH2) was reported to be brighter than HPS lighting.

Identification of booths	**Null condition using HPS lamps**			**Null condition using CFL lamps**		
	Reference illuminance (lux)			Reference illuminance (lux)		
	2.0	7.5	15.0	2.0	7.5	15.0
Test vs. Reference	*57*	*47*	*56*	*53*	*54*	*49*
Difference between test & reference booths*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Left vs. Right	*51*	*61*	*61*	*58*	*63*	*54*
Difference between left & right booths*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Table 4

Brightness ranking null-condition results – percentage frequency with which the test booth or left-hand booth were noted as brighter. In all cases, n=72. *Difference tested using Dunn-Rankin variance stable rank sums.

White lamp	CFL			MH1			MH2		
Reference illuminance (lux)	2.0	7.5	15.0	2.0	7.5	15.0	2.0	7.5	15.0
Mean illuminance ratio (white/HPS)	0.694	0.718	0.732	0.729	0.733	0.724	0.679	0.724	0.738
Std. Dev.	0.153	0.119	0.162	0.165	0.161	0.157	0.193	0.167	0.193
n	84	84	84	84	84	84	84	84	84
Departure from unity (*t*-test)	p<0.01	p<0.01	p<0.01	p<0.01	p<0.01	p<0.01	p<0.01	p<0.01	p<0.01
	Results collated across the reference illuminances								
Mean illuminance ratio (white/HPS)	0.715			0.728			0.714		
Std. Dev.	0.147			0.161			0.186		

Table 5

Results of brightness matching tests. These are the mean illuminance ratios at equal brightness.

Illuminance ratio		Reference illuminance (lux)		
		2.0	**7.5**	**15.0**
Left / Right	Mean	0.99	0.99	1.00
	Std dev	0.12	0.10	0.09
	n	144	144	144
	Departure from unity*	n.s.	n.s.	n.s
Test / Reference	Mean	1.05	0.99	0.97
	Std dev	0.13	0.10	0.08
	n	144	144	144
	Departure from unity*	**p<0.01**	n.s	**p<0.01**

Table 6

Results of brightness matching null-condition tests. n.s. = not significant (p>0.05). *Departure tested using the *t*-test.

Initial illuminance of adjusted lamp	Test / Reference illuminance ratio	Reference illuminance (lux)		
		2.0	**7.5**	**15.0**
Higher	Mean	1.08	1.00	0.98
	Std dev	0.12	0.10	0.08
	n	72	72	72
Lower	Mean	1.02	0.99	0.97
	Std dev	0.13	0.10	0.08
	n	72	72	72
Difference between *higher* and *lower* mean illuminance ratios*		**p<0.01**	n.s.	n.s

Table 7 Results of brightness matching null-condition tests: analysis of initial illuminance of the adjusted booth. *Difference tested using the *t*-test.

Model	Predicted ratio of mesopic luminances			RMS error
	CFL/HPS	MH1/HPS	MH2/HPS	
Sagawa, 2006	0.99	0.94	1.05	0.045
Palmer, 1968	0.96	0.91	1.04	0.061
Kokoschka & Bodmann, 1975	0.96	0.89	1.02	0.069
V(λ)	*0.71*	*0.73*	*0.71*	*0.281*
Rea, Bullough, Freyssinnier-Nova & Bierman, 2004	1.46	1.26	1.66	0.487

Table 8 Ratios of mesopic luminance predicted using models of mesopic photometry. The input data assumes a photopic luminance of 0.1 cd/m^2 for the HPS lamp.

Lamp pair	Experimental results		Predicted ratio of photopic illuminance (*white*/HPS) for equal mesopic illuminance			
	Mean illuminance ratio	99.9% confidence interval	Sagawa	Palmer	Kokoschka & Bodmann	Rea *et al.*
MH1/HPS	0.728	0.695 – 0.762	0.776	0.788	0.820	0.573
MH2/HPS	0.714	0.675 – 0.752	0.677	0.661	0.670	0.405
CFL/HPS	0.715	0.684 – 0.745	0.721	0.722	0.716	0.476

Table 9 Predicted ratios of photopic illuminance for equal mesopic illuminances using four models of mesopic photometry. The predicted photopic illuminance ratios in **bold** font are those which lie within the 99.9% confidence interval of the experimental mean value.

Figure 1

Laboratory used for semantic rating tests. The room is of dimensions 10.5m deep x 6.1m wide x 5.7m high. The photograph shows the view from the participants' observation point. When making the ratings the participant was instructed to look forwards, and hence the nearer cluster of luminaires was not in the field of view.

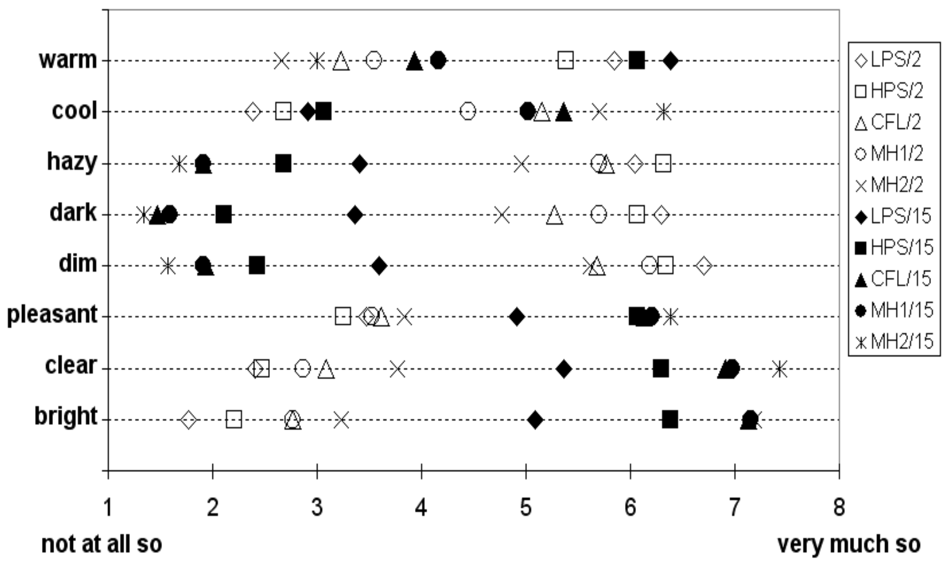

Figure 2
Mean results of semantic rating. The legend identifies the combination of lamp type and illuminance (lux).

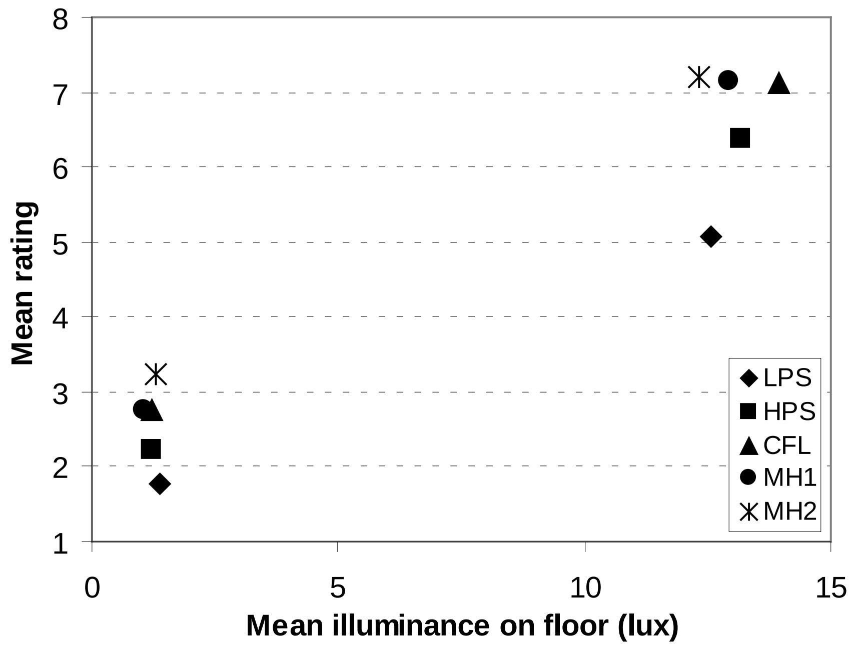

Figure 3
Mean ratings of bright' according to illuminance. In this scale 8 = brighter and 1 = dimmer.

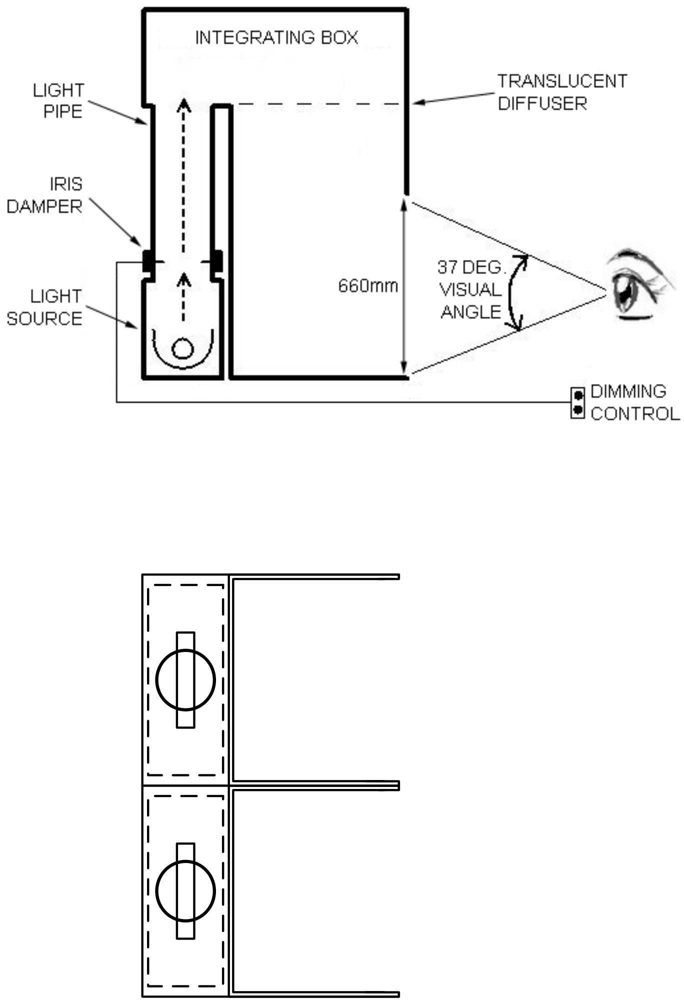

Figure 4
Vertical and horizontal sections through the side-by-side booths used in brightness ranking and brightness matching tests.

Correction: ***Lighting for subsidiary streets: investigation of lamps of different SPD. Part 2 – Brightness***

Fotios S & Cheal C, Correspondence. Correction: Lighting for subsidiary streets: Investigation of lamps of different SPD. Part 2 – Brightness, Lighting Research & Technology, 2009; 41(4); 381-383

This communication provides correction to a recent article[1] in which predictions of relative brightness made using mesopic visual efficiency systems were compared with experimental data. Specifically, this communication identifies two errors we made when using the Sagawa model[2] and the implications of these on the predictions made.

Equation 1 is the system of photometry for brightness at any level as proposed by Sagawa.

$$Leq = (L)^{a}(L')^{1-a}.10^{C} \qquad (1)$$

In Equation 1, the terms L and L' represent the photopic and scotopic luminances respectively. The chromatic contribution to brightness in Equation 1 is defined by 10^{C} where *c* is the product of the chromatic adaptation coefficient (a_c) and the chromatic effect, *f(x,y)*; this latter term is the Nakano et al brightness/luminance equation, and was defined by Sagawa[2] as:

$$f(x,y) = 0.5 \log (\mathbf{-0.054} - 0.21x + 0.77y + 1.44x^2 - 2.97xy + 1.59y^2 - 2.11zy^2) - \log y \qquad (2)$$

This is the form of equation used in our previous analysis.[1] Unfortunately, we failed to check the primary source. In the article by Nakano et al[3] equation 2 is written as:

$$f(x,y) = 0.5 \log (\mathbf{-0.0054} - 0.21x + 0.77y + 1.44x^2 - 2.97xy + 1.59y^2 - 2.11zy^2) - \log y \qquad (3)$$

a from that has been checked by communication directly with Dr Yasushisa Nakano; i.e. Sagawa had incorrectly stated the first constant.

The second error we made was in the application of the achromatic adaptation coefficient *a* and chromatic effect *c* in Sagawa's model. When using a spreadsheet to calculate mesopic luminances for a pair of lamps, the values of coefficients *a* and *c* determined for one lamp were mistakenly used for both lamps.

A further problem is that Sagawa's article is not clear as to whether the model uses two-degree functions (*L, X, Y, Z*), ten-degree functions ($L_{10}, X_{10}, Y_{10}, Z_{10}$) or some combination of these. Our interpretation is that photopic luminance in Equation 1 is derived from the two-degree observer (V_λ) but the colorimetric observer used in Equation 3 and the luminance used to determine the achromatic and chromatic adaptation factors *a* and a_c are ten-degree observers ($V_{\lambda,10}$, X_{10}, Y_{10}, Z_{10}). Hence in addition to correcting the previous errors, Tables 1 and 2 also present data that assume the model uses either ten-degree or two-degree observer data throughout.

The experimental data comprised the results of brightness matching tests. Two metal halide lamps (MH1, MH2) and a compact fluorescent lamp (CFL) were compared against a high pressure sodium lamp (HPS). The mesopic models were applied assuming a photopic luminance of 0.1 cd/m^2 for the HPS lamp and this is repeated here using the corrected version of Sagawa's model. Table 1 shows predicted ratios of mesopic luminances at equal brightness. This is shown for four variants of Sagawa's model: (1) the incorrect version we used previously; (2) the corrected model with adaptation coefficients appropriate for each stimulus; and this latter version using either two-degree (3) or ten-degree (4) observer data throughout. The input data are the photopic luminances of the reference (HPS) and test (CFL, MH1, MH2) stimuli at equal brightness, with equal brightness being defined as the mean result from the brightness matching trials.[1] A successful prediction would be a mesopic luminance ratio of 1.0. To compare predictions the final column of Table 1 shows the root-mean-squared (RMS) error between the predicted ratios and unity.

Table 2 presents ratios of photopic luminance for equal mesopic luminance. If equal mesopic luminances predict equal brightness, these ratios of photopic luminance would match those found in the experimental work. A successful prediction is suggested to be one which lies within the 99.9% confidence interval about the mean value.

It can be seen from Tables 1 and 2 that predictions made from the correctly used version of Sagawa's model (2) are only very slightly different than those previously reported (1). Similarly the use of two-degree (3) or ten-degree (4) observers produces predictions which are only slightly different from predictions made using a combination of these as our interpretation of Sagawa's intentions (2). Whilst the difference is small it should be reported accurately.

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Version of Sagawa's model	Predicted L_{mes} ratio at equal brightness			RMS error from unity
	CFL/HPS	MH1/HPS	MH2/HPS	
1. Version as used in 2007 article	0.99	0.94	1.05	0.045
2. Corrected model	1.00	0.93	1.07	0.056
3. Model assuming only two-degree functions	1.01	0.94	1.09	0.062
4. Model assuming only ten-degree functions	1.01	0.94	1.10	0.068

Table 1 Predicted ratios of mesopic luminances (L_{mes}) at equal brightness, assuming HPS photopic luminance of 0.1 cd/m^2. An accurate prediction would be an L_{mes} ratio of 1.0.

	Lamp Combination		
	CFL/HPS	MH1/HPS	MH2/HPS
Experimental Results			
Mean illuminance ratio	0.715	0.728	0.714
99.9% confidence interval	0.684-0.745	0.695-0.762	0.675-0.752
Predicted ratio of photopic illuminances for equal mesopic illuminances			
1. Version as used in 2007 article	**0.721**	0.776	**0.677**
2. Corrected model	**0.716**	0.781	0.658
3. Model assuming only two-degree functions	**0.709**	0.776	0.647
4. Model assuming only ten-degree functions	**0.704**	0.773	0.637

Table 2 Predicted ratios of photopic illuminance for equal mesopic illuminances. The predicted photopic illuminance ratios in **bold** font are those which lie within the 99.9% confidence interval of the experimental mean value.