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The association between CCT and S/P ratio

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Abstract

The S/P ratio is a design parameter that may be considered in road lighting. This article compares the S/P ratios and CCTs of the 297 light source spectra identified in IES TM-30-15 to test the assumption that higher S/P ratios demand higher CCTs. The results suggest that, for a given lamp type, there is a strong association between S/P ratio and CCT, and hence that for a given CCT only a small variation in S/P ratio is available. However, the results also suggest that a larger variation in S/P ratio is possible if the lighting designer is able to consider a change in lamp type.

1 Introduction

Correlated Colour Temperature (CCT) and S/P ratio are two metrics derived from lamp spectrum which might be used to characterise lighting, the latter becoming more commonly used in recent years in association with road lighting [PLG03 2012, CIE 206 2014, Fotios & Gibbons, 2018]. CCT is the temperature of the Planckian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution [CIE eILV 17-258; accessed 17/03/2018]: it is a metric of appearance. The S/P ratio is the ratio of the luminous output of a light source evaluated according to the CIE scotopic spectral luminous efficiency function to the luminous output evaluated according to the CIE photopic spectral luminous efficiency function [CIE 191:2010]: it describes the relative stimulation of the rods and foveal cones.

In minor roads, pedestrian needs are the primary target of road lighting. Following evidence of the benefit of higher S/P ratio for the visual tasks of pedestrians [Fotios and Cheal, 2009, Fotios & Cheal 2007, 2011, Fotios and Goodman, 2012] road lighting guidance in the UK allows a lower photopic illuminance to be used when using lighting of higher S/P ratio [BS5489-1:2013], with the degree of illuminance reduction specified by the CIE system for mesopic photometry [CIE 191: 2010]. Lamps of higher S/P ratio permit a greater reduction in photopic illuminance for the same mesopic luminance. Using a lower photopic illuminance may lead to a lower demand for energy (although that depends also on many other parameters [Boyce et al, 2009]) and thus those authorities responsible for paying the costs of road lighting have good reason to prefer lamps of higher S/P ratio. A lighting designer might therefore pay attention to both CCT and the S/P ratio, the former for describing colour appearance and the latter for visual performance and hence light level and overall efficiency.

It is common to associate higher S/P ratios with higher CCT; that is a reasonable assumption to make given that both CCT and S/P ratio are spectrum derived measures associated with the relative proportions in the short wavelength and long wavelength regions of the visible spectrum. Within the UK the demand for a higher S/P ratio has contributed to a rise in the CCT of lighting used in minor roads. In turn, this has led toward a reaction from the public against the replacement of sodium lighting with lighting of higher CCT and hence cooler appearance. While such public criticism may be a reaction against change, or a reaction to changes such as better optical control associated with the change from traditional to LED light sources, colour appearance is the focus of criticism and is therefore a target local authorities seek to remedy.

Is it correct to associate higher S/P ratios with higher CCT? An early pioneer of the S/P ratio was Berman. In one article [Berman 1992] he listed the S/P ratios for 16 common types of lamp and illuminant (Figure 1) and these give the impression of a positive association. For five lamps/illuminants the CCTs were also reported, and plotting S/P ratio against CCT for these five lamps reveals a strong association (R^2=0.97, n=5) (Figure 2).

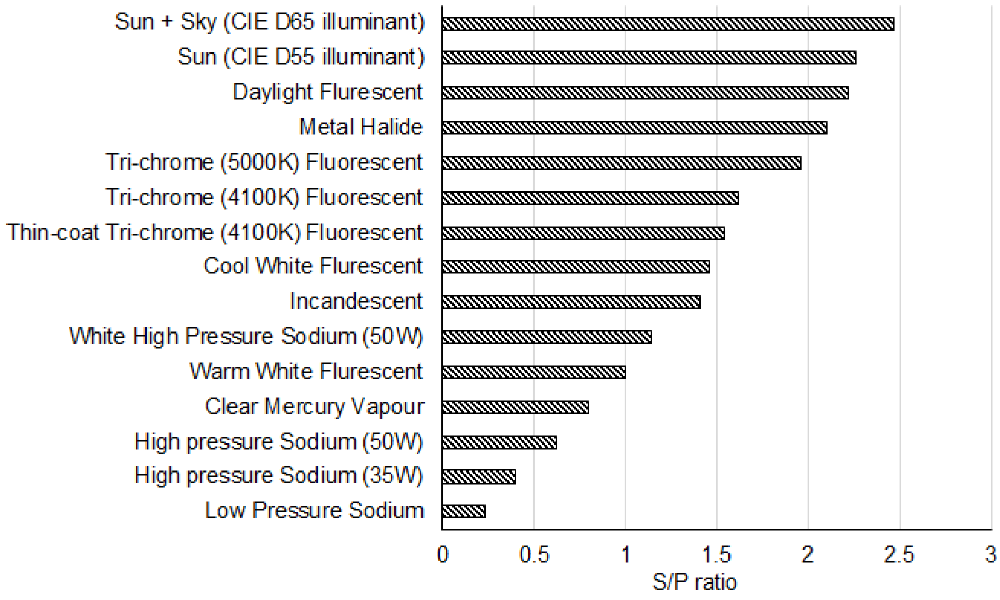

Figure 1. S/P ratios of some lamps as reported by Berman [Berman 1992].

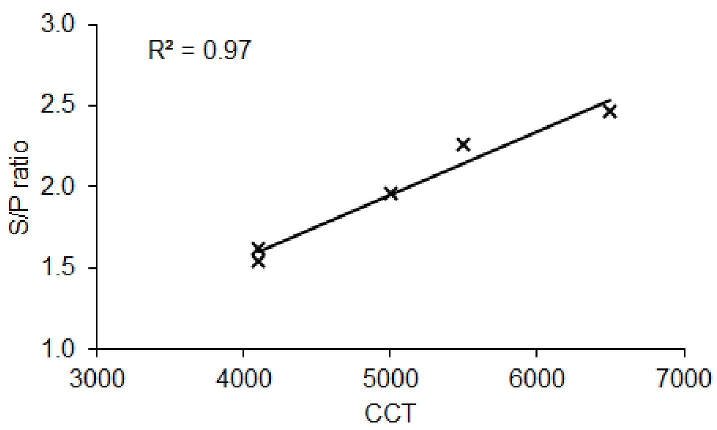

Figure 2. S/P ratio plotted against CCT for those lamps of Figure 1 where CCTs were reported.

A further comparison was drawn by Ashdown [Ashdown 2014] who analysed the spectra of 90 "*LED-based roadway and area lighting luminaires*" collected for performance testing. Plotting S/P ratio against CCT for these LEDs again suggests a strong association (R^2=0.83, n=69) (Figure 3). As was noted by Ashdown, a limitation of this finding is that the sample was limited to only one type of light source (white LEDs).

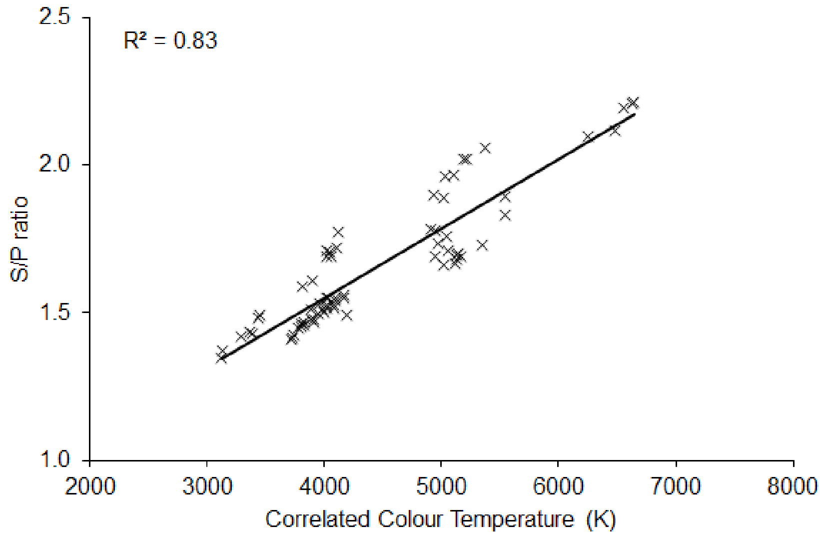

Figure 3. S/P ratio plotted against CCT for LEDs as reported by Ashdown [Ashdown 2014]. Note: included here are 69 of the 90 cases, these being the ones determined by digitising the graph.

While Figure 3 shows a strong association between CCT and S/P ratio, some variation can be seen. For example, at approximately 4000K, the S/P ratios range from 1.5 to 1.7. In two experiments investigating spatial brightness at photopic levels [Berman et al 1990, Fotios et al 2015] and one investigating hazard detection at mesopic levels [Uttley et al 2017] this range was purposefully enhanced. These experiments characterised colour appearance using chromaticity which is a more precise metric than CCT. The intention of these experiments was to study the effect on spatial brightness (or detection) of changes in one metric (S/P ratio) while the second metric (chromaticity) was held (near) constant. Table 1 shows S/P ratio differences of greater than 0.5, which is larger than found in Figure 3. Berman et al achieved this using pairs of fluorescent lamps. The first combination (WWG) was a single warm white lamp combined with a single gold lamp. The second combination (R213) comprised three red lamps and a special lamp used in photocopy apparatus (213 referred to the manufacturers phosphor number). Other than the warm white lamp, these were not light sources for interior lighting. Fotios *et al* and Uttley *et al* used a four-primary tuneable array of LEDs.

Study	Light setting	x	y	S/P	Approx CCT (K)
Berman et al 1990	R213	0.46	0.42	2.40	2800
	WWG	0.48	0.41	0.85	2400
Fotios et al 2015	A	0.49	0.40	1.02	2200
	B	0.49	0.40	1.77	2200
Uttley et al 2017	Low	0.46	0.42	1.2	2800
	Medium	0.46	0.42	1.6	2800
	High	0.46	0.42	2.0	2800

Table 1. Description of the LED spectra and blended fluorescent lamps used in investigations of spatial brightness and hazard detection. Fotios *et al* and Uttley *et al* derived lamp properties from SPDs measured from the observer's view of the test apparatus. Berman *et al* did not report S/P ratios: these were determined from the photopic and scotopic luminances reported in their Table 2.

While is possible to vary S/P ratios whilst holding CCT approximately constant, previous comparisons of commonly used lamps suggest that this is not usually the case, and an increase in S/P ratio tends to demand an increase in CCT. In this article we report a further comparison of CCT and S/P ratio but using a much larger set of lamp spectra and a wider range of lamp types than considered in previous comparisons.

2 Data source

The analysis was carried out using the library of sample lamp spectra included in IES TM-30-15 [IES 2015]. These spectra were collated for a document associated with colour rendering characteristics and not for the comparison of S/P ratios and CCT; they may, therefore, be considered as an unbiased data set for the current analysis. We have used the first 297 of the 318 spectra in the library, omitting the final 21 which are labelled as theoretical spectra. The light sources are categorised into different types, of which 55 are labelled fluorescent lamps (FL), 14 are high intensity discharge lamps (HID), 14 are incandescent lamps, 15 are hybrid LEDs, 64 are mixed LEDs, and 129 are phosphor LEDS. The CCTs of these spectra were reported in the TM-30-15 library. S/P ratios were not reported, and for the current analysis were determined by calculation. The spectra are reported at 1nm intervals in the range 380 to 780nm.

The sources from where these spectra were gathered are described by Houser et al [Houser et al, 2013]. The library includes three types of LED (phosphor, mixed, and hybrid) according to the manner in which the narrow band spectra emitted by LEDs are manipulated to create white light [IES Handbook 2011]. Phosphor LEDs (also known as down-conversion phosphor) use a phosphor convert short wavelength light to a broader distribution, in a similar manner to the phosphor coating of fluorescent lamps. Mixed LEDs take advantage of additive colour mixing of two or more types of LED chip of different colour. Hybrid LEDs employ both mixed LEDs and one or more phosphors.

3 Analysis

Figure 4 shows S/P ratio plotted against CCT for all 297 spectra. There is a reasonable degree of association (R^2=0.65, n=297, p<0.001) but it is clear that some spectra do not follow the trend.

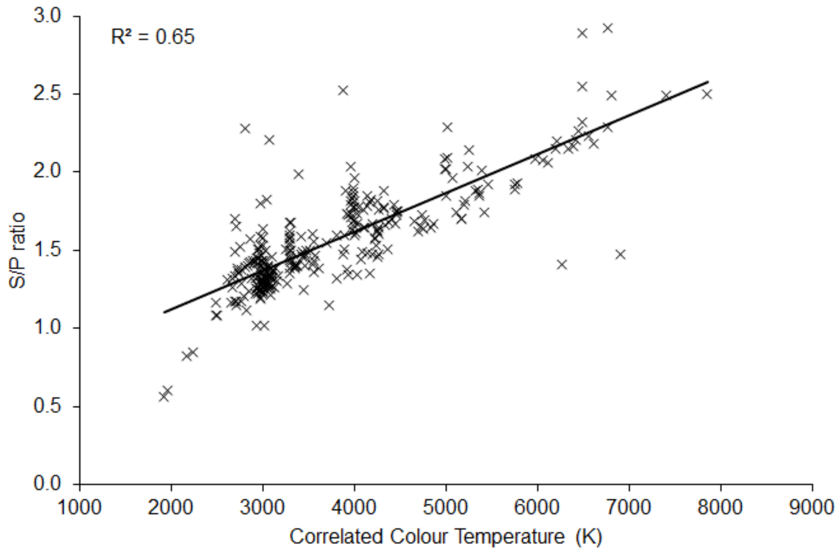

Figure 4. S/P ratio plotted against CCT for the 297 spectra included in the library of IES TM-30-15 [IES 2015].

The source of variance was investigated by considering separately the different types of lamp, and this was done following the lamp names given in the TM-30-15 library. Figure 5 and Figure 6 show florescent lamps and phosphor type LEDs. For these two types of lamp there is a strong association between S/P ratio and CCT (fluorescent, R^2=0.91, n=55, p<0.001; phosphor LED R^2=0.89, n=129, p<0.001).

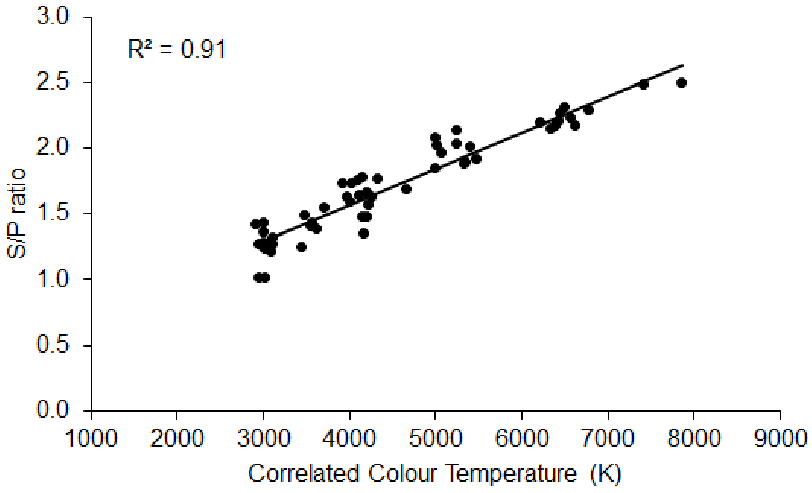

Figure 5. S/P ratio plotted against CCT for the 55 fluorescent spectra included in the library of IES TM-30-15 [IES 2015].

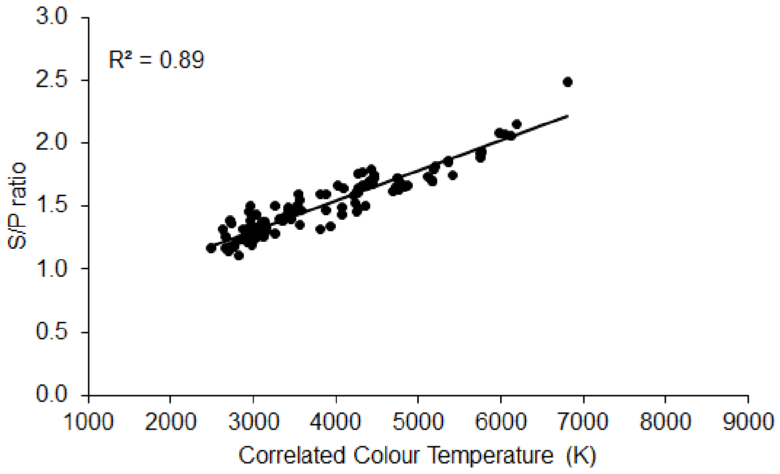

Figure 6. S/P ratio plotted against CCT for the 129 LED phosphor spectra included in the library of IES TM-30-15 [IES 2015].

Figures 7 and 8 show the data for mixed and hybrid LEDs respectively. The association between CCT and S/P ratio for these spectra are also significant (mixed LED, R^2=0.63, n=64, $p<0.001$; hybrid LED R^2=0.66, n=15, $p<0.001$).

Figure 9 shows the 14 incandescent lamps from TM-30-15. There is strong association between S/P ratio and CCT (R^2=0.80, n=14, $p<0.001$). There are three outliers in these data (a filtered halogen lamp, and two neodymium lamps, numbers 84, 88 and 89 in the library): if these are excluded the association slightly increases (R^2=0.88, n=11).

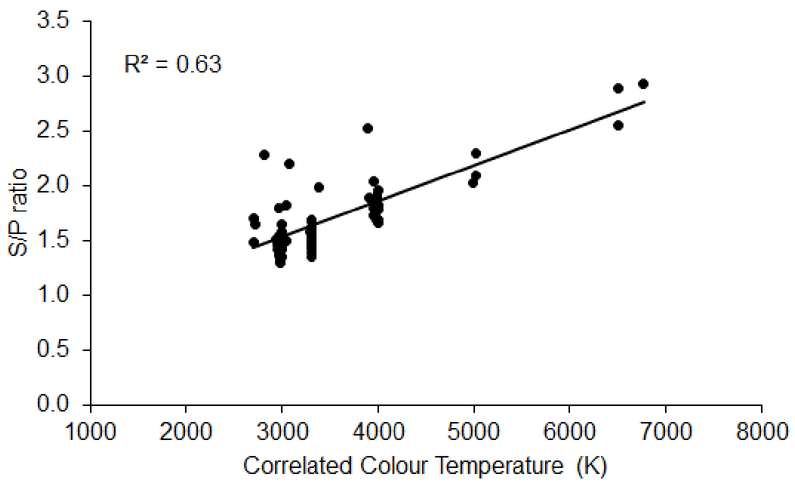

Figure 7. S/P ratio plotted against CCT for the 64 LED mixed spectra included in the library of IES TM-30-15 [IES 2015].

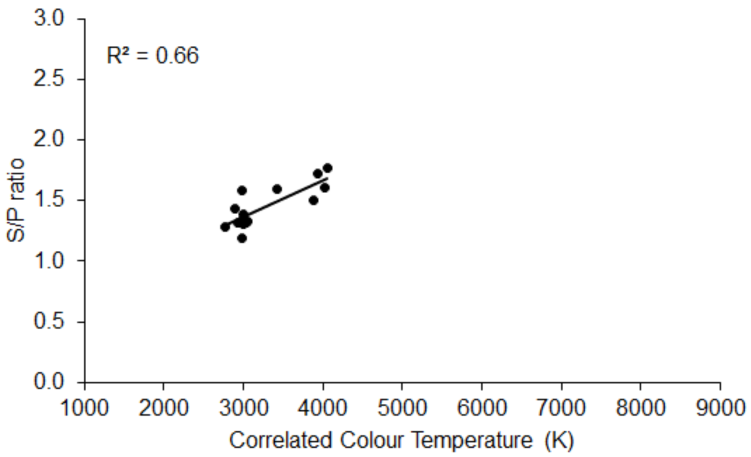

Figure 8. S/P ratio plotted against CCT for the 15 LED hybrid spectra included in the library of IES TM-30-15 [IES 2015].

Figure 10 shows the 20 HID lamps from the TM-30-15 library. The association between S/P ratio and CCT is significant (R^2=0.41, n=20, p=0.001) but the graph suggests a large degree of scatter. However, the HID category contains several different types of lamp and further analysis by these subcategories of HID lamp shows a strong association between S/P ratio and CCT for two types as shown in Figure 11 (HPS, R^2=0.99, n=6, p<0.001; Metal Halide R^2=0.80, n=10, p<0.001) but not for one type (Mercury R^2=0.75, n=4, p=0.068).

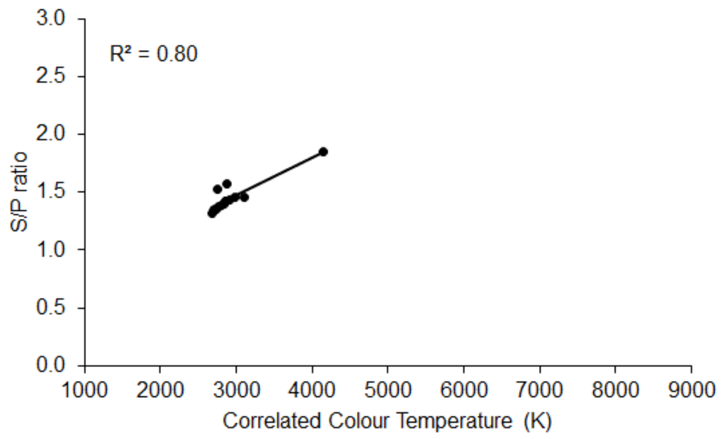

Figure 9. S/P ratio plotted against CCT for the 14 incandescent lamp spectra included in the library of IES TM-30-15 [IES 2015].

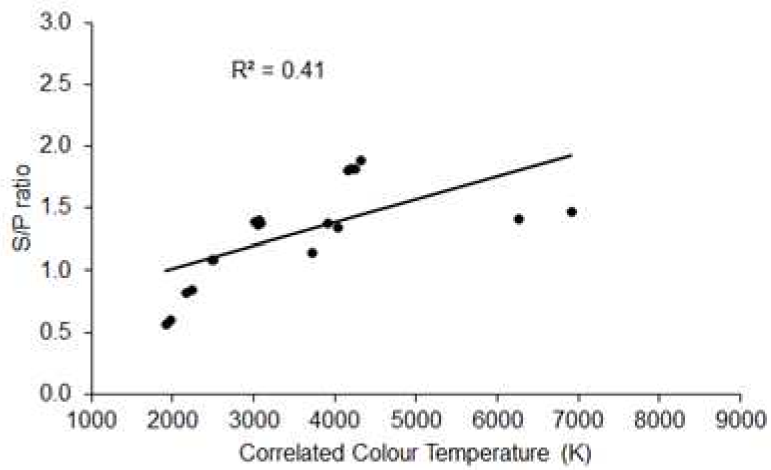

Figure 10. S/P ratio plotted against CCT for the 20 HID lamp spectra included in the library of IES TM-30-15 [IES 2015].

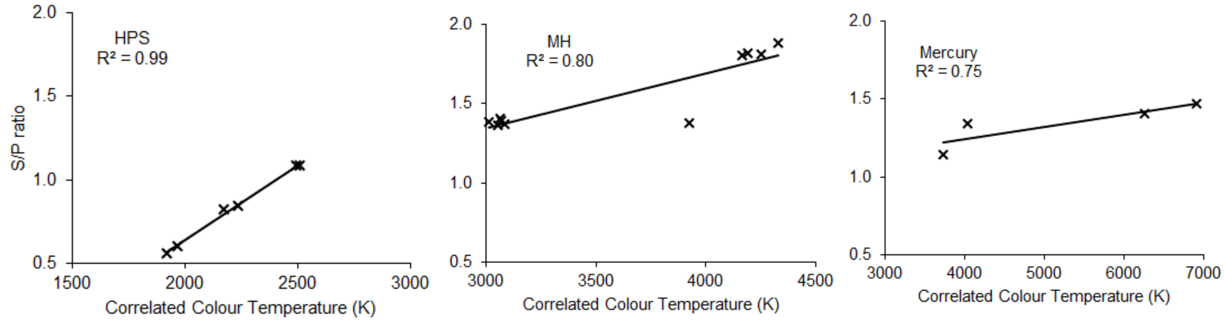

Figure 11. S/P ratio plotted against CCT for the three types of HID lamp spectra included in the library of IES TM-30-15: HPS (left), MH (center) and Mercury (right) [IES 2015].

When calculating S/P ratios for this analysis the two degree photopic observer was used. It is also possible to use a ten degree photopic observer, and the two might lead to different S/P ratios for any spectra having significant emission in the short wavelength region. Figure 12 plots the S/P ratios for the 297 spectra calculated using the two degree observer against those calculated using the ten degree photopic observer. There is a high degree of association (r^2=0.99, n=297) and this is a good fit for all but one spectrum (#166, RGBA LED). For the range of spectra considered, this suggests the choice of photopic observer was of negligible importance.

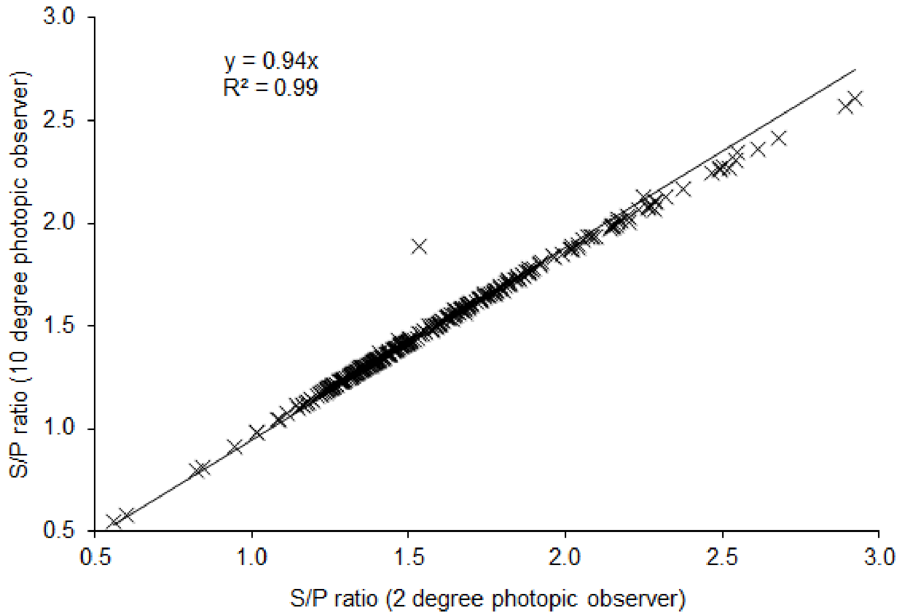

Figure 12. Comparison of S/P ratios of the 297 spectral in the library of IES TM-30-15 when calculated with the two-degree and ten-degree photopic observers.

4 Summary

For any given type of lamp or LED, the spectra considered here suggest a general tendency for those of higher CCT to also provide a higher S/P ratio. This confirms that it is reasonable to assume that for commonly used light sources the demand for a higher S/P ratio means a higher CCT is likely. It is possible to select different S/P ratios at a given CCT but in these data the range available is relatively small (Table 2 shows the range for fluorescent lamps as an example).

It could be that lamp manufacturers have purposefully targeted a higher CCT for lamps of higher S/P ratio, leading to the current results.

Figure 13 shows the same data as plotted in Figure 4 but with the different types of lamp separately identified. This shows that it is possible to extend the range of S/P ratios available at a given CCT, but that this requires choosing a different type of lamp or LED (Table 2), or for lamp manufacturers to give this association some consideration when selecting the spectra for new products. A change in lamp type has implications for other design parameters such as optical control, maintenance, and costs, which means it is not a simple consideration. Note also that the future availability of further types of LED which use a different technology may, in turn, require them to be treated as a 'new' lamp type in the context of this paper.

Given the public reaction to white lighting then it is useful to consider other routes by which the reaction may have arisen and may be remedied. When discharge lamps were introduced in the 1930s, it is reported that they '*gave light of an unfamiliar colour which has strange and unflattering effects on personal appearance*' compared with the filament and gas lighting they replaced [Waldram 1950]. It thus appears that the public now desire to retain the light sources previously thought to be unfamiliar and unflattering. This suggests a reluctance to change rather than a reaction to the lighting, with colour appearance being the most prominent distinguishing feature of the change. In which case, better management of the change is needed rather than placing limits on the technology.

Table 2. Examples of the range of S/P ratio found at a given CCT according to collation of only fluorescent lamps or across all types of lamp.

CCT	**Range of S/P ratios possible for collated lamps***	
	Fluorescent lamps only (Figure 5)	**Any type of lamp (Figure 4)**
3000K	1.00 – 1.35	1.0 – 2.0
4000K	1.25 – 1.70	1.25 – 2.25
5200K	1.75 – 2.00	1.60 – 2.15

*These are the approximate lower and upper S/P ratios for the given type(s) of lamp at the given CCT.

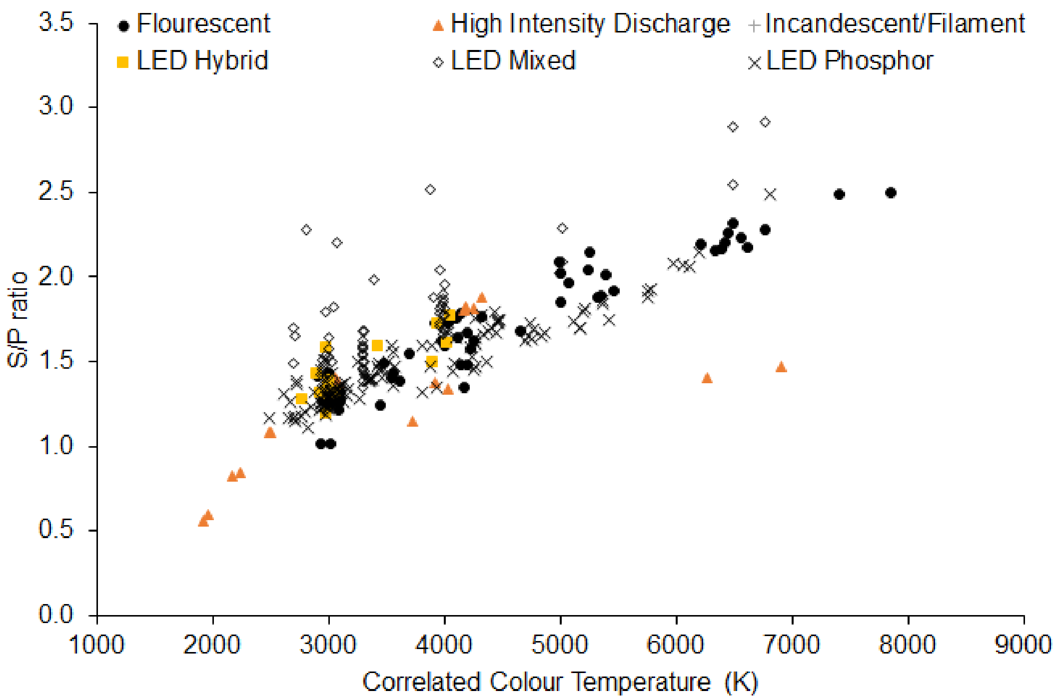

Figure 13. S/P ratio plotted against CCT for the 297 spectra included in the library of IES TM-30-15 [IES 2015].

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