

Spectral Characteristics Influencing the Metameric Uncertainty Index

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SPECTRAL CHARACTERISTICS INFLUENCING THE METAMERIC UNCERTAINTY INDEX

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Abstract

This article examines the relationship between various attributes of light source spectral power distributions (SPDs) and a recently proposed measure of colour rendition, the Metameric Uncertainty Index (R_t). For SPDs comprised of discrete spectral emissions (primaries), the maximum achievable R_t value (corresponding to a reduced likelihood of metameric mismatch) increases with both the number of primaries and their bandwidth. This work also explores how R_t relates to and interacts with other measures of colour rendition—in particular, the Fidelity Index (R_f)—and luminous efficacy of radiation (k). This is important, because there is an intrinsic tradeoff between luminous efficacy of radiation and colour rendition, which informs the application-dependent optimization of illumination. When white-light SPDs are engineered to maximize k , subject to maintaining a minimum required R_t value, the result is a small number of narrow primaries and hence a comparatively poor R_t value. This can only be mitigated by including R_t among the colour rendition optimization constraints. Therefore, from this perspective, R_t is an independent and key aspect of colour rendition.

Keywords: Colour Rendition, Metameric Uncertainty, Spectral Optimization, Luminous Efficacy of Radiation, Colour Fidelity

1 Introduction

A new measure of colour rendition, the Metameric Uncertainty Index (R_t) was recently developed (David et al., 2019) and proposed as an adjunct to CIE 224:2017 R_t (CIE, 2017) and ANSI/IES TM-30-18 (IES, 2018a), with which it shares a common underlying computational framework. R_t correlates with the likelihood of noticeable metameric mismatches being induced by a given light source. This is an important consideration in many lighting applications (e.g., retail, textile production), yet it has received comparatively little attention and lacks a standardized method of quantification.

As with other measures of colour rendition, R_t is determined from the change in appearance of colour samples that results from the difference between the spectral power distribution (SPD) of the test light source and that of a correlated colour temperature (CCT)-matched reference illuminant. The colour shift for each sample is construed to be the vector sum of two components: (1) a *base* colour shift that depends on the *colour* of that sample, and (2) a *metameric* colour shift that depends on the underlying details of that sample's spectral reflectance function.

Base colour shift varies smoothly in the a - b plane of colour space—a pattern that has previously been alluded to (de Beer et al., 2015, van der Burgt and van Kemenade, 2010, van Kemenade and van der Burgt, 1995, Royer et al., 2018). Therefore, it can be modelled well by a vector field represented by a second order polynomial vector function of the (a, b) coordinates that has 12 adjustable numerical parameters. A simple direct computation can determine the parameter values that optimize the fit between this vector function and the actual pattern of sample colour shifts caused by the test light source. Metameric colour shift is then calculated as the vector difference between the modelled base colour shift and the actual colour shifts, for a reasonably large set of colour samples—in this case, the 99 colour evaluation samples (CES) of CIE 224:2017 and ANSI/IES TM-30-18. The size, diversity, and spectral uniformity of this sample set, along with the associated modern colour space, makes this a reliable, useful measure that can be meaningfully compared to R_t and other related colour rendition measures.

In the same way that R_t characterizes total colour shift, R_t characterizes metameric colour shift with a scale of 0 to 100, with 100 corresponding to no colour shifts. Lower R_t values indicate successively greater degrees of metameric colour shift. Thus, as R_t is reduced, there is an increased likelihood of perceptible colour mismatch of surfaces that are metameric under the reference illuminant. Consequently, for light sources with lower R_t values, current colour rendition measures, such as R_t ,

are less reliable predictors for general scenes in which the surfaces differ from the standard colour samples used by such measures. The cause of this reduced reliability is the increased variability in the magnitude and direction of colour shifts for metameric surfaces.

The analysis presented here focuses on how R_t varies over a wide variety of SPDs having different spectral features. R_t and R_f are correlated, but because metameric colour shift is only part of total colour shift, there are important deviations. This is studied by configuring SPDs that comprise several narrow emission bands (hereafter termed primaries). The role of R_t in optimizing light source SPDs for luminous efficacy of radiation (k) is also examined. This work is intended to introduce the utility of the R_t measure and thus help guide the future design of architectural light sources.

2 Methods

The relationship between specific spectral characteristics and R_t values was examined using several approaches. One used a large set of theoretical SPDs that began with 100,000 SPDs calculated by varying the number of primaries (three, four, five, six, or seven) and their bandwidth (2-11 nm [“narrow”], 20-51 nm [“medium”], 50-101 nm [“wide”], or 2-101 nm [“mixed”]). There were 5,000 SPDs with each combination of features. Each primary was calculated as a Gaussian distribution, using a random number generator to vary the peak wavelength, full-width-half-maximum (FWHM), and maximum intensity. CCT was limited to nominally 2700 to 6500 K, with distance from the Planckian locus (D_{uv}) limited to the range of 0.006 to -0.018, or the approximate limits of the standard and extended chromaticity targets of ANSI/NEMA C78.377-2017 (NEMA, 2017). An additional 50,000 four-primary SPDs with mixed FWHM characteristics were also included, as were approximately 15,000 other randomly generated SPDs with similar constraints that were used in a previous analysis (David et al., 2019). The total set of approximately 165,000 theoretical SPDs was used in a previous analysis of energy efficiency tradeoffs with various measures of colour rendition (Royer, 2019c), where it is described further, and is available for download (Royer, 2019d, Royer, 2019b).

The second approach involved using the nonlinear generalized reduced gradient function of Microsoft Excel Solver, including multiple starting points to increase the likelihood of determining global optima. Four-primary SPDs optimized for maximum luminous efficacy of radiation were previously generated under a variety of constraints on both colour rendition characteristics (e.g., R_t , R_a , etc.) and spectral characteristics (peak wavelength and FWHM ranges) (Royer, 2019c). These included *theoretical* spectral characteristics allowing FWHM as narrow as 1 nm with D_{uv} as high as 0.006, and *realistic* spectral characteristics that varied by peak wavelength according to existing capabilities (e.g., 15 nm minimum FWHM for primaries less than 490 nm) and with D_{uv} as high as 0.000. Previously, this approach had examined constraints based on the colour rendition measures of ANSI/IES TM-30-18. Here, for the first time, the effects of also including R_t within optimization constraints are introduced.

Finally, a set of 886 SPDs for real lighting products was compiled from a variety of sources to provide a reasonable baseline for current light sources and allow some general comparisons of technology types (e.g., LED vs. fluorescent). Data sources included the ANSI/IES TM-30-18 calculator tool library (IES, 2018b), U.S. DOE CALiPER program test results, LED Lighting Facts submissions, personal communications, and SPDs supplied to CIE R1-62. The database includes 112 fluorescent SPDs, 58 HID SPDs, 42 incandescent/filament SPDs, 668 LED SPDs, and 6 others.

3 Results

3.1 R_t Performance Baselines

For the 165,000 theoretical SPDs with a given R_f value, there was a wide range of possible R_t values (Figure 1), despite moderate correlation ($r^2 = 0.75$). Typically, R_t ranged from a minimum of slightly greater than R_f to a maximum of approximately $100 - (100 - R_f) / 4.5$. For example, at $R_f = 80$, the range of R_t was approximately 83 to 96.

Figure 1 also shows values for real SPDs. Within the set of real SPDs, 669 products had an $R_t \geq 80$, which is typical of interior architectural environments. This set of products was used to establish a baseline of performance to help guide expectations of future light sources. Among those 669 products, the minimum R_t value was 88, the mean was 95, and the maximum was 100 (for incandescent lamps). All but one LED product, which was a specialty product with a CCT of 1856 K, had an R_t value of 92 or greater—the LED products included a range of phosphor-converted (pc), hybrid, and colour-mixed architectures.

The real SPDs with $R_t \geq 80$ that had the greatest metameric uncertainty were typically triphosphor fluorescent lamps, with R_t values between 89 and 93. Although speciality fluorescent lamps can have an R_t value as high as 97, “80 Series” fluorescent lamps with $80 \leq R_a \leq 86$ (many of which do not have $R_t \geq 80$) had R_t values between 85 and 95 with a mean of 90. Accordingly, a reasonable *baseline* (i.e., a typical starting point for quality comparisons) for fluorescent lamps was estimated to be $R_t = 85$. It should be noted a small portion of the variation may be due to the specifications of the spectrometer used for measurement and/or the increment of the reported SPD (e.g., 1 nm vs. 5 nm). SPDs measured and/or reported with reduced precision may incorrectly appear to have slightly broader spectral, which could falsely increase the calculated R_t value.

“80 CRI” pc-LEDs with $80 \leq R_a \leq 86$ had R_t values between 88 and 96 with a mean of 94. Excluding the outlier at 88, the range was 92 to 96. On this basis, a reasonable baseline for LEDs was estimated to be $R_t = 92$.

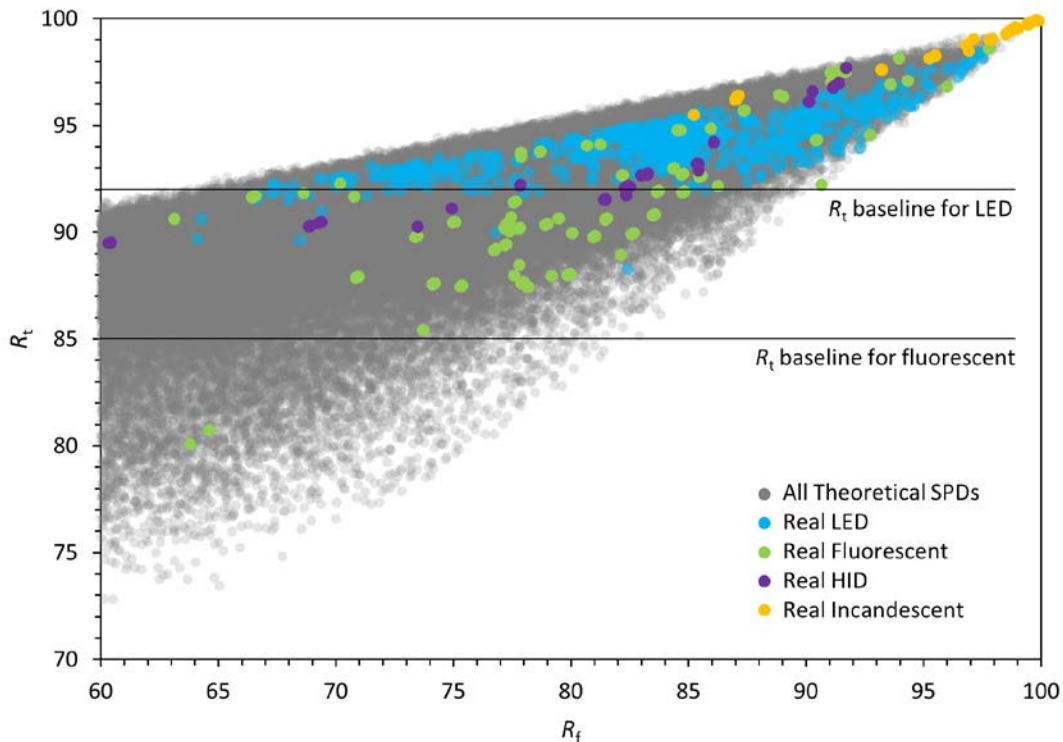


Figure 1. R_t vs R_f for theoretical and real SPDs, with newly established baselines

3.2 Spectral Features

Within the large set of theoretical SPDs, the FWHM of primaries had a modest effect on the maximum achievable R_t value. For the narrow, medium, and wide sets ($n = 25,000$ each), the maximum R_t values were 94, 97, and 99, respectively. This indicates that it is *possible* to have an SPD with relatively narrow primaries that has an R_t value comparable to current products—the key is to have enough of them. Notably, the range of R_t values expands greatly as FWHM is reduced (Figure 2), and the minimum R_t value can be worse than the previously estimated baseline regardless of the FWHM of the primaries. For example, at $R_f \geq 80$, the minimum R_t values for the narrow, medium, and wide sets were 84, 85, and 89, respectively. In other words, using wide primaries does not guarantee appropriate performance in terms of R_t . (As an aside, additional points are achievable within the somewhat sparsely populated regions near the perimeter of the data points shown in Figure 2; the scarcity near the boundaries occurs because the SPDs were randomly generated and finite in number. In principle, almost any point within the boundary could be generated by targeted spectral design.)

The decrease in R_t value with narrow primaries can be mitigated by including more primaries. The maximum R_t values for the theoretical SPDs with three, four, five, six, and seven narrow primaries ($n = 20,000$ each) were 83, 89, 91, 93, and 94, respectively. Nonetheless, it is important to note that very narrow primaries generally result in lower R_t values for any given R_f value. The lower limit of R_t for a given R_f value is found for SPDs with laser-like primaries. To achieve R_t values comparable to current light sources, at least five lasers are needed, with six or seven providing a more appropriate solution.

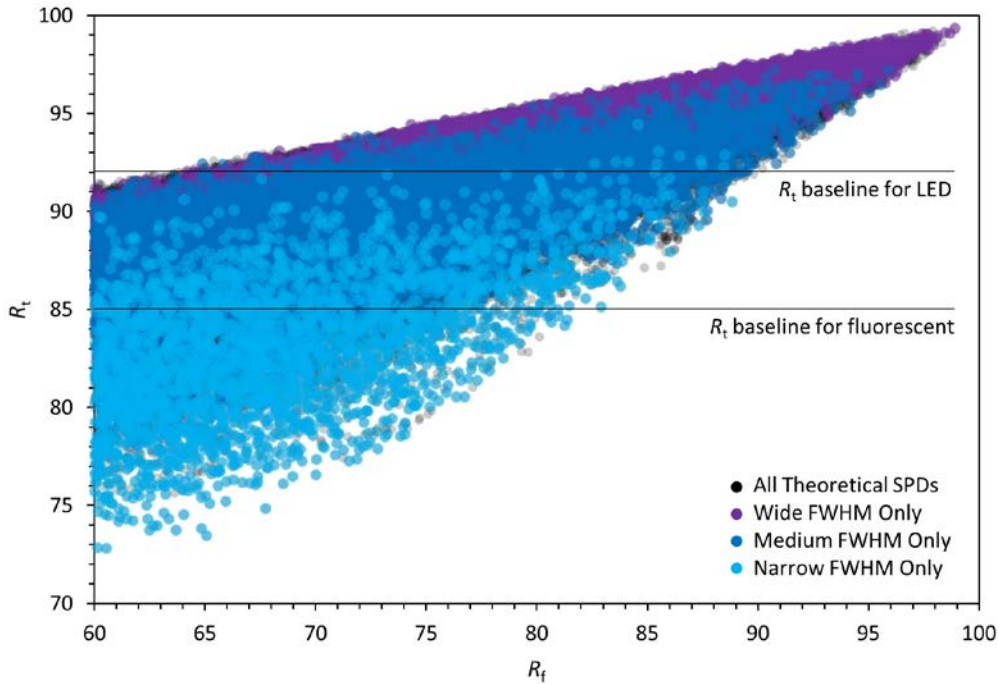


Figure 2. R_t versus R_f for theoretical SPDs according to the width of primaries

3.3 Spectral Efficacy

The tradeoff between R_f (or R_a) and luminous efficacy of radiation is well documented (Royer, 2019c, David et al., 2015, Zhang et al., 2017b, Papamichael, K. et al., 2016). Figure 3 shows the compounding tradeoff between luminous efficacy of radiation and the combination of R_f and R_t . That is, the maximum luminous efficacy of radiation for a given minimum R_f value occurs at or near the minimum R_t value. This occurs because SPDs along the Pareto boundary for luminous efficacy of radiation and R_f have the narrowest possible primaries that can achieve a given average colour fidelity criterion. Only optimally efficient SPDs with $R_f \geq 90$ can achieve $R_t \geq 92$, which is the LED baseline.

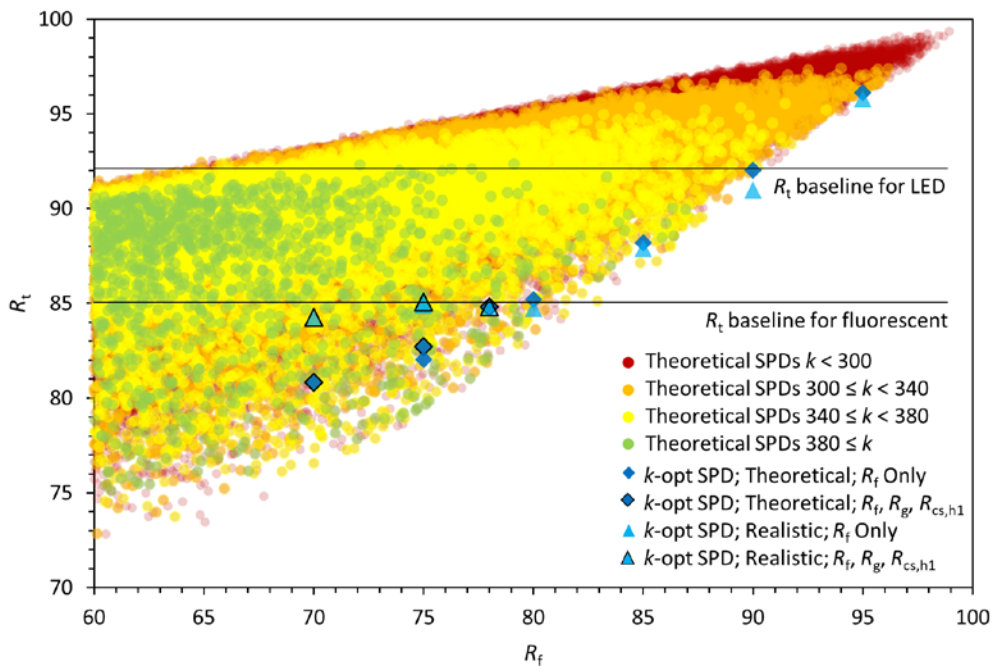


Figure 3. R_t versus R_f for theoretical and optimized SPDs according to luminous efficacy of radiation (k , units $\text{lm}/\text{W}_{\text{optical}}$)

Engineering an SPD to maximize luminous efficacy of radiation under the constraint of specified colour rendition criteria that promotes colour preference (Royer, 2019a, Royer et al., 2019) also results in lower R_t values, at or below the fluorescent baseline. Figure 4 illustrates this by showing the tradeoff between the luminous efficacy of radiation and the combination of R_t and ANSI/IES TM-30-18 $R_{cs,h1}$ (a measure of red chroma that is closely related to colour preference (Royer et al., 2019, Royer et al., 2018, Royer et al., 2017, Royer et al., 2016, Zhang et al., 2017a, Esposito and Houser, 2018)).

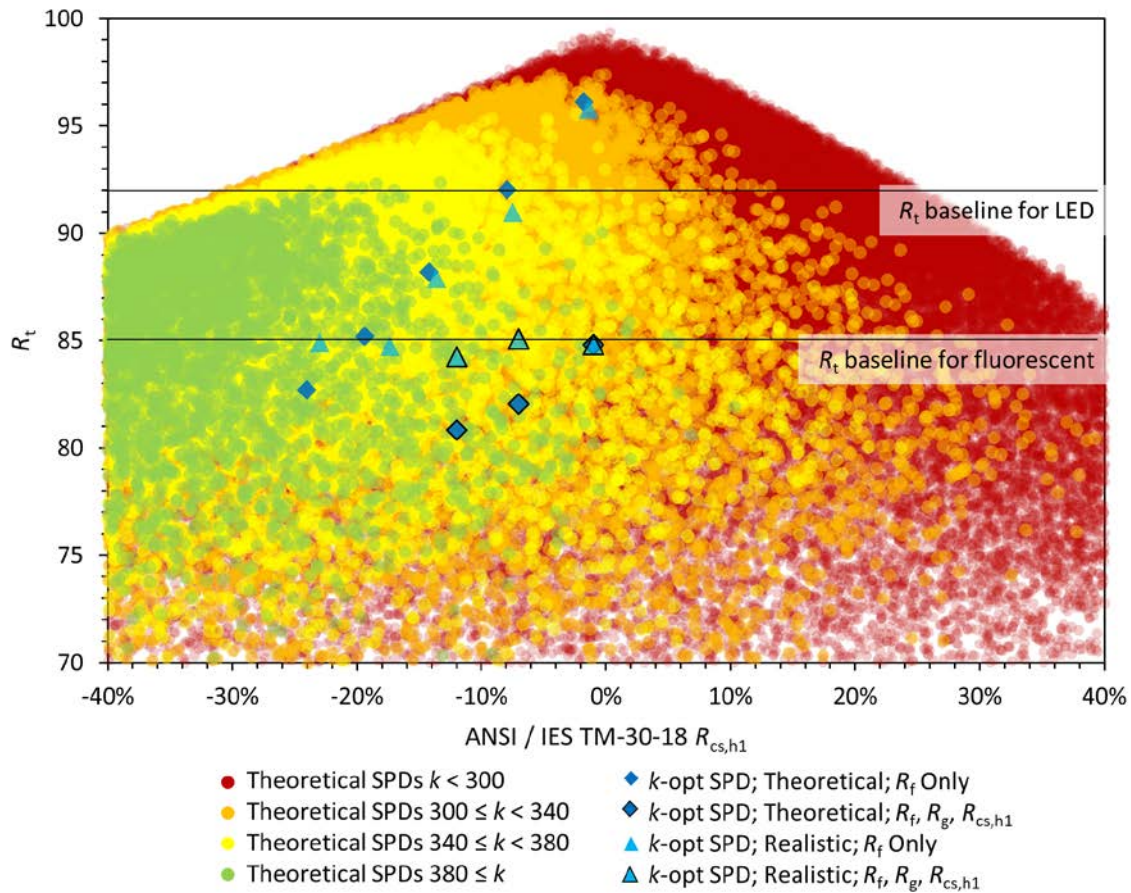


Figure 4. R_t versus $R_{cs,h1}$ for theoretical and optimized SPDs according to luminous efficacy of radiation (k , units $\text{lm/W}_{\text{optical}}$)

Table 1 shows the maximum possible values of luminous efficacy of radiation (k) for *theoretical* and *realistic* four-primary light sources, as previously described, with constraints on R_t alone (five levels shown in five rows for each group of spectral characteristics) or the same levels of R_t with one of two constraints for R_t . The R_t levels correspond to the fluorescent and LED baselines. Many other combinations of colour rendition measures could be examined.

Those values shown in red correspond to cases where the added R_t constraint reduced the achievable luminous efficacy of radiation. In other words, the SPDs optimized without a constraint on R_t had R_t values less than one or both baselines, as visible in Figures 3 and 4. In those cases, the SPDs optimized with consideration for R_t differed from those optimized without that new constraint: The “blue” primary was generally wider and often the “green” primary was too. The added R_t constraint sometimes narrowed the “amber” and “red” primaries, perhaps reflecting different spectral regions of maximum influence for R_t and R_t . Typically, both the amount of spectral change, and the corresponding reduction in luminous efficacy of radiation, correlated with the size of the increase in R_t that arose from the additional constraint. Requiring R_t to exceed 92 generally reduced the luminous efficacy of radiation, except for the cases where R_t was constrained to exceed 90.

Table 1. Reductions in maximum luminous efficacy of radiation (k) when supplementing minimum R_f with minimum R_t criteria

Baseline R_f criterion	k_{\max} with R_f baseline (lm/W_{opt})	k_{\max} with R_f baseline and $R_t \geq 85$ (lm/W_{opt})	k_{\max} with R_f baseline and $R_t \geq 92$ (lm/W_{opt})
Theoretical Features			
$R_f \geq 75$	449	448	418
$R_f \geq 80$	436	436	415
$R_f \geq 85$	421	421	409
$R_f \geq 90$	398	398	398
$R_f \geq 95$	359	359	359
Realistic Features			
$R_f \geq 75$	427	427	392
$R_f \geq 80$	416	416	388
$R_f \geq 85$	401	401	385
$R_f \geq 90$	381	381	378
$R_f \geq 95$	342	342	342

3.4 Complementary System

During the development of R_t , multiple colour sample sets were considered (David et al., 2019). Numerical analysis showed that sparse sample sets (e.g., the eight test colour samples [TCS] used to calculate R_a) were unsuitable for generating an accurate vector field model for base colour shift and subsequently R_t -like measures. This has also been expressed by others (van der Burgt and van Kemenade, 2010). The left plot of Figure 5 illustrates the discrepancy that exists between R_t and a conceptually equivalent measure generated from the eight TCS used to calculate R_a . For context and comparison, the right plot of Figure 5 shows the minimal discrepancy between R_t and a conceptually equivalent measure generated from the 4,880-sample reference set (David et al., 2015). For this figure, only a subset of the full set of SPDs is considered, totalling approximately 15,000 SPDs, as considered in a previous study (David et al., 2019). Note that the range of R_t calculated using the eight TCS is much smaller. This is because the vector field model can perfectly match the shift of six samples, so effectively only 2 out of the 8 contribute to R_t . Even ignoring the scale differences, there are substantial differences in R_t derived using the 99 CES and 8 TCS. These differences are analogous to those demonstrated between R_f and R_a (Royer, 2017).

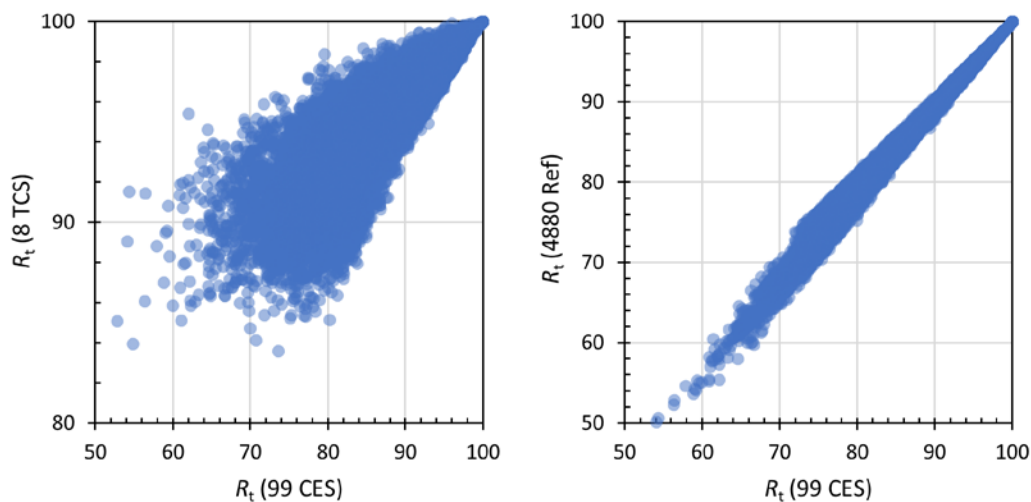


Figure 5. Comparison of R_t calculated using different colour samples

Combining R_t with R_a for colour rendition specification is not recommended. This would distort the separation of colour shift into the base and metameric components. In fact, it would suggest that metameric colour shift can exceed total colour shift, which is not possible. This is demonstrated in Figure 6, which illustrates a broader spread in R_t at a given value of R_a than a given value of R_f (e.g., Figure 1). Note that SPDs with R_a of 95 can have R_t values as low as 87, which occurs when an SPD

is optimized for high luminous efficacy of radiation. In such cases, the R_a value is an inflated measure of colour fidelity achieved through optimization for only the eight TCS used in the calculation.

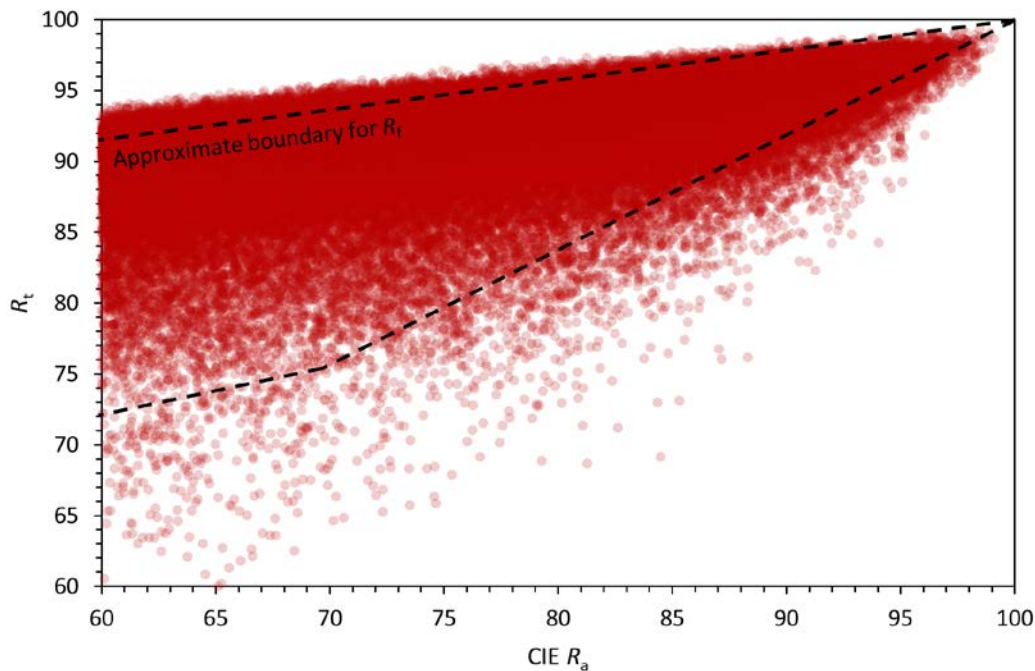


Figure 6. R_t versus CIE General Colour Rendering Index R_a , with comparison boundaries for R_t versus R_t

4 Discussion

4.1 Meaning of R_t

Measures of colour rendition should predict the colour quality of objects illuminated in a real architectural environment, yet they must rely on a standardized set of spectral reflectance functions to be relevant for commerce. It is therefore important to consider how well those spectral reflectance functions represent the colour-shift behaviour of real objects in the environment of interest. Most familiar measures of colour rendition, such as R_t , R_a , or the measures of ANSI/IES TM-30-18, focus on accurately predicting total colour shift, and there is a need to understand the extent to which the results are generalizable. R_t can help with that because it characterizes the metameric component of total colour shift, which relates to uncertainties in those other measures of colour rendition. When R_t is high (indicating minimal metameric colour shift), one can be confident that the colour shifts predicted by other measures of colour rendition will be realized in an architectural environment.

R_t also has another interpretation that can be explained by considering several successive stages of colour shift predictions: (1) In the simplest case, consider two pairs of metameric colour samples, one pair red and the other blue. A general colour fidelity measure assesses an average colour shift that would be equally applicable to all four samples. In other words, all four shifts are predicted to be of equal magnitude, but unknown direction. (2) This information could be enhanced by assessing hue-specific aspects of the magnitude of colour shift, which could predict that the red samples would shift more than the blue samples, for example, but the predictions would still be directionless. (3) Measures of local chroma shift and local hue shift, as found in ANSI/IES TM-30-18, could improve the prediction further by identifying the magnitude and direction of expected shifts, but the predicted shift for each of the red samples would be identical, and this would also be the case for the blue pair. Yet, because they are only metameric under the reference illuminant, the two red samples will generally shift differently, as would the two blue samples, and in many cases, these differential shifts could be undesirable, so key information is missing. (4) R_t addresses this need by providing a reasonable estimate for the likely magnitude of the differential shifts of metameric samples. Of course, R_t does not predict the expected direction and size of the differential shift for a specific metameric pair, but it does provide a useful probabilistic depiction of the likely range of magnitudes of differential colour shifts of metamers.

Naturally, it could also be useful to predict the actual expected direction and magnitude of differential shift for a specific metameric pair. However, the only way to do this would be to first know their spectral reflectance functions and then use a colour appearance model in conjunction with the test and reference illuminant SPDs. This procedure is prohibitively difficult in most practical situations. Thus, R_t is a very practical middle ground.

This work studied the performance of conventional light sources to estimate baseline R_t values that could be used in future specifications. Experiments should be conducted to further establish practical, application-specific performance thresholds, but the approach will need to differ from past colour rendition work. One possibility is to examine the tolerability of metameric mismatch in realistic settings, via carefully curated colour pairs.

4.2 Implications for Future Light Source Development

Fluorescent lamp technology progressed from broadband to narrowband emissions, and it would not be surprising for LED technology to evolve along a similar path, especially because previous standardized methods for evaluating light source colour rendition are not sensitive to metameric mismatch, and there is a widespread desire to increase the luminous efficacy of light sources. Notably, it has been projected that colour-mixed LEDs will exceed the luminous efficacy of pc-LEDs in the future (DOE, 2019). Narrowband emissions could also be possible with other solid-state lighting (SSL)-based technologies, such as quantum dots, laser diodes, or simply narrowband phosphors. For these reasons, it is important to understand the implications of SPDs containing narrowband features.

Narrowband fluorescent lamps have lower R_t values than light sources with otherwise comparable colour rendition characteristics, such as pc-LEDs. Although “80 Series” fluorescent lamps were never favoured in applications where colour matching was important, they were nevertheless used in a wide variety of environments—perhaps because no suitable alternative was available. The textile industry could cope with the metameric uncertainty induced by this lamp type using physical sample evaluation in light booths, which was practical because there was relatively little variation among the few manufacturers of such lamps. In contrast, it is unlikely that future colour-mixed SSL devices would be similarly homogeneous, so metameric uncertainty could be much more problematic.

Future SSL technology developers and users will face important choices. R_t and R_f can be maximized simultaneously, but only at the expense of luminous efficacy of radiation. Maximizing luminous efficacy of radiation while only considering R_t leads to reduced R_f values; if R_t exceeds 83, R_f will not be worse than “80 Series” triphosphor fluorescent lamps (i.e., 85) and if R_t exceeds 92, R_f will not be substantially worse than “80 CRI” pc-LEDs (i.e., 92). Adding a minimum R_t requirement of 92 to optimizations for maximum luminous efficacy of radiation, with R_t exceeding 80, reduces the maximum luminous efficacy of radiation by approximately 7%, depending to some extent on the limitations of the spectral characteristics (number of primaries, peak wavelengths, and FWHMs). Interestingly, SPDs with R_t values as low as 65 can achieve R_f values as high as 92. Overall, it seems unlikely that considering only R_t or R_f alone would yield desirable results.

A related consideration involves spectral optimization for colour preference rather than colour fidelity. This allows higher maximum luminous efficacy of radiation values (Royer, 2019c), principally due to reduced requirements for average colour fidelity (e.g., R_f). However, such optimized SPDs have R_t values between 83 and 85, which is at or below the level for “80 Series” triphosphor fluorescent lamps. Unlike the relative synergy of increasing average colour fidelity and reducing metameric uncertainty (at the expense of luminous efficacy of radiation), increasing colour preference and reducing metameric uncertainty can be conflicting if energy efficiency is also a concern. Note, however, that excellent colour fidelity, excellent colour preference, and excellent metameric uncertainty can all be achieved simultaneously, at the expense of maximizing luminous efficacy of radiation. Such a solution could be practical if the resultant benefits more than compensate for the illuminance reduction or increase in energy use.

The tradeoff between desirable colour rendition and luminous efficacy or radiation is fundamental in nature and not the result of technological limitations. The individual measures of colour rendition, such as R_t , R_f , or $R_{cs,h1}$ tend to compound with one another in the tradeoff with energy efficiency. This is because the goal of increased luminous efficacy of radiation calls for placing as much energy as possible near the peak of the CIE photopic luminous efficiency function, $V(\lambda)$. The optimal balance of spectral characteristics will undoubtedly depend on the lighting application and, in that context, the comparative human value of illuminance and the different aspects of colour rendition. These are key questions for ongoing human factors research.

4.3 Scale of R_t

The range of R_t values is notably smaller than that for R_i . This is because the colour shifts used in the calculation of R_t necessarily include contributions from the metameric colour shift, although many may be unaware of this fact. In other words, as currently defined in support of internal consistency, R_t cannot be lower than R_i . It would certainly be possible to rescale R_t so that it has an average relationship that is closer to 1:1 with R_i . This would entail adjusting the colour difference scaling factor, which was preliminarily matched to that for R_i , at 6.73, to a value of about 17. While this might make it somewhat easier to compare different light sources, some might find this confusing. In any case, this decision would have no practical impact, since for any adjustment of the scaling factor there would be a compensatory adjustment to any recommended thresholds for R_t .

4.4 Future Work

Improving SPDs is a very complex endeavour because there are several important quality measures, with a new one, R_t , now added to the mix. Further, there are many different possibly ways to incorporate colour quality constraints into optimization routines. In the future, it will be important to consider not only the luminous efficacy of radiation of a given SPD, but also the luminous efficacy of a practical lamp that can produce it.

A secondary consideration is that R_t has so far only been defined as a global average measure. That is, local (hue-specific) versions have not been defined, as they have been for colour fidelity, chroma shift, or hue shift in ANSI/IES TM-30-18. Work is needed to investigate the extent to which metameric uncertainty varies by hue and if that variation can be usefully quantified.

On a more practical level, investigation is needed into the influence of SPD measurement and reporting precision on calculated values for R_t —and more broadly for all measures of colour rendition. This is particularly important as measures of colour rendition become more specific and the spectral features of some solid-state lighting devices become narrower.

5 Conclusions

R_t characterizes a unique and important aspect of colour rendition. It is preferable for R_t to be high, all other things being equal, although R_t is only one of several factors that may have varying degrees of desirability in different settings. This analysis shows that when luminous efficacy of radiation is maximized at a given value of R_i , R_t will be relatively low. That is, the need to maintain R_t exacerbates the already-known tradeoff between luminous efficacy of radiation and colour fidelity.

If light source designers consider developing laser-like narrowband light sources for use in general illumination settings, it is important to understand that there may be negative consequences from resultant colour mismatches of metameric surfaces. Fortunately, it is possible to reduce that problem by using a sufficiently large number of narrow primaries, which can improve colour fidelity as well. In general, the optimization of light source characteristics will likely yield different preferred solutions for different applications.

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