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CIE Whiteness and Tint: Possible Improvements

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Summary

To introduce some measure of standardization in the face of the endless variety of whiteness formulas being used, the "Commission internationale de l'éclairage" proposed in 1986 a whiteness and a tint formula for practical trials. The formulas in question were simplified derivatives of those used in the Ganz/Griesser method. The difference is that the CIE proposes fixed formula parameters and recommends the formulas only for relative assessments valid just for measurements with a single instrument at a given time and without reference to a white scale. Use of the two formulas is restricted to samples differing not too widely in tint and fluorescence. With these restrictions the formulas yield relative, not absolute, white assessments reportedly adequate for commercial use in many cases. The measuring instruments must have sample illumination resembling daylight.

Assessment with the formulas is appreciably improved if the sample illumination is stabilized and fitted as close as possible to a desired standard illuminant, as with the Gärtner/Griesser UV adjustment device. The samples to be compared then do not need to be measured at the same time. It also greatly improves the matching of different measuring instruments, though only for whiteness. The tint values can only be satisfactorily matched by instrument-specific calculation of the formula parameters as practised in the Ganz/Griesser method. The CIE method can be upgraded and markedly extended in scope by incorporating components of this new procedure, as suggested in the present paper. This takes account of the growing need to be able to achieve a close match even between the results obtained with instruments of different designs. The representative numerical data used in the calculations enable computer programs based on them to be checked for errors.

White and tint assessment by the method proposed by the CIE

The method's components [1, 2, 3, 4] for the 10° observer are:

- Instrument with illumination resembling daylight
- Whiteness (CIE) = $Y + 800 * (x_n - x) + 1700 * (y_n - y)$ (1)
- Tint (CIE) = $900 * (x_n - x) - 650 * (y_n - y)$ (2)

Where Y is the Y-tristimulus value of the sample, x and y are the x, y chromaticity coordinates of the sample, and x_n, y_n are the chromaticity coordinates of the perfect diffuser, all for the CIE 1964 supplementary standard colorimetric observer. With the tristimulus values [5] for standard illuminant D_{65}: X = 94.81, Y = 100.00 and Z = 107.33 and the chromaticity coordinates x = 0.313795 and y = 0.330972 calculated from them the two formulas can be resolved as follows (valid for D_{65}/10°):

Whiteness (CIE) = Y + (-800 * x) + (-1700 * y) + 813.6890 (3)
Tint (CIE) = (-900 * x) + (650 * y) + 67.2834 (4)
The lightness Y is weighted with 1 in formula (3), and it can be given the same structure as customarily assigned to the whiteness formula (Ganz) with the parameters D, P, Q, C. Formula (4) however has the same structure as the tint deviation formula (Ganz/Griesser) with its parameters m, n, k [6]:

Whiteness (CIE) = (D * Y) - (P * x) - (Q * y) + C (5)
Tint (CIE) = (m * x) + (n * y) + k (6)

Restrictions of the CIE method

The CIE proposal for the evaluation of whiteness and tint [3] includes the following restrictions:

"The application of the formulae is restricted to samples that are called "white" commercially, that do not differ much in colour and fluorescence, and that are measured on the same instrument at nearly the same time; within these restrictions, the formulae provide relative, but not absolute, evaluations of whiteness, that are adequate for commercial use, when employing measuring instruments having suitable modern and commercially available facilities."

For non-fluorescent samples these restrictions are less critical. For samples treated with FWAs however this generally means working with results relative to an assumed standard sample with all associated drawbacks.

Improvement by illumination stabilizing

Assessments with these formulas will give improved results when it is feasible to stabilize the sample illumination, e.g. with the UV adjustment device (Gaertner/Griesser) [2, 4, 6, 7, 8, 9, 10]. The samples that are to be compared then need not be measured at the same time. Also the conformity of different instruments can be improved by this, but of course only for whiteness results, not for tint results, because the yellow-blue axis is in principle not as critical as the red-green axis.

Comparison with the Ganz/Griesser method

A good agreement of instruments of different types for the tint results on the critical red-green axis is only attainable with instrument-specific formula parameters as practised with the Ganz/Griesser method [6]. For this method the above mentioned restrictions are not valid. The two methods have different scalings and similar preferences (white taste). While the CIE method of calculation is fixed and bears no reference to any existing standard, the Ganz/Griesser method is flexible in every respect. The scaling can be related as required to any other transfer standard in addition to the generally used Hohenstein cotton white scale [11]. It can also be related to theoretical standards. The preferences for hue, saturation and lightness can also be freely selected.

Analysis of the preferences of both methods

First let us compare the white preferences, i.e. the contribution to the whiteness of the qualities hue, saturation and lightness in the two methods. The dominant wavelength λ_d = 470 nm is the common basis, namely the reference wavelength RWL.

RWL = 470 nm — Reference dominant wavelength.
x_d = 0.1152 } Point of intersection of the RWL with the spectrum locus,
y_d = 0.1090 } dependent on the observer, but not on the illuminant.
X_n = 94.81 } Tristimulus values for
Y_n = 100.00 } standard illuminant D_{65} and
Z_n = 107.33 } CIE 1964 standard observer.
$x_n = X_n / (X_n + Y_n + Z_n) = 0.313795$ } Coordinates of the (7)
$y_n = Y_n / (X_n + Y_n + Z_n) = 0.330972$ } achromatic point. (8)
$\eta = \text{atan}[(y_n - y_d) / (x_n - x_d)] = 48.18154° = 0.84093$ (radians) = (9)
angle between RWL and x-axis of chromaticity chart.

The formula's "white flavor" , that is the contributions of hue, saturation and lightness to the whiteness, is defined for the whiteness formula (Ganz) by the following values:

$\delta W / \delta Y$ = 1 — Contribution of lightness to whiteness.
$\delta W / \delta S$ = 4000 — Contribution of saturation to whiteness; scaling.
φ = 15° = 0.26180 (radians) — Hue preference, referred to the perpendicular to the RWL.
$\delta W / \delta H = -\delta W / \delta S * \tan(\varphi) = -1071.7968$ — Contribution of hue to whiteness. (10)
W_0 = 100 — Degree of whiteness of physical ideal white.

From these standard values can be calculated the formula parameters D, P, Q, C:

$D = \delta W / \delta Y = 1$
$P = (-\delta W / \delta S) * (\cos (\varphi + \eta) / \cos (\varphi)) = -1868.322$ (11)
$Q = (-\delta W / \delta S) * (\sin (\varphi + \eta) / \cos (\varphi)) = -3695.690$ (12)
$C = [W_0 * (1 - \delta W / \delta Y)] - (P * x_n) - (Q * y_n) = 1809.441$ (13)
Whiteness (Ganz) = $(D * Y) + (P * x) + (Q * y) + C$ (14)

Further equations in the context of the contributions of hue and saturation to whiteness are:
$\psi = \varphi + \eta + \pi / 2 = 153.18154° = 2.67352$ (radians) (15)
$S = (\tan(\psi) * (x_n - x) - (y_n - y)) / (\tan(\psi) * \cos(\eta) - \sin(\eta))$ (16)

Figure 1 shows at bottom left the angle η, formed by the RWL and the x-axis. We also see the perpendicular to the RWL and the angle φ, in this case +15°, and the angle ψ, which forms its lateral side with the x-axis [12].

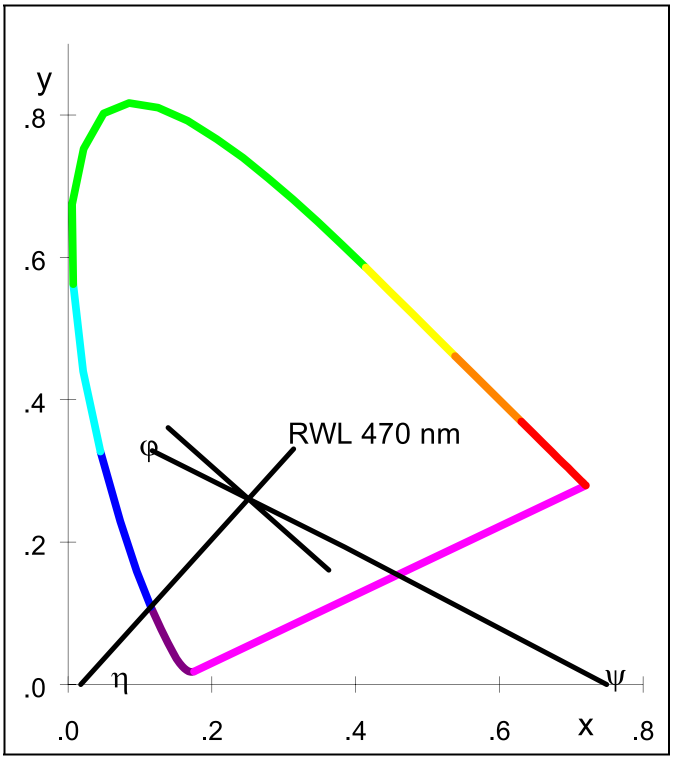

Fig. 1. Chromaticity chart D_{65}/10° with RWL = 470 nm, its perpendicular and the angles φ = 15° and ψ = 153.18°.

Using the CIE method parameters contained in formulas (3) and (4) the following characteristics can now be determined:

φ = atan(Q / P) - η + [(1 - (Q / P) / abs(Q / P)) * π/2]= 16.6173° = 0.29003 (rad.) (17)
δW / δS = -P * cos(φ) / cos(φ + η) = 1800.36 (18)
δW / δH = -δW / δS * tan(φ) = -537.3044 (19)
BW = sin(atan(n / -m)) / n = 0.000901 (20)

BW is the bandwidth in the tint formula and determines the formula's scaling [13]. Tables I and II compare the characteristics of the two methods for exactly the standard illuminant D_{65}/10° observer.

TABLE I. Characteristics of the two methods: common parameters.

	both methods	
RWL	470 nm	
δW / δY = D	1	
W_0	100	
	degree	***radians***
η	48.18154°	0.84093

TABLE II. Characteristics of the two methods: dissimilar parameters.

	Ganz/Griesser method		CIE method	
	degree	*radians*	*degree*	*radians*
φ	15°	0.26180	16.6173°	0.29003
δW / δS	4000		1800.36	
δW / δH	-1071.7968		-537.3044	
BW	0.0008		0.000901	

Questions

In addition to the facts known to date we should now clarify the following questions by carrying out a new, rather more extensive trial with different measuring instruments and different white samples:

1. What differences in whiteness and tint are to be expected if the CIE formulas are used unaltered, i.e. with their defined parameters, and if the sample illumination is not affected? In this case the UV excitation is dependent on the lamp type, the lamp in use, its age and on all other optical attributes of the instrument. The match can therefore range quite fortuitously from very poor to very good.

2. What further differences occur if as the first step to harmonize the results from different instruments the CIE formulas are retained in their original form but the sample illumination is matched to D_{65} by means of the UV adjustment device?

3. What further improvements can be achieved if besides matching the illumination as a second step the formula parameters are adapted instrument-specifically analogously to the Ganz/Griesser method? For practical considerations the CIE-specific input values for the parameter calculation were rounded off as follows:

   φ = 17° (radians = 0.29671)
   δW / δS = 1800
   BW = 0.0009

4. We also studied the effects of adapting just the parameters and leaving the illumination as it happens to be.

Measuring instruments / conditions

Seven spectrophotometers of various ages were used. See Table III. The illumination from instr. No. 4 is not yet "triplet-free". Instruments Nos. 2, 3, and 6 have remarkably intense UV excitation without UV adaptation.

The basic calibration of all instruments was carried out with a white standard certified by the PTB in Braunschweig (frosted opal glass; PTB 4.12-490) with the exclusion of specular (SEX). Instr. No. 1 is used in-house as a reference instrument. Its illumination was ideally adjusted to D_{65} with a cotton white scale (5.4-SRM-494) certified by the BAM in Berlin. For the present test the nominal values of a new scale were determined with this instrument and used with all instruments to determine their specific formula parameters for illumination adjusted and non-adjusted to D_{65}.

TABLE III. Instruments used.

Instr. No.	Prod.	Type	Serial No.	Aperture	Dots in diagrams	
1	Datacolor Intern.	Spectraflash 500	282W	30 mm	-	-
2	ICS-Texicon	Spectraflash 500	246W	30 mm	green	✧
3	Macbeth	Color-Eye 3100	391194	25 mm	blue	Δ
4	Datacolor Intern.	3890	457.05/052	27 mm	red	□
5	Minolta	CM-3700d	16511008	27 mm	magenta	o
6	Datacolor Intern.	Spectraflash 600	S1 486	28 mm	yellow	+
7	Datacolor Intern.	Elrepho 3000	425	33 mm	cyan	x

Table IV lists the formula parameters for both the adjusted and the non-adjusted illumination conditions of the 7 spectrophotometers.

TABLE IV. Instrument-specific formula parameters for adjusted and non-adjusted sample illumination.

Instr.	Ill. adj.	D	P	Q	C	m	n	k	δW/δS
1	no	1	-695.6754	-1504.3067	714.8686	-901.1522	649.9943	67.7563	1585
2	no	1	-584.4270	-1263.7467	598.2139	-901.0133	650.1869	67.6647	1332
3	no	1	-535.4928	-1157.9329	545.7156	-880.6883	677.4629	51.9296	1220
4	no	1	-763.4662	-1650.8954	785.2564	-877.6552	681.3878	49.7125	1739
5	no	1	-635.9042	-1375.0594	651.2516	-867.7149	694.0020	42.2990	1449
6	no	1	-523.0193	-1130.9606	531.8599	-898.1533	654.1320	65.4687	1192
7	no	1	-640.8196	-1385.6882	656.7256	-897.4319	655.1213	64.7952	1460
1	yes	1	-788.2095	-1704.3995	811.1421	-901.1713	649.9679	67.6671	1796
2	yes	1	-789.3199	-1706.8007	810.2835	-896.8781	655.8792	64.2035	1798
3	yes	1	-786.7348	-1701.2106	807.8773	-872.3683	688.1435	45.6502	1792
4	yes	1	-789.8167	-1707.8750	812.7683	-877.0454	682.1724	49.2212	1799
5	yes	1	-791.0798	-1710.6061	813.9479	-861.6350	701.5361	37.7568	1802
6	yes	1	-788.2313	-1704.4467	809.4237	-889.9825	665.2061	58.9522	1796
7	yes	1	-785.7882	-1699.1638	808.3879	-892.0258	662.4635	60.5845	1790

Samples

A set of 88 samples in all was measured which roughly covers the normal "white spectrum" of practical importance. Apart from one ceramic and 6 paper samples all the others were of textile material (bleached cotton), some whitened by dyeing, others by scouring.

Some of the 88 samples were fluorescent whitened slightly, some more heavily, and others not at all. Most contained no shading dye, but 9 had been slightly to heavily shaded with one, two or three dyes to different tints. Five of these were paper samples. All samples, however, met the condition that W should be smaller than 5*Y-280 in order to still count as white rather than pastel colored. This of course does not necessarily mean a value of T differing markedly from 0, depending on the hue of the shading dye. The other condition laid down in [3] that T should be bigger than -3 and smaller than +3 was also met by all samples. A mask ensured that measurement was always performed at the same point on all samples, thereby virtually ruling out possible unevenness. The samples were all sufficiently opaque.

Evaluation of results

An important criterion in assessing the results is the average distinguishing threshold of a trained observer for whiteness (W) and for tint (T) [6, 14]. Differences below that threshold are not perceived and are therefore irrelevant in practice. From decades of experience with the scalings customarily used by our company and by the Hohenstein Institute we can set the threshold for W at about 5 units and for T at about 0.5 unit. For the different scalings of the two CIE formulas the thresholds were transferred by means of the samples measured here and displayed in the form of the two parallel straight lines. For W we found 2.3, for T 0.45. Here, it should be noted that the tolerances are markedly greater than these threshold values. The following diagrams show the results obtained with instruments 2-7 (ordinates), plotted against reference instrument No. 1 on the abscissa. The key to the corresponding colours and dots is given in Table III.

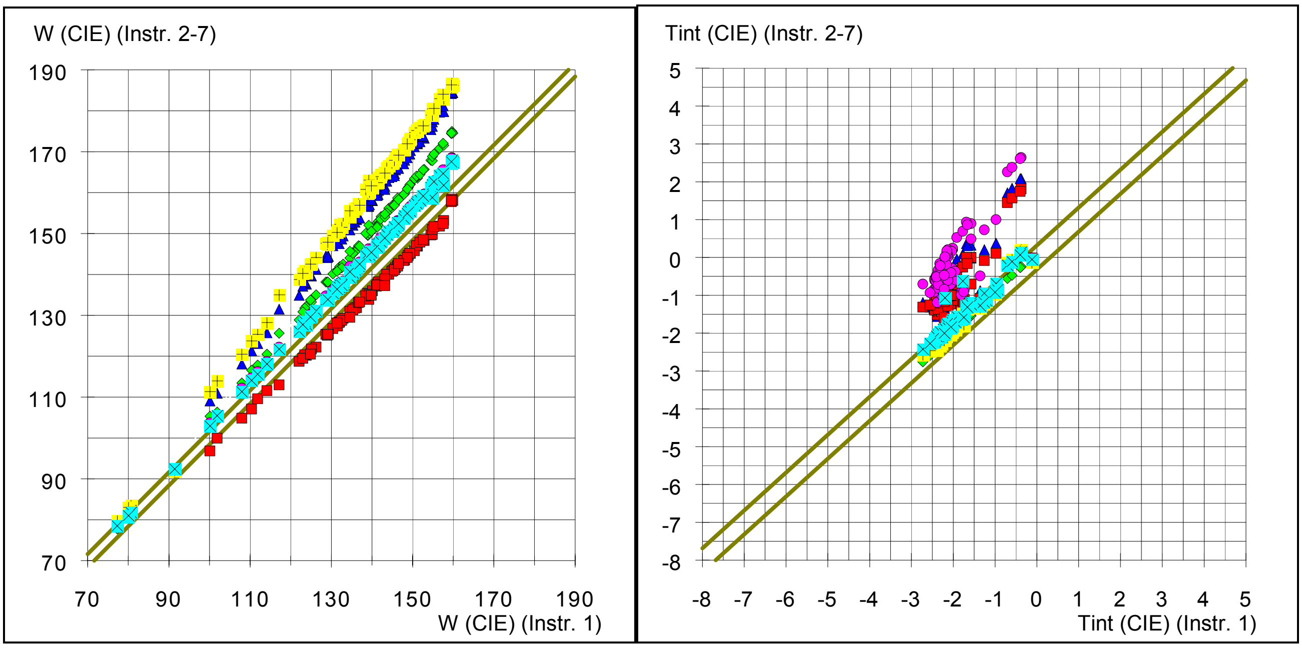

Fig. 2. Neither illumination nor parameters adjusted.

In Figure 2 we see that the results drift apart very markedly unless both sample illumination and formula parameters are adjusted in some way. All whiteness results lie on straight lines which are not parallel to each other. The tint results show much greater variation. Noteworthy is the strong UV excitation of instruments 2 (green), 3 (blue) and 6 (yellow) mentioned earlier which shows up in W.

Figure 3 shows the dramatic influence of sample illumination adjustment on agreement in W. Against that there has been very little change in T. Between instruments of different designs there is no comparability whatsoever. Unfortunately this is reflected in the present situation of recent international standards and draft standards [3, 15].

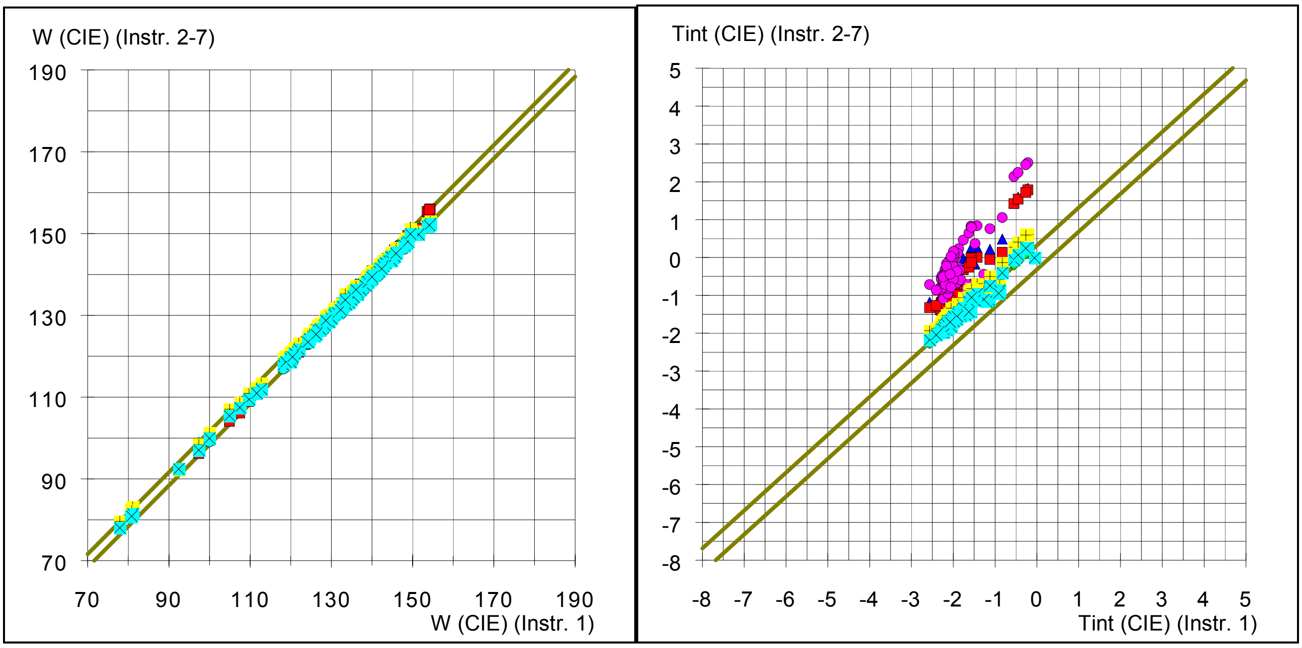

Fig. 3. Illumination adjusted, parameters not adjusted.

Figure 4 shows a dramatic improvement in the tint values. This proves that parameter adjustment on the whole gives better results even when, as here, the illumination has not been adjusted.

A further slight improvement can be achieved, as shown in Figure 5 by adjusting to the instrument design both the sample illumination and the formula parameters for whiteness and tint. Actually there is no objection to extending the present standards along these lines, particularly since the necessary software is available from all instrument makers concerned. The software would at most need adjusting to permit storage of several parameter sets, e.g. for simultaneous or alternate calculation on the basis of the Ciba/Hohenstein and CIE scalings to date. There might also be a need to correlate the whiteness assessment with both the cotton white scale and a plastic white scale. Very little is required of the organizations distributing certified scales. In addition to the nominal values issued to date, only the nominal values have to be calculated with formulas (3) and (4).

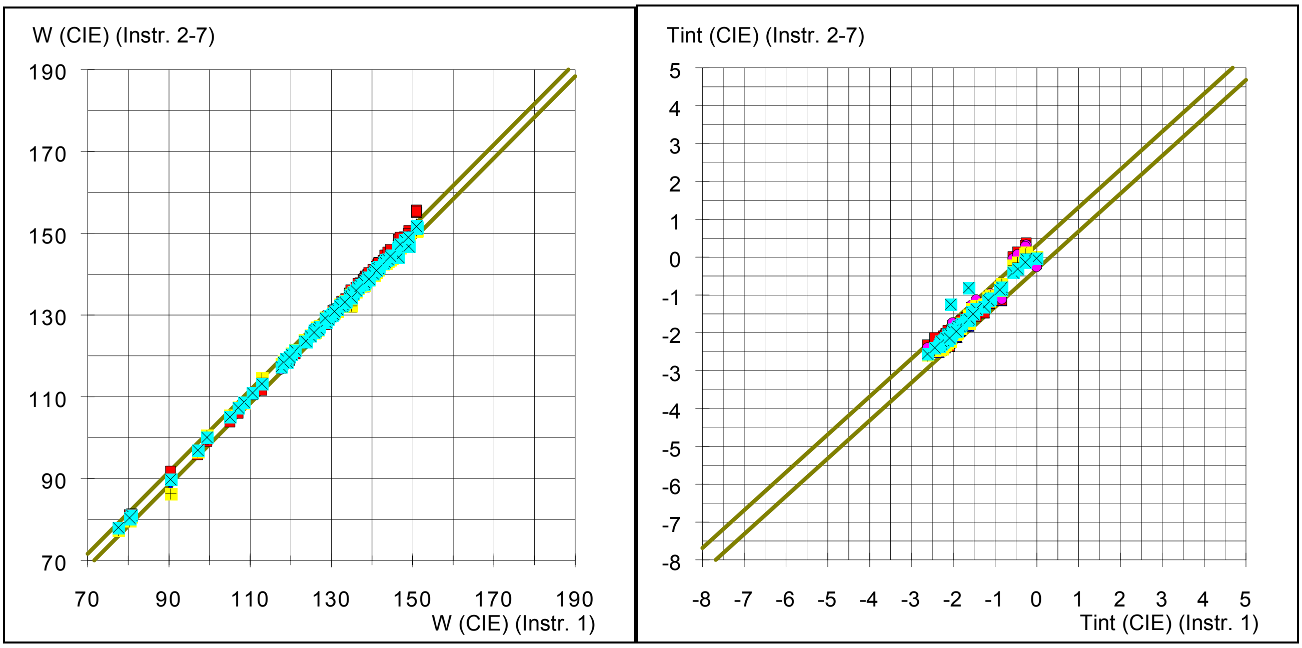

Fig. 4. Illumination not adjusted, parameters adjusted.

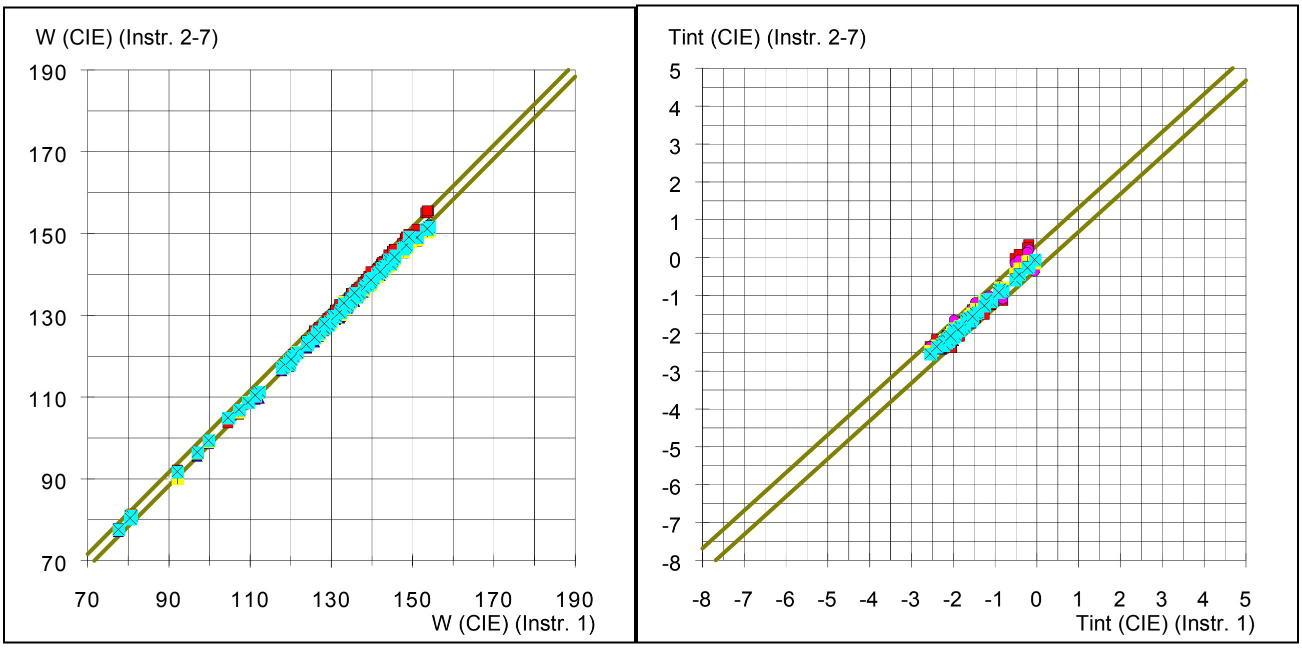

Fig. 5. Both illumination and parameters adjusted.

Special samples

To identify the limitations and scope of the whiteness assessment system described here, 20 more specially made or selected samples were measured under the same conditions. Some of these samples had a marked triplet effect, others were so heavily shaded with dye as to border on pastel shades (which can still mean a neutral T), and owing to the effect of shading dye one had a T beyond the CIE limits of -3 and +3.

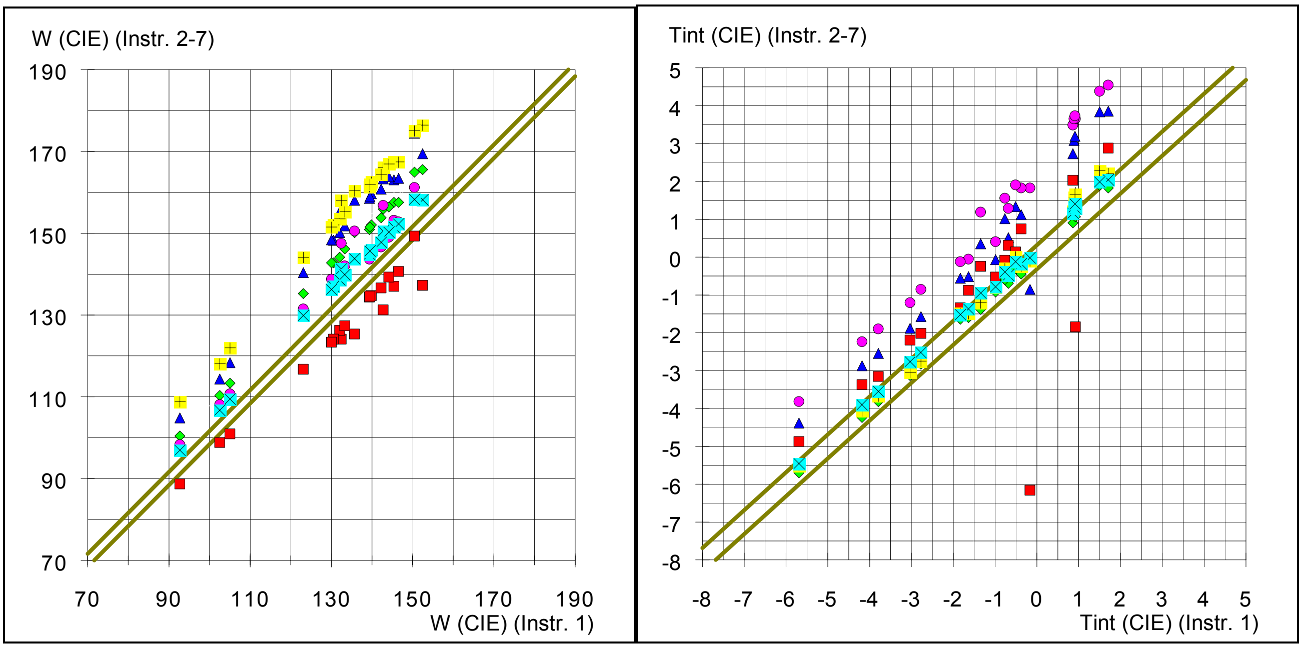

Fig. 6. Neither illumination nor parameters adjusted.

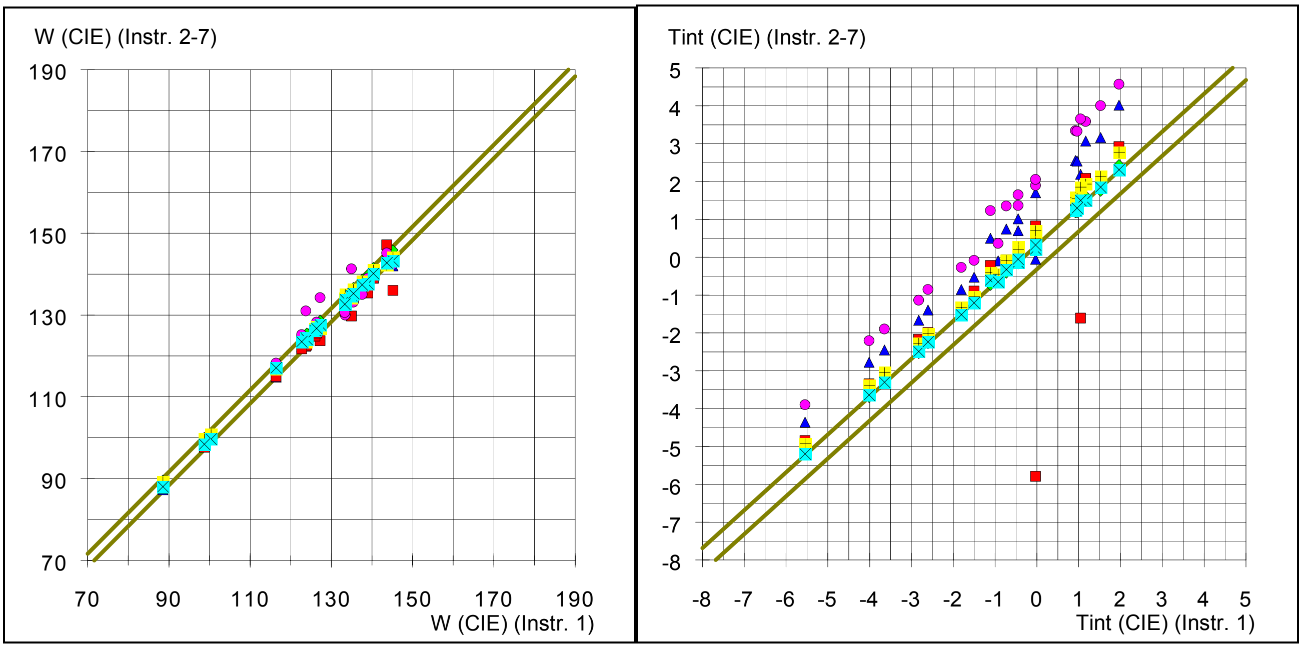

Fig. 7. Illumination adjusted, parameters not adjusted.

Comparison of Figures 6 and 7 shows that, even with these samples, adjusting the illumination brings about a substantial improvement in W but not in T. In respect of this last criterion two samples in particular stand out: they are the only ones to lie below the band formed by the distinguishing threshold. They exemplify a triplet effect of the FWAs CI185 and CI199 on polyester.

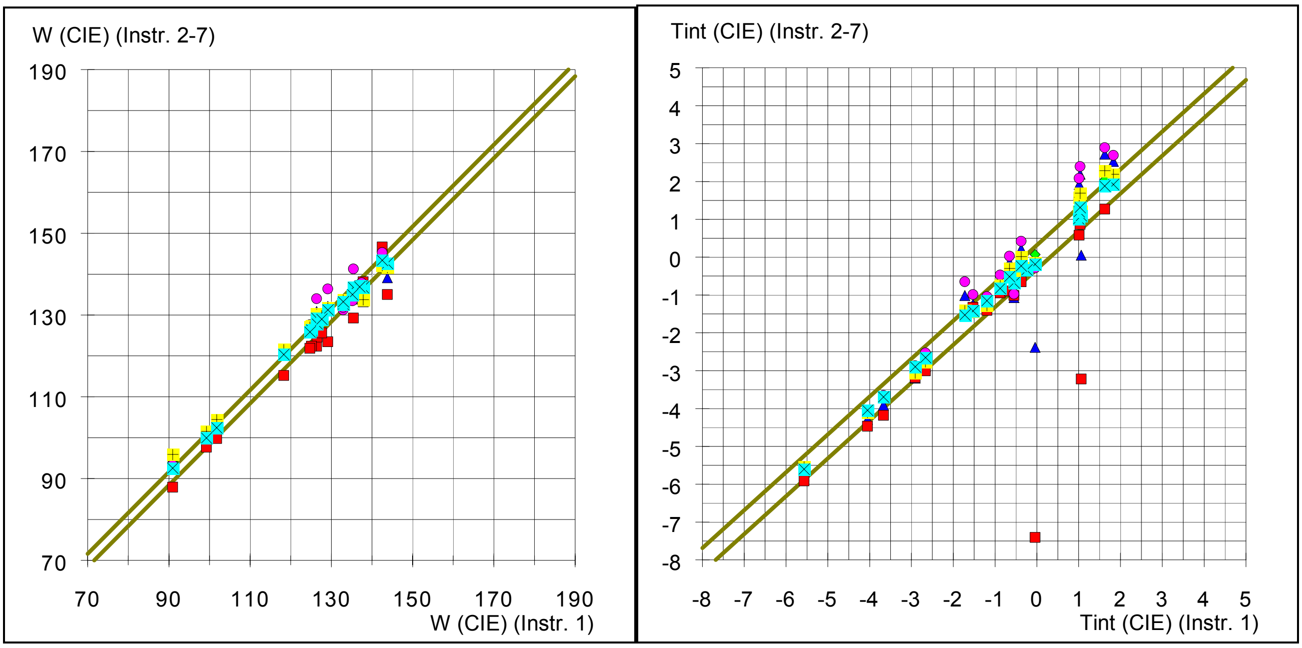

Fig. 8. Illumination not adjusted, parameters adjusted.

Adjusting only the parameters (Figure 8) results in a clear-cut improvement in T, unlike adjusting only the illumination (Figure 7). Carrying out both adjustments together clearly produces the best result even with these off-standard samples, as Figure 9 shows. In W only the triplet effects and a few polyester samples treated with FWA CI179 and measured with instrument No. 5 lie very markedly outside the norm. In T as well these samples diverge the most. It might be instructive to examine illumination with instrument No. 5 more closely in comparison to the others.

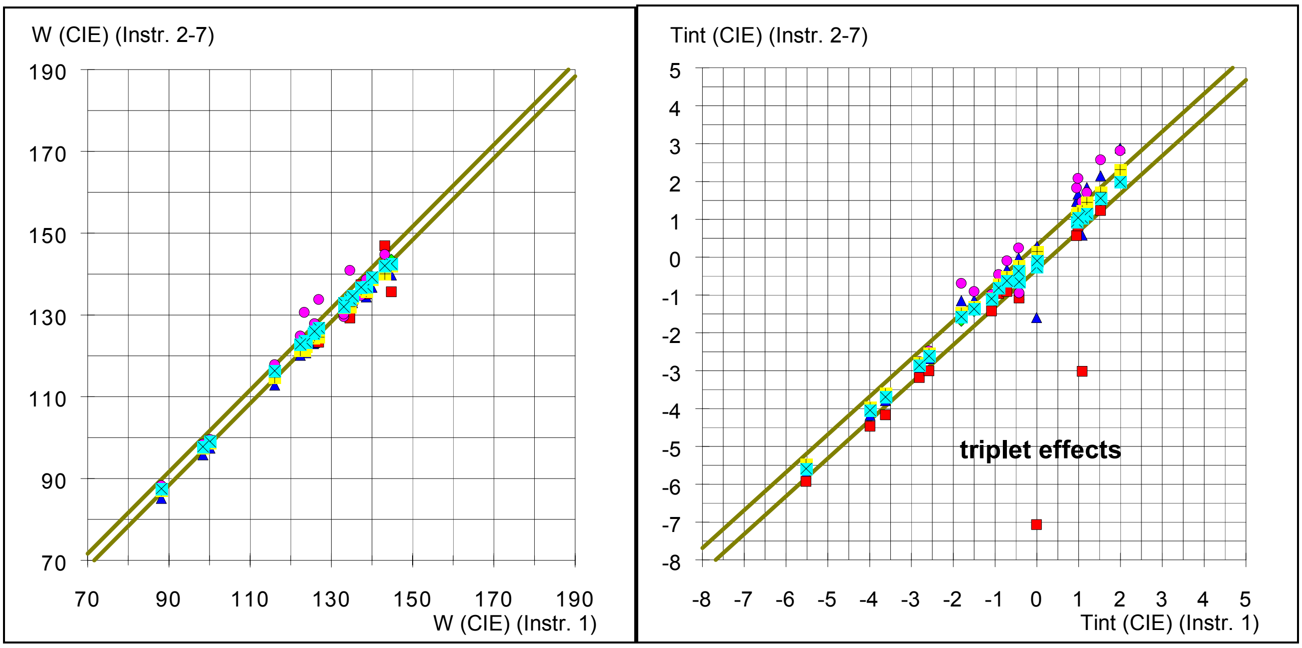

Fig. 9. Both illumination and parameters adjusted.

Evaluation of uniformity of the assessments

In order to measure the accuracy of standardization in Figures, in addition to gaining a visual impression of Figures 2-5 and 6-9, coefficient of determination (COD) was selected. This is the square of the correlation coefficients, which in turn is the geometric mean of the two regression coefficients b_{yx} and b_{xy}. COD gives no indication on agreement of the results, but does give information on the uniformity of the respective assessment. It reacts sensitively to outlies such as samples with a triplet effect measured with instrument No. 4. With this type of assessment, too, instruments 2-7 were related to instrument 1.

Correlation coefficient r = (regression coefficient b_{yx} * regression coefficient b_{xy})$^{0.5}$ (21)

Coefficient of determination (COD) r^2 =
$$\left(\left(\Sigma(x*y) - (\Sigma x*\Sigma y)/n \right) / \left(\Sigma x^2 - (\Sigma x)^2/n \right) * \left(\Sigma(x*y) - (\Sigma x*\Sigma y)/n \right) / \left(\Sigma y^2 - (\Sigma y)^2/n \right) \right)^{0.5} \quad (22)$$

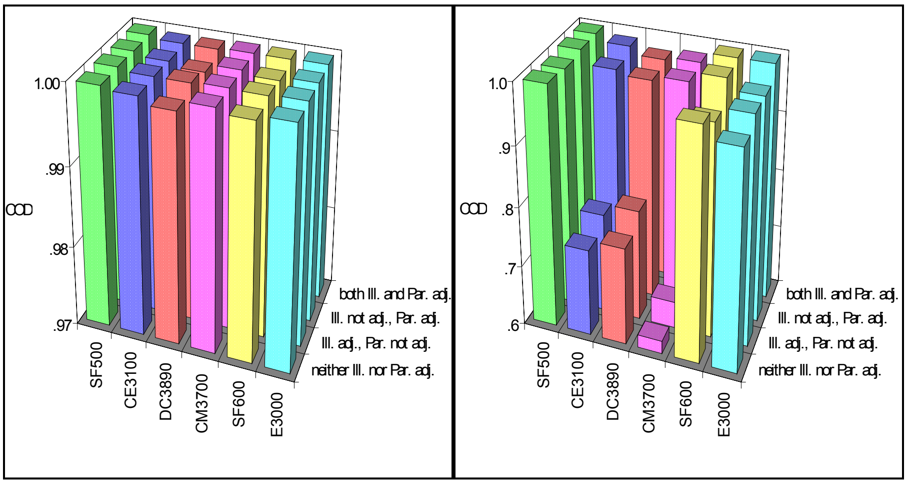

Fig. 10. Coefficient of determination (COD) for whiteness and tint of normal samples.

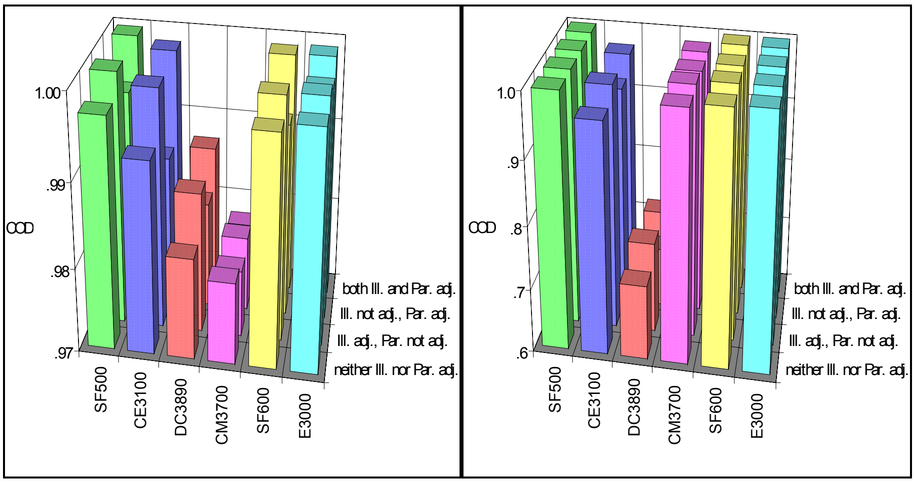

Fig. 11. Coefficient of determination (COD) for whiteness and tint of special samples.

The left side of Figure 10 shows that there are no outlies in whiteness assessment of normal samples. As already mentioned, the marked deviations between the individual instruments that can be seen in the left side of Figure 4 are not recorded here. However, in tint assessment (Fig. 10, right), as long as the parameters are not adjusted, the results for instruments 3, 4 and 5 are considerably poorer. This, however, does not mean that these instruments are poorer, but merely that the illuminants of instruments 2, 6 and 7 are very similar to one another and to reference instrument 1. If another instrument were chosen as reference, another picture would result. Adjusting the parameters allows the results to be markedly improved.

Figure 11 shows the special samples. If whiteness is assessed with instruments 4 and 5, all outlies cannot be brought into line by adjusting the parameters. With instrument 4, the triplet effect is the main cause. Instrument 5, however, evidently has a spectral energy distribution in the illuminant that differs from the others. Moreover, no statement can be derived from this, either, as to which illuminant is closer to D_{65}. Only differences can be observed. In tint assessment, adjusting the parameters may well also improve the results sufficiently for instrument 5. The triplet effects with instrument 4, which is fairly old, cannot, of course, be corrected.

Illumination/measuring geometry d/8° vs. d/0°

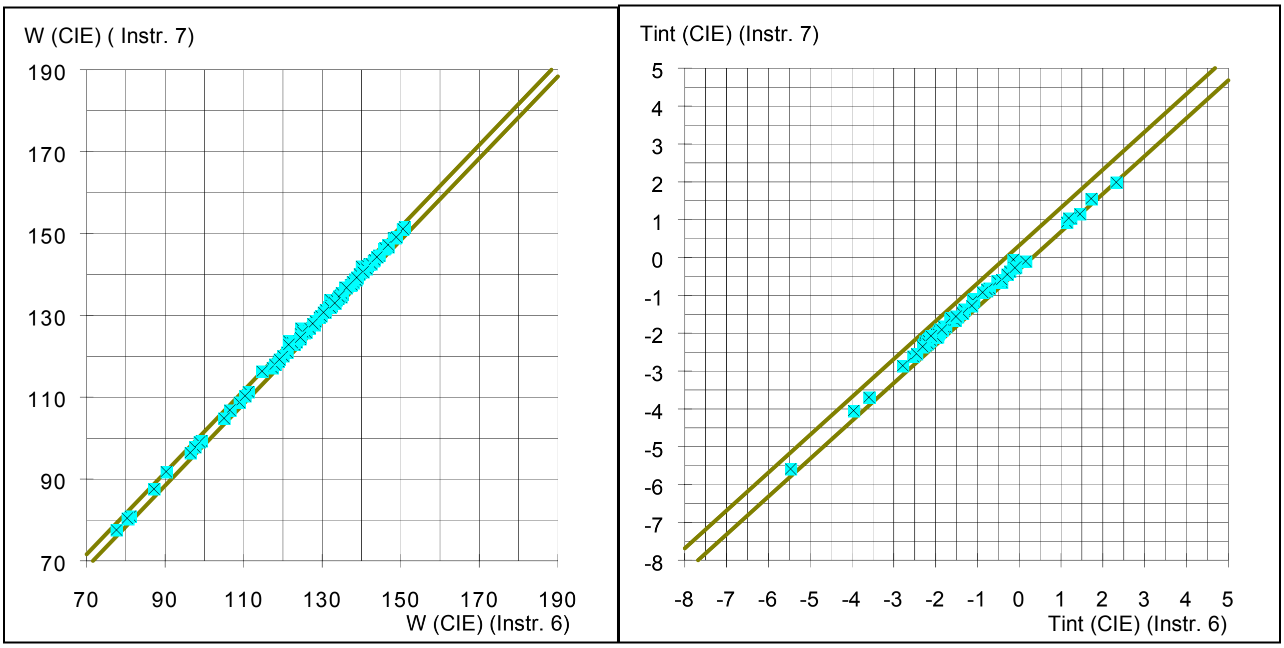

Fig. 12. Both illumination and parameters adjusted. All 108 samples.

The two spectrophotometers, 6 and 7, are largely identical new constructions. They only differ significantly in their measuring geometry: instrument 6 measures below 8°, instrument 7 below 0°. A comparison of these instruments with one another suggested itself, to quantify any effect of the measuring geometry on the results. The measuring conditions are the same as those described above. With instrument 6, gloss was again excluded, with instrument 7 this is construction-related and always the case. However, this time all 108 samples were included in the comparison, the 88 "normal" ones and also the 20 problematical "special" ones. The results are shown in Figure 12. They are highly satisfactory throughout. The widest deviations occurring are: Δ Whiteness = 2.4 and Δ Tint = 0.33 on a polyester sample treated with FWA CI179. Most deviations, however, are well below this. Both maximum values are therefore markedly below the distinguishing threshold. This could stimulate discussion as to whether there is really a point in prescribing a mandatory measuring geometry and a specific size of measuring aperture.

Basic considerations

Basically, it can be said that although the method of adjusting illumination and parameters is currently the best option we have for obtaining comparable results despite different equipment construction and illuminants, it cannot perform a miracle. Illumination adjustment, with its one cut-off filter, can only affect the ratio of energy in the UV range to that in the visible range. Thus the sample illumination must be similar to the reference one, i.e. the normal D_{65}, and the deviations and ageing effects to be corrected are within the framework of this ratio. Parameter adjustment, however, is strictly speaking only valid for samples with the same base white and the same absorption and fluorescence properties as those of the white scale used as transfer standard. Both adjustments apply, of course, only to the fixed measuring conditions (size of the measuring aperture, inclusion or exclusion of gloss, number of measured layers, sample backing).

The poorer the matching of the sample illumination to D_{65}, and the more the samples to be measured differ from the reference white scale, the less well the method will work. This explains why different types of equipment from a manufacturer are better matched between themselves, as long as the same bulbs are used, than they are to equipment from another manufacturer. This also explains why better standardization is achieved on samples from the paper, textile and detergent industries based on bleached cellulose with high base white than on samples based on polyester or plastic, for example.

The better the adjustment of the sample illumination to D_{65}, the less important these restrictions. If D_{65} conditions could be perfectly reproduced, the choice of white scale would not be critical. A single, fluorescent-whitened sample could also be used to match the UV excitation. Samples of all kinds would be correctly assessed.

Triplet Effect

The so-called triplet effect is an artefact which is observed in whiteness and colour assessments using instruments with pulsed light sources. With instruments having a continuous sample illumination the triplet effect is not measurable. In absorption processes caused by continuous lamps or daylight interaction of light with species (molecules) in their short lived singlet states are observed. With flash lamps enough long lived triplet species can be produced. As a consequence also transitions between triplet states can be detected. This effect is mainly observed with certain FWA or dyestuffs (light dyeings). With FWA additional absorption typically occurs in the wavelength region between 450 and 600 nm. To avoid triplet effects the spectrophotometers used for very light samples have to be equipped with lamps of reduced flash intensity ("soft flash").

In Figure 13 can be seen how a measuring instrument virtually free from triplet effects (No.1) and an older instrument highly prone to these effects (No. 4) assess two polyester samples. Sample No.11 (CI199) shows a marked triplet effect, sample No. 6 (CI185) even a very marked triplet effect.

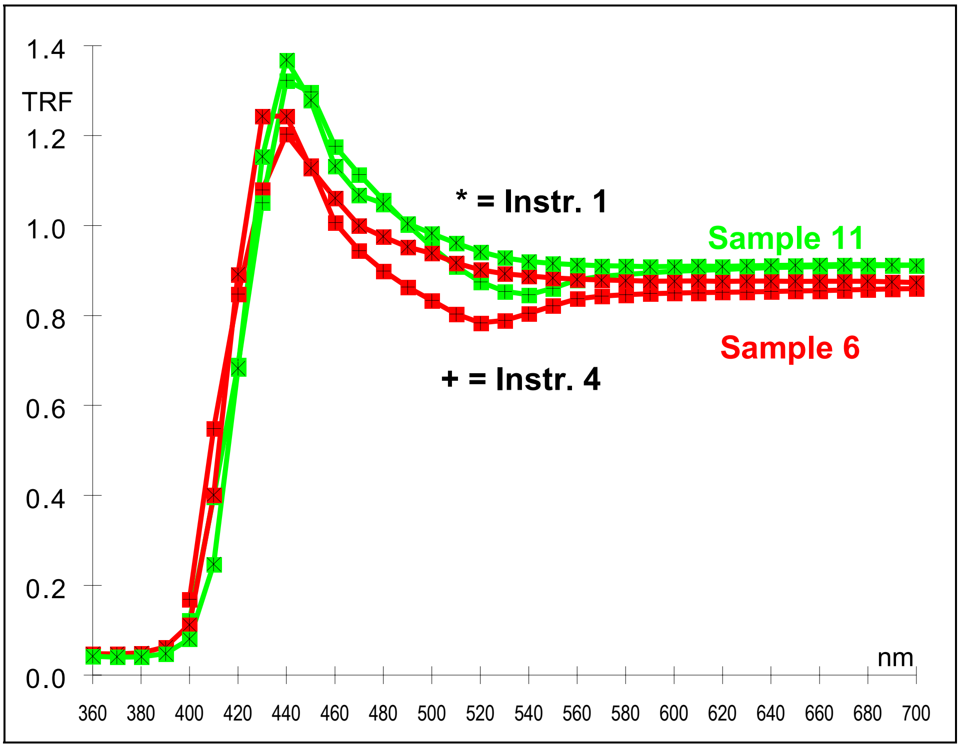

Fig. 13. Instrument No. 4 shows triplet effect.

Conclusions

The sample illumination had to be adjusted to a given standard in order to standardize the whiteness values of different measuring equipment constructions and illuminants. However, this measure helps little to standardize the tint values. This is unfortunately the current position of the relevant standards or draft standards [15]. However, standardization of the formula parameters, even with unchanged sample illumination, is by far the more effective measure: both whiteness and tint values are matched.

There is nothing against carrying out both optimization measures in the interest of aligning the results, i.e. adjusting both illumination and parameters. Both options are possible or easy to create with up-to-date equipment and software. The expense is minimal. The relevant standards should be expanded. It should no longer be ignored that the tint values cannot be standardized merely by adjusting the illumination.

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