Psychophysical tests for Visual-Numerical Correlation of Whiteness Formulas

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Abstract- Measures of Whiteness are very important to the paper industry. Such measures must have good correlations with visual observations. In this study, psychophysical tests were conducted to determine if a visual correlation could be found between the CIE whiteness formula and Fleming-Aksoy[1] formula, previously derived by us. The Lightness value of the substrate has a significant impact on perception of whiteness, so observer trials were carried out at approximately the same lightness levels. Perceptions of whiteness and their changes with different light sources were studied. Psychophysical tests were conducted using D_{50}, and D_{65} light sources for visual correlations, under controlled viewing conditions at a two degree field angle. The Psychophysical results were then compared to the two different formulas. Considering available light sources for observer experiments and the standards used by the graphic arts industry, and the effect of Optical Brightening Agents (OBA) on whiteness perception, recommendations for use of a different light source by the paper industry are provided.

Introduction: - In the paper and printing industries, the whiteness of paper is very important. The perception of color depends on the type of light source used for viewing. In the printing industry, D_{50} is used. In the paper industry illuminant C is used for the calculation of color values. Practically, illuminant 'C' is not a readily available light source for viewing conditions. As a result, the CIE discontinued illuminant C and replaced it with D_{65}[2]. The difference between these two illuminants is that D_{65} is richer in the UV region than illuminant C[3]. Ideally, an illuminant used for calculation and its corresponding light source should be used for the visual inspection of paper in order to obtain a better correlation between measurements and perception of color. In our experiments, a D_{50} (CRI[4]-95) was used because the majority of paper made for the printing industry and printing is viewed under a D_{50} illuminant. D_{65} (CRI-90) was also used because it is normally used as a daylight illuminant.

The Lightness value of a coated paper has an impact on the perception of paper whiteness. In the CIELAB color space, theoretically, a paper with color values of a*=0 and b*=0 with a lightness value (L*) of 100 are accounted as standard white, although paper white always has some tint. If the amount of tint increases, white is no longer white. So it is important to define a boundary where white is no longer white, but is a light shade. Numbers should match what the eyes perceive.

Literature Review: - Over time, many attempts have been made to derive formulas for the calculation of whiteness as a one dimensional scale. The CIE whiteness formula[5] was accepted by the paper industry for calculating the whiteness of paper. The CIE whiteness formula works on the assumption of "Bluer is whiter". This assumption is correct, but it has limits. The CIE formula is limited by inequalities. The Fleming-Aksoy formula[1] uses the assumption that after a certain limit, increasing the blue cast results in "white remaining no more white" but becomes a light shade of blue. This assumption is very important for deciding the maximum amount of OBA or blue colorant added to papers.

Illuminants – An illuminant is a set of numbers defined by a relative spectral power distribution that may or may not be physically realizable as a source[6 7]. All illuminant data are published by CIE. So, some of CIE standard illuminants are mentioned below.

CIE Standard Illuminant C[8] – Is derived from Illuminant A. It was an early daylight, or overcast sky, Illuminant C has a correlated color temperature of 6774 K. According to CIE[2] recommendations, illuminant C should be replaced with illuminant D_{65}, but the paper industry still uses C, as TAPPI standards have not been updated.

CIE 'D' series of illuminants[9] –The method of calculation for this series is based on a correlated color temperature. D_{65} is recommended[2] by CIE as a standard illuminant. It represents day light at noon with a color temperature of 6504 K. D_{50} has been adopted by the graphic art industry in the USA as a standard illuminant, and it represents direct sun light with a color temperature of 5000K.

Illuminant and light source are distinct concepts. An illuminant is defined by mathematical data, which are used in colorimetric calculations and a light source is a physical source, which emits electromagnetic radiation in the visible region. Not all illuminants have physical light sources. Light sources are made by targeting illuminant data and the difference between target (illuminant) and light source is known as the color rendering index[4].

Paper Whiteness and Color Reproduction:-

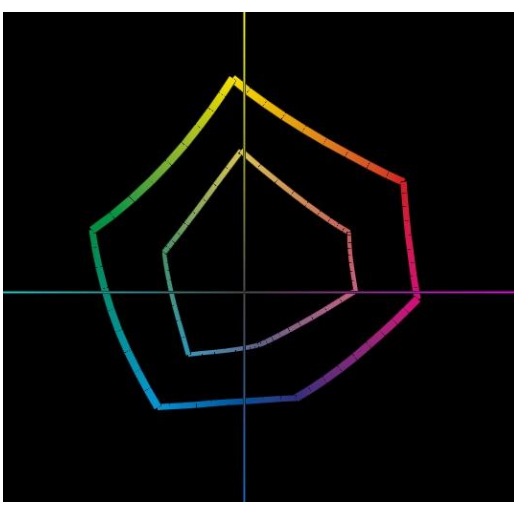

Figure 1:- Color gamut of news paper & coated stock

Process color inks are transparent and light is reflected from paper. The color gamut[10] is based on ink and substrate combination. For same ink whiter & smoother paper gives paper gives a wider gamut. In Figure 1, the same process color pigments are used for printing on coated and news stock. Coated stock gives a wider gamut than news stock. As the whiteness of paper plays an important role in color reproduction, its measurement and accruement assessment is necessary.

Indeed, "paper white" is a well-known contributor to the color gamut[10] of color printing on a substrate by a given process. However, other properties, such as permeability[11] of the paper are stronger contributors. The color gamut volume in CIELAB space for a printing device can be interpreted as the number of colors that can be printed within a Δ Tolerance of √3[10]. In fact, the loss of optical brightening effects from accelerated lightfastness effects leads to a reduction of color gamut volume by 6-8%[12]. It is also well known that a brighter paper white improves contrast and increases color gamut[12]

CIE Whiteness Formula-

The CIE whiteness formula is based on: -- Bluer is whiter. The CIE recommended an equation for whiteness, in 1981[,5,13]. This formula was inspired by Ganz[14,15]. This equation uses the CIE chromaticity coordinates of the sample and illuminant along with the Y value.

$$W_{CIE} = Y + 800(x_n - x) + 1700(y_n - y) \quad (1)$$

where x and y are the CIE chromaticity co-ordinates and x_n and y_n are the corresponding co-ordinates for the perfect reflecting diffuser in the reference illumination.

As whiteness is based on a one-dimension scale, it is on the Blue-Yellow axis with a dominant wavelength of 466 nm. This equation is complemented by the tint value equations, which are on the Red-Green axis of the opposing color theory:

$$T = 1000(x_n - x) – 650(y_n - y), \text{ for a } 2° \text{ observer} \quad (2a)$$

or

$$T = 900(x_n - x) - 650(y_n - y), \text{ for a } 10° \text{ observer} \quad (2b)$$

A positive value of T indicates greenishness and a negative value indicates reddishness.

These equations are to be used only in a limited region. The criteria for whiteness, W, must fall within the limits given by[5]:

$$5Y-280 > W_{CIE} > 40 \quad (3a)$$

and the tint value T shall fall within the limits given by:

$$3 > T > -3 \quad (3b)$$

According to this definition the perfect reflecting diffuser has a whiteness of 100 and a tint value of zero.

The CIE whiteness formula is used for the relative evaluation of whiteness by the same instrument and without reference to a white scale[5]. This system of equations does not clarify whether the whiteness has any component of blueness or yellowness. Evaluations with the formula are significantly improved if the sample illumination is stabilized and fitted as closely as possible to a desired illuminant. This also improves the matching of different measurement instruments for whiteness, but the tint deviation or hue value can still not be adequately matched.

A restriction on the CIE formula is that samples differ not too broadly in tint and fluorescence[5]. The formulae produces relative, not absolute, whiteness assessments, seemingly adequate for commercial use in many cases, but considers bluer to be whiter, which is not acceptable to the eyes if the blueness becomes so high that the sample is no whiter, but instead a light shade of blue. Again, the measuring instruments must have illumination resembling daylight.

If the sample illumination is stabilized, assessments with the CIE formulas are significantly improved, and samples to be compared do not have to be measured at the same time. This also improves the matching of different measuring instruments for whiteness. The tint deviation or hue value can still not be adequately matched.

In 2009, the CIE formed TC1-77, “Improvement of the CIE-Whiteness and Tint Equations”, as recommended by Joanne Zwinkles[16]. Among the issues raised by Zwinkles were

1. Measurement geometry
2. Illumination
3. Limited range of validity
4. CIE Whiteness limits

Zwinkles serves on this TC as, does one of us (PDF) with Robert Hirschler as chair. Unfortunately, no progress has been reported[17] yet. One of the purposes of this work is to provide more data and interpretation to be considered by TC1-77.

Fleming-Aksoy Whiteness Formula (WFA)

Recently, we have proposed two new whiteness formulas[1], based a combination of theoretical and empirical considerations. One formula, N_{FA}, corresponds to a maximum whiteness at the perfectly reflecting diffuser, i.e. zero chroma in the CIE[18] L*a*b* space (or HunterLab space). The other formula, W_{FA}, is based on the assumption that observers prefer a more “blue” white, but only if it is not too blue. Thus, a local maximum in whiteness is expected. The coefficients in W_{FA} were determined from the CIE formula by requiring that the two formulas have the same value and derivatives with respect to a* and b* at zero chroma (a*=b*=0) for a give Y (or L* value).

These formulae are given by:

$$N_{FA} = L^*(1/2)^{(C/C_0)^2} \qquad (4)$$

and

$$W_{FA} = Y(1/2)^{[a^*(a^*-2a_1^*)+b^*(b^*-2b_1^*)]/C_2^2} \qquad (5)$$

where

$C = (a^{*2}+b^{*2})^{1/2}$ is the chroma and C_0 and C_2 are characteristic chroma values determined from the boundary region defined by inequalities 3. a_1^* and b_1^* are the coordinates for the local maximum whiteness at constant lightness Y (or L*). They are determined by equating the corresponding derivatives of W_{FA} and W_{CIE} with respect to a_1^* and b_1^* to one another. The expressions are[1]:

$$a_1^* = \alpha(Y_n/Y)^{4/3}C_2^2/(200\ln 2) \text{ and} \quad (6)$$

$$b_1^* = -\beta(Y_n/Y)^{4/3}C_2^2/(200\ln 2) \quad (7)$$

where

$\alpha = 3x_n(900y_n - 800z_n)/500$ and $\beta = 3z_n(800x_n + 1700y_n)/200$, with Y_n, x_n and y_n being the illuminant luminance and chromaticity values.

Experimental - In the experiment, the Fleming-Aksoy whiteness formula, equation 5 (W_{FA}), was tested against the CIE whiteness formula by conducting psychophysical tests. C_2 was taken as the largest Chroma value consistent with inequalities 3. Tests were conducted under the following conditions-

Field angle- A 2° field angle was used because practically, when many patches are compared, it is confined to distances corresponding to a 2° observer window. So, the printing industry also uses the 2° observer in colorimetric calculations.

Sample size- 25 x 25 mm was chosen to accommodate 2° observers, considering size of the standard viewing booth available for the experiment.

Sample to observer distance: - To accommodate a 2° field angle in the available standard viewing condition booth, this distance is 72 cm.

Light sources- D_{50}, and D_{65}, were used for illuminating samples.

Background and surround- A standard viewing booth has walls that are painted gray, but in this experiment to get good contrast, a black background and surrounding were used.

Sample making- Only one kind of coated paper was used to eliminate the effect of the other variables. Small patches were printed on paper by using an ICC profile of an HP Color LaserJet CP3505 printer with Adobe Photoshop CS5. The patches were designed to have Lab values of approximately 92,0,b*, where b* is between 0 and -10. These printed patches were used for testing.

Psychophysical tests- The pair comparison method was the basis for this psychophysical test. Being a large number of samples, an elimination method was used for selection of the whitest patch. 23 observers with proper training participated in conducting the psychophysical sampling. Following is the procedure used for conducting these tests;

1) Conduct Ishihara test to confirm observers are not colorblind
2) Allow observer eyes to adapt to illuminating condition.
3) Observer has to select the whitest patch among all randomly placed samples for 3 times.
4) Patches are organized in sequential manner b*=0 to b*= -10 for selection.
5) Considering a patch selected by an observer, patches around it are shown for pair comparison, until the observer selects one patch constantly for 5 times.
6) This procedure is repeated for the other light source.

Elimination method-

1) Show observer b*=0 & b*=-1 and ask are they different or not?
2) If observer can tell the difference, then select observer for the test.
3) Show all 11 patches randomly placed to observer under D_{50}
4) Observer has to select the whitest patch.
5) Repeat steps 1 & 2 for 3 times.

6) Place patch in sequential order from b*=0 to b*=-10
7) Observer has to select whitest patch.
8) Based on above whitest patch show ± 2 for selecting whitest patch randomly and sequentially.
9) To check consistency show ± 1 patches around it randomly and sequentially.
10) Repeat step 7 for 3 times to check consistency.

Measuring conditions- An Xrite i1_io, without a UV filter, was used for obtaining reflectance data. Averaging of three measurements was used. Repeatability of instrument is within 0.1 ΔE_{1976}. The same color patch can show different - geometry of instrument, light source, range, number of detectors, types of light splitting system, aperture size, etc.

Result and Discussions-

The reflectance of the samples was measured to calculate the CIE colorimetric values. The reflectance graphs of all the samples are plotted in Figure 2. Analysis of the reflectance data shows that the paper sample used in the experiment contains OBA. Almost all patches have a similar trend in reflectance. In the region of 400 nm to 470 nm, as the bluer content of the paper increases, it's apparent that the reflectance increases. The patches having b*=-5 and b*=-4 show a higher reflectance in the green and red regions, but not so high in the blue region. But the patch of b*=-7 shows a higher reflection in the blue region than the patch b*=-5 and b*=-4 but slightly less in green and red regions. This could be a reason that the maximum number of observers selected b*=-7 as the whitest patch. A summary of the observations is given in Table 1.

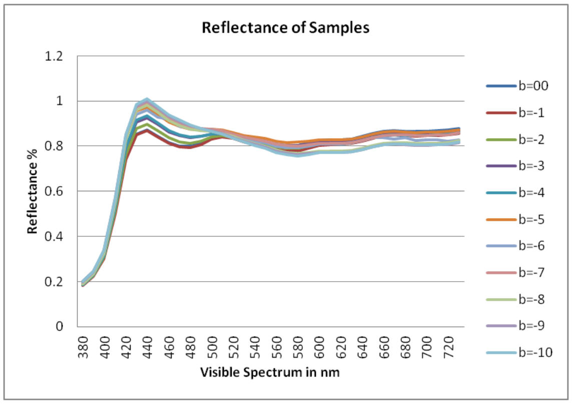

Figure 2a**:- Reflectance of samples used.**

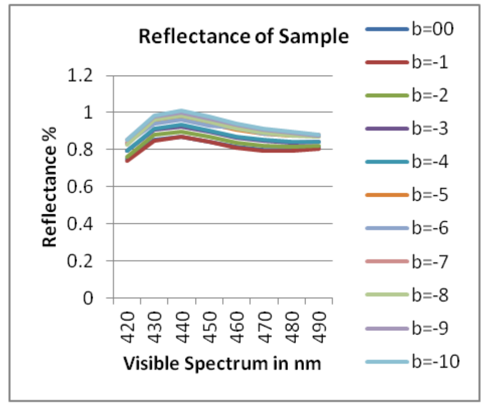

Figure 2b:- Reflectance data in 420 to 500 nm region

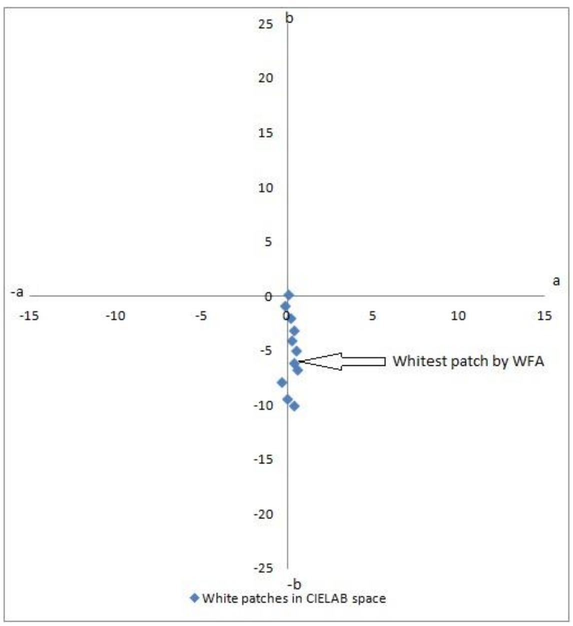

Figure 3: White patches in CIELAB color space

When white patches are plotted in CIELAB color space then they lie near the b* axis. Every white patch has slight color cast of red, green, blue or yellow color. As per CIE bluer is whiter, so whiter patches continues to blue region on –b axis. As per W_{FA} formula, the whitest patch is shown by the arrow in figure 3 after that, the calculated whiteness decreases. Also, whiteness largely depends on illuminant used. In this figure 3, illuminant D_{50} was used to calculate CIELAB color coordinates for plotting.

As shown in Table 1, color difference values (ΔE_{1976}) for the tested patches from the target color values were all below 1.0, except for two patches under D_{50} illuminant, namely, b*= -5 and b*= -7. ΔE_{1976} values were 1.46 and 1.08 for b*=-5 and b*=-7, respectively.

Table 1:- Whiteness by CIE and Fleming-Aksoy (WFA) formula.

Ideal patch	Measurements	Color diff.	Measurements	Whiteness values							
CIELAB	CIELAB $D_{50}/2^o$	ΔE_{76} D_{50}	CIELAB $D_{65}/2^o$	CIE $D_{50}/2^o$	W_{FA} $D_{50}/2^o$	CIE $D_{50}/10^o$	W_{FA} $D_{50}/10^o$	CIE $D_{65}/2^o$	W_{FA} $D_{65}/2^o$	CIE $D_{65}/10^o$	W_{FA} $D_{65}/10^o$
92,0,-0	92.71, 0.08, 0.14	0.72	92.71, -0.12, 0.23	81.72	81.72	80.52	80.47	81.21	81.18	79.69	79.69
92,0,-1	91.9, -0.16,-0.88	0.22	91.92, -0.27,-0.76	84.18	83.85	82.74	82.48	84.05	83.77	82.25	82.05
92,0,-2	92.27, 0.18,-2.05	0.33	92.3, 0.23,-1.94	90.00	88.51	88.56	87.54	90.40	89.01	88.58	87.77
92,0,-3	92.77, 0.56,-3.02	0.95	92.8, 0.56, -3.01	95.61	92.70	94.18	92.02	96.47	93.52	94.65	92.69
92,0,-4	92.47, 0.24,-4.03	0.52	92.52,0.54, -3.9	98.75	93.07	97.15	92.75	99.94	94.26	97.91	93.77
92,0,-5	93.37,0.52,-5.0	1.47	93.43,0.98,-4.89	104.78	98.64	103.24	98.41	106.38	99.78	104.39	99.69
92,0,-6	92.62,0.38,-6.12	0.73	92.7,0.89,-5.94	107.92	94.79	105.94	95.75	109.73	96.44	107.27	97.48
92,0,-7	92.9,0.56,-6.79	1.08	92.98,1.22,-6.65	111.33	96.67	109.53	97.89	113.54	98.08	111.23	99.69
92,0,-8	91.82,-0.3,-7.93	0.36	91.94,0.49,-7.72	113.91	82.21	111.78	86.06	116.46	85.93	113.77	89.15
92,0,-9	91.66,-0.03,-9.42	0.54	91.79,0.95,-9.22	119.99	72.51	117.81	79.21	123.06	76.73	120.30	82.76
92,0, -10	91.52,0.36,-10.04	0.60	91.65,1.39,-9.84	122.41	66.81	120.12	74.68	70.29	125.65	122.76	78.13

These results show that, as –b* increases, the CIE whiteness increases, but in the Fleming-Aksoy formula, the whiteness diminishes after a certain level. In the CIE formula until the patch with b* = -3 for the 2º observer and b*=-5 for the 10º observer, there is little effect of the illuminant. After that, for the same patch, the whiteness number is greater for D_{65} than D_{50}. In the Fleming-Aksoy formula, whiteness is always more for D_{65}. This shows that the calculated whiteness depends on the kind of illuminant/light source used. The CIE formula shows as the blue contents of a patch increases, the calculated whiteness increases. Field angle has a very nominal effect on whiteness, but both field angles follow the same direction in the CIE and Fleming-Aksoy formulas. So a change in field angle doesn't show much of a difference in the predicted whiteness of paper, with either formula.

As shown in Table 1, the Fleming-Aksoy whiteness increases with decreasing (negative) b* values (blue) and reaches to a maximum at b*=-5 under D_{50} for both 2º and 10º observer. Then as the b* value decreases further, the Fleming-Aksoy whiteness decreases slightly for b*=-6 and then increases slightly for b*=-7. This decrease in whiteness continues at lower b* values but far more rapidly at b=-8 and lower. This apparent double maximum is because the L* value was lower than the target for b*=-6. Similar results are obtained with the Fleming-Aksoy formula under the D_{65} illuminant in regards to change in whiteness values with varying b* values in the blue region. Table 2 shows results of the psychophysical tests.

Table 2:- Results of psychophysical tests: - Selection of whitest patch.

$D_{50/2°}$ Sample	Selection Frequency
b=0	1
b= -4	1
b= -5	2
b= -6	4
b= -7	15
Mean b	-6.1
STD	1.6

$D_{65/2°}$ Sample	Selection Frequency
b= -2	1
b= -5	17
b= -6	2
b= -7	2
b= -9	1
Mean b	-5.2
STD	1.2

Under the D_{50} light source, the maximum number of observers selected the patch corresponding to b*=-7 under $D_{50/2°}$ as the whitest patch. Under $D_{65/2°}$ the greatest number of observers selected the patch corresponding to b*=-5 under $D_{50/2°}$. However, the expected value of b* is -6.1 for $D_{50/2°}$ and -5.2 for $D_{65/2}$, based all the observer results. When psychophysical results are compared with the CIE formula, then under both light sources the patch corresponding to b*=-10 under $D_{50/2°}$ is the whitest patch, but for observers it is not the whitest. Under light source $D_{50/2°}$, after the patch corresponding to b*=-8 under $D_{50/2°}$ observers feel that it is no more white, but a light blue shade. Under $D_{65/2°}$, the observer patch corresponding to b*=-7 under $D_{50/2°}$ observers feels that it is no longer white. This indicates that the CIE whiteness formula fails to follow what observers see. Therefore, if a paper manufacturer has 2 papers with CIE b*=-7 and b*=-10 in $D_{50/2°}$, then the CIE whiteness formula says the patch with b*=-10 as whiter, when visually it is not. This result could mislead manufacturers seeking to make the whitest paper and lead them add more expensive OBA, when it actually hurts the perceived whiteness.

However, the Fleming Aksoy formula is consistent with the observer results for both light sources. For the D_{50} illuminant, the largest value of W_{FA} (98.6) occurs for nominal b*=-5 (-5.0 actual). A secondary maximum (96.7) occurs for nominal b*=-7 (-6.8 actual). The calculated value at nominal b*=-6 (-6.1 actual) is 94.8.

Thus, these are consistent with the expected value of b*=-6.1. Furthermore, the calculated W_{FA} values indicate nearby local maximum values (100.3, 94.9, 96.8) for the corresponding Y values (83.8, 82.1, 82.7) at $b^*=b_1^*=$ (-7.2, -5.7, -6.2) corresponding to measured b* = (-5.0, -6.1, -6.8) respectively. Similarly, for the D_{65} illuminant, the largest value for W_{FA} (99.8), occurs for nominal b*=-5 (-4.9 actual). A secondary maximum (98.1) occurs at nominal b*=-7 (-6.6 actual). In between at nominal b*=-6 (-5.9 actual) the calculated value is 96.4. Again these are consistent with the expected value of b*=-5.2. Furthermore, the calculated W_{FA} values indicate nearby local maximum values (102.1, 96.8, 98.8) for the corresponding Y values (84.0, 82.3, 82.9) at $b^*=b_1^*=$ (-7.1, -5.8, -6.3) corresponding to measured b* = (-4.9, -5.9, -6.6) respectively.

Conclusion: - The CIE Whiteness formula has poor visual-numerical correlation. This causes confusion between accepting visual or numerical results for selection of whitest papers among those available. The CIE whiteness formula has limitations for comparing whiteness with higher bluer tone under any D_{50} and D_{65} light sources. The Fleming-Aksoy formula shows much better visual-numerical correlation than the current CIE whiteness formula. Visual and numerical results are very close. Observer/Field angle appears to have little impact on whiteness scale. The Fleming-Aksoy (W_{FA}) formula is suitable for the paper industry under light sources D_{50} and D_{65} for both field angles.

Recommendations:-

1) Additional tuning of Fleming-Aksoy formula to fit ours' and others' psychophysical tests.
2) Replacing of illuminant 'C' by D_{50} or D_{65} for paper optical properties tests.
3) Replacing the CIE whiteness formula with the Fleming-Aksoy formula.

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