Selecting a Substrate for Color Proofing

Robert Chung and Elena Fedorovskaya

Keywords: color, OBA, whiteness, psychometric, paper, proofing, printing

Abstract

To develop a method for selecting a proofing substrate that closely matches a specified printing paper stock, we defined a psychometric term, Apparent Whiteness, as the perceived whiteness of a paper relative to the whitest sample in a specified illumination. In a series of visual experiments 10 observers ranked Apparent Whiteness of 39 samples in the ISO 3664 (2000) and the ISO 3664 (2009) lighting conditions. The ranking data was transformed into interval data using Thurstone's law of comparative judgment. We also measured several paper metrics - color, gloss, opacity, CIE whiteness, and OBA, to determine if Apparent Whiteness correlates with the measured paper metrics. The results indicate that the Apparent Whiteness in the ISO 3664 (2009) viewing condition has a strong linear relationship with the CIE Whiteness (M1). Thus, we are able to select a proofing substrate based on the similarity of its CIE Whiteness with the printing stock. Furthermore, we can use ΔE_{00} (M1) to predict the numerical color match between the two substrates and use ΔOBA to indicate the criticalness of lighting in the visual match between the proofing substrate and the printing stock. Finally, we verify the visual match by considering gloss, color and texture of the sample in the ISO 3664 (2009) compliant viewing booth.

Introduction

There are many printing stocks varying in grammage, opacity, whiteness, color, OBA and gloss. Yet, there are a limited number of proofing stocks in the graphic arts market. As a result, proofing substrates often do not match the printing stocks in routine production.

Both the old ISO 3664 (2000) compliant lighting booths and the new ISO 3664 (2009) compliant lighting booths are used in the market. Switching from the old lighting to the new lighting has been a slow process. Some people attempted to insert a UV absorber in the new lighting that further complicates the viewing condition.

Rochester Institute of Technology

These market conditions give rise to the research question, "Is there a method for selecting a proofing substrate that matches a specified printing stock closely?"

Objectives

The objectives of the study are to (a) assess the Apparent Whiteness of the paper samples in two different ISO 3664 lighting conditions, and (b) correlate Apparent Whiteness with paper metrics, including opacity, CIE whiteness, OBA index, and ΔE00, and (c) devise a method to select a proofing substrate that matches a specified printing stock closely.

Literature Review

Whiteness is the measurement of light reflectance of a sample according to CIE Publication 15: 2004, i.e.,

$$W = Y + (W, x)\,(x_n - x) + (W, y)\,(y_n - y) \qquad \text{Eq (1)}$$

CIE defines whiteness only for D65/10 and measurement data on d:0 geometry instruments. In this research, CIEYxy values are derived from M1 (D50 and 1931 2-degree observer) spectrophotometric measurement conditions (ISO 13655, 2009). Thus, we use the ASTM E313 table of values for D50 and 1931 2-degree observer to compute CIE whiteness, i.e.,

$$W = Y + 800\,(0.3457 - x) + 1700\,(0.3585 - y) \qquad \text{Eq (2)}$$

OBA is the measurement of the amount of optical brightening agents in a sample. OBA amount in a sample, per ISO/FDIS 15397 (2013), is the b* difference between two measurements, $OBA = b^*_{M2} - b^*_{M1}$. In other words, the higher the OBA is, the more OBA amount is in the sample.

ΔOBA is the OBA difference between two samples. The higher the ΔOBA is, the more critical of lighting is in the visual match between the sample and the reference.

Coppel (2009) studied how perceived and measured whiteness of printed samples is affected by gloss and FWA (fluorescent whitening agent or OBA) in two conditions: with homogeneous overhead 5000K illumination, and under illumination with an additional UV lamp. He concluded that (a) gloss has no significant effect on perceived whiteness, and (b) the CIE whiteness predicts perceived whiteness well. He further added, "the perceived whiteness prediction was only valid when the measurement was performed under the same illumination as for the visual evaluations".

In this research, we define a psychometric term, *Apparent Whiteness*, as the perceived whiteness of a paper relative to the whitest sample in a specified illumination using rank order procedure.

Methodology

There are 39 samples in this project. Epson provides 12 printing paper samples (P1~P12, 3” x 4” in size) and 16 proofing substrate samples (pf_1a, pf_1b, etc., 1.5” x 1.5” in size). Kodak provides 11 printing paper samples (KF1, KF2, KM1, KM2, KM3, KS1, KS2, KS3, KG1, KG2, KG3, 8.5” x 11” in size). All samples are trimmed to similar sizes and labeled accordingly.

We use an X-Rite i1 Pro2 spectrophotometer to measure each sample five times with a white backing. Their spectral reflectance values are averaged and CIELAB values computed. We also use an ISO 3664 2009 compliant (gti) viewing booth, and an ISO 3664 2000 compliant (Just) viewing booth for visual assessment of these samples.

Gloss is the measurement of surface reflectance at 75 degree from the normal (TAPPI, 2015). In this research, we use a BYK-Garner Glossmeter.

Psychometric Experiments

A total of 10 observers were asked to perform visual ranking by: (a) taking the FM 100 Hue color discrimination test to ensure normal color vision, (b) ranking all samples (1-39) starting from the whitest sample to the least whitest sample in the ISO 3664 (2009) gti viewing booth, and (c) repeating the experiment in the ISO 3664 (2000) Just viewing booth. We asked participants to disregard other attributes, such as gloss, coating, thickness, but only focus on the apparent whiteness of the sample. Figure 1 illustrates the visual ranking (Figure 1).

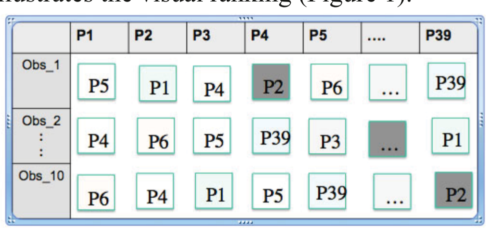


Figure 1. *An illustration of visual ranking*

Each observer was then asked to estimate the apparent whiteness difference pair-wise between the whitest sample and every other sample using a scale (0~4) in that 0 corresponds to no difference; 1 - just noticeable difference; 2 - slight difference, 3 - moderate difference, 4 – large difference. To assist in the process, an anchor pair between the whitest sample and the 30th ranked sample was selected to visually signify what’s ‘3 - moderately different.’

The average score of each sample, based on the 10 observers, represents the visual difference of the sample in relation to the whitest sample. While we can use the averages to rank all samples from the most apparent whiteness to the least apparent whiteness, but we do not know how much apparent whiteness differences are between any sample pair.

Converting Apparent Whiteness from Ordinal to Interval Scale

To construct interval scale from ordinal data obtained via rank-order procedure we use the Thurstone's law of comparative judgment (1994). The first step is to tabulate the data showing how often each patch was placed in each rank position. The next step is to calculate the mean rank (7*78 + 6*11 + … /100). Mean rank values represent an ordinal scale, but they do not contain information about the perceived differences between the patches. By assuming a normal distribution model and using Thurstone's law of comparative judgment, case 5, we can derive an interval scale from the rank data. This involves first calculating the proportions for each sample as the ratio: (# of ranks – mean rank)/(# ranks – 1), and then converting proportions to z-scores (Figure 2)

judged rank	paper sample						
	P1	P2	P3	...	P11	...	P39
7th	78	8	10	0	0	0	0
6th	11	81	10	2	0	0	0
5th	0	1	65	33	0	0	1
4th	10	1	10	52	0	17	10
3th	0	0	2	11	0	12	75
2th	0	8	0	2	16	68	12
1th	1	1	3	0	84	3	2
mean rank (Mr)	6.53	5.68	5.04	4.22	2.96	2.43	1.16
ordinal scale	*7*	*6*	*5*	*4*	*1*	*2*	*3*
proportions p=(Nr-Mr)/(Nr-1)	0.078	0.22	0.327	0.463	0.973	0.762	0.673
interval scale: z-scores z(p)	*-1.416*	*-0.772*	*-0.449*	*-0.092*	*1.932*	*0.712*	*0.449*
Apparent Whiteness: z(p)+constant	*0.7*	*1.3*	*1.6*	*2.0*	*4*	*2.8*	*2.5*

Figure 2. *An illustration of Apparent Whiteness Analysis*

In Figure 2, Z-scores correspond to values of patches on an interval scale of relative Apparent Whiteness. By adding a constant, we are able to make all numbers positive with the whitest sample value scaled to 4.

Results

Table 1 shows the resulting Apparent Whiteness values for two illumination conditions. Sample ID, P, represents printing stock and sample ID, pf, represents proofing substrate. The arrow points to the whitest sample corresponding to P11.

Whitest Sample → P11

Sample	Apparent Whiteness for ISO 3664 (2009)	Apparent Whiteness for ISO 3664 (2000)	Sample	Apparent Whiteness for ISO 3664 (2009)	Apparent Whiteness for ISO 3664 (2000)
P1	2.7	2.3	pf_5a	3.7	1.8
P2	1.7	2.3	pf_5b	3.5	1.7
P3	3.7	2.2	pf_6a	3.7	1.9
P4	2.4	2.3	pf_7a	1.9	3.0
P5	4.0	2.2	pf_8a	1.8	3.7
P6	3.6	2.5	pf_8b	1.7	3.8
P7	2.4	2.2	pf_9a	3.8	3.9
P8	1.4	1.2	pf_9b	2.5	3.1
P9	2.1	0.4	KF1	2.8	2.0
P10	3.0	3.2	KF2	3.0	2.4
P11	4.0	4.0	KM1	1.3	1.3
P12	3.9	2.3	KM2	0.9	0.6
pf_1a	2.7	2.3	KM3	1.3	1.1
pf_1b	2.6	1.7	KS1	3.9	3.9
pf_2a	1.5	1.5	KS2	3.8	3.5
pf_2b	1.3	1.5	KS3	2.5	2.6
pf_3a	3.9	3.7	KG1	1.1	0.9
pf_3b	3.9	2.4	KG2	2.3	2.9
pf_4a	2.3	3.7	KG3	1.3	1.1
pf_4b	3.5	3.6			

Table 1. *Apparent Whiteness values for two ISO illumination conditions*

Analysis of Apparent Whiteness

As evident from our experiment, the samples' Apparent Whiteness is influenced by the OBA in the paper and the UV energy of illumination, a finding similar to Coppel (2009).

Figure 3 shows relative spectral power distributions for two light sources used in the viewing booths. Compared to ISO 3664 (2000), ISO 3664 (2009) viewing illumination has more energy in the UV and blue region of the spectrum, between 370-420 nm, as outlined by the ellipse in Figure 3.

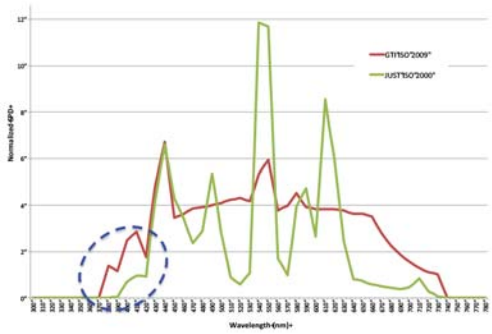


Figure 3. *Relative spectral power distributions for the two light sources*

Figure 4 shows the Apparent Whiteness of all samples in two ISO 3664 lighting conditions. To explain, the samples, along the 45-degree straight line, are ranked the same in both lighting conditions. The samples, aligned vertically, have the same Apparent Whiteness in the ISO 3664 (2009) lighting. The samples, aligned h orizontally, have the same Apparent Whiteness in the ISO 3664 (2000) lighting.

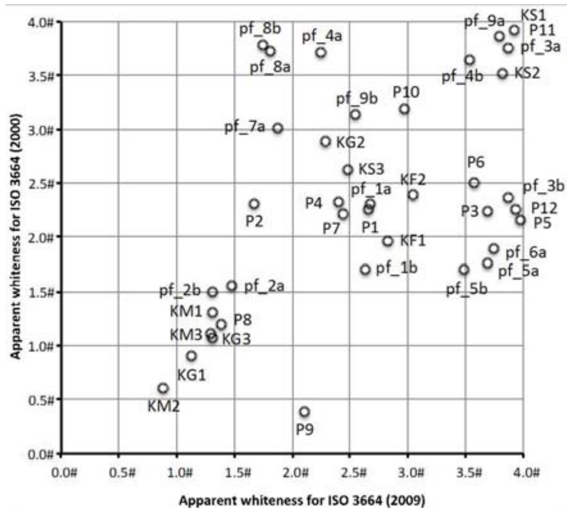


Figure 4. *Apparent Whiteness of all samples in two ISO 3664 lightings*

If the two lighting conditions were the same and observers were consistent, all samples should be plotted as a 45-degree straight line. Instead, some samples are ranked low in one lighting and high in the other lighting and vice versa. For example, pf_5a, has low Apparent Whiteness value (< 2) in the ISO 3664 (2000) lighting condition and high Apparent Whiteness value (3.5) in the ISO 3664 (2009) lighting condition. This is because the Apparent Whiteness of a paper is affected by (a) OBA amounts in the paper and (b) UV energy amounts of the illumination.

Analysis of Paper Metrics

We measured samples with an X-Rite i1 Pro2 spectrophotometer using a specified white backing. For each sample, we captured M0, M1, and M2 spectral reading (380-730 nm) five times, and saved the data file in the CGATS.17 file format.

The average of the five spectral reflectance data, was used to derive CIEXYZ and CIELAB initially using the CGATS 2010 spreadsheet (courtesy of David McDowell). We, then, computed a number of quantitative metrics, including CIE whiteness and OBA Index.

L vs. Apparent Whiteness*

The L* variation is less than 3.5 L* units amongst all 39 samples in three (M0, M1, and M2) measurement illuminations. There is no correlation between L* values and Apparent Whiteness scale as one can see from Figure 5.

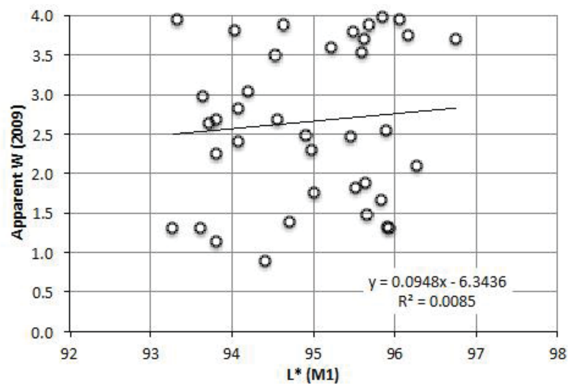


Figure 5. *L* (M1) versus Apparent Whiteness in ISO 3664 (2009)*

Paper Color

Paper chromaticity contributes to paper shade differences. Figure 6 illustrates the chromaticity variation of all paper samples in a*b* coordinates. The M1 (UV_inc) has larger negative b* value than M2 (UV_cut) value. This points out the importance of the alignment between the measurement illumination (M1) and the viewing illumination (ISO 3664, 2009) when we want to correlate color measurement with color perception.

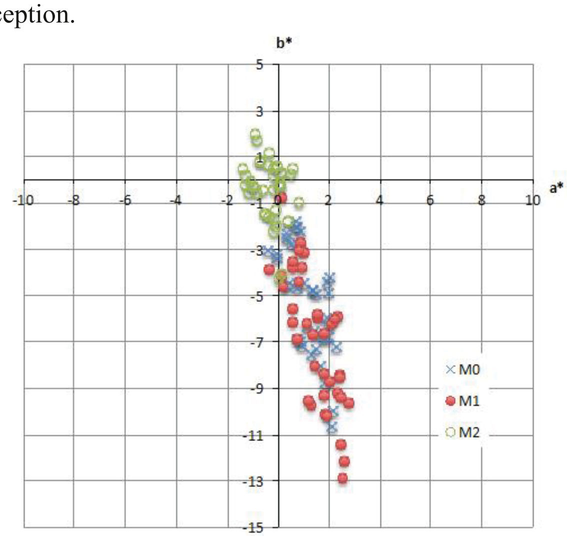


Figure 6. *Chromaticity variation of all paper samples in a*b* coordinates*

Gloss vs. Apparent Whiteness

Gloss measurement ranges from 4 to 79 Gloss Unit (% reflection of the incident light). As with the L* values, there is no significant correlation between gloss and Apparent Whiteness, which can be observed from Figure 7.

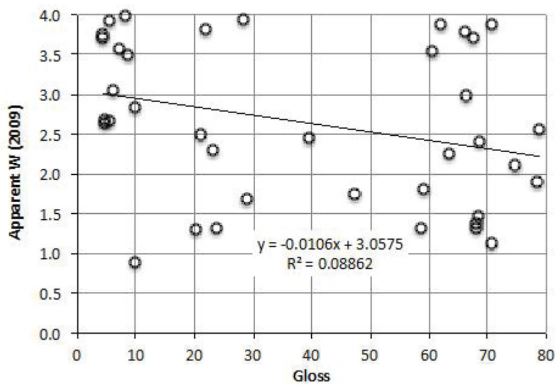


Figure 7. *Gloss versus Apparent Whiteness*

OBA vs. Apparent Whiteness

Out of the 39 samples measured, the OBA amount ranges from 1.3 ~ 10 (Figure 12). When OBA-loaded paper is viewed under UV-rich lighting conditions, its Apparent Whiteness increases.

Unlike L* and gloss, the OBA amount of the paper correlates well with the Apparent Whiteness of the paper (R2 = 0.8) (Figure 8). This is consistent with the existing knowledge in printing and paper industry about the influence of OBA on paper whiteness, where higher amounts of OBA make paper appear whiter.

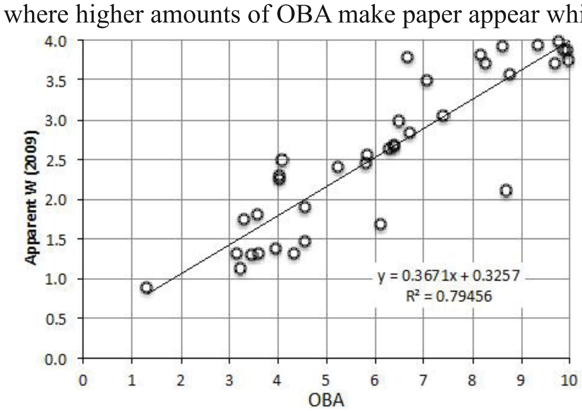


Figure 8. *High correlation between Apparent Whiteness and OBA in paper*

CIE Whiteness vs. Apparent Whiteness

The CIE Whiteness (M1) measurements range from 90~138. As shown in Figure 9 (left), there is a strong linear relationship between the Apparent Whiteness in ISO 3664 (2009) lighting and CIE Whiteness in M1 measurement condition ($R^2 = 0.91$). However, the correlation between Apparent Whiteness in ISO 3664 (2000) and CIE Whiteness for M0 measurement is rather poor (Figure 9, right).

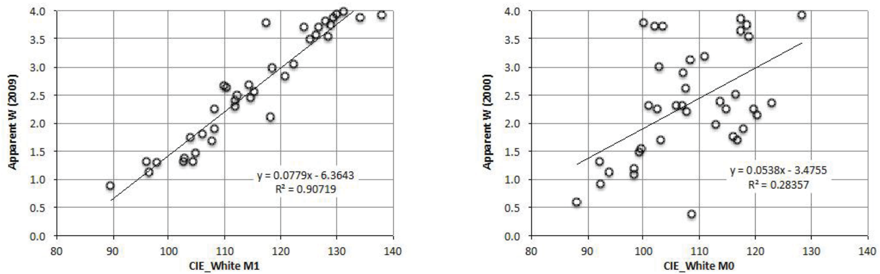


Figure 9. *Apparent Whiteness plotted versus CIE Whiteness: (left) for ISO 3664 (2009) and M1; (right) for ISO 3664 (2000) measurement and M0*

Selecting a Substrate for Color Proofing

Based on the results of our experiment and the fact that the Apparent Whiteness in the ISO 3664 (2009) viewing condition has a strong linear relationship, $R > 0.9$, with the CIE Whiteness (M1) (Figure 9), we propose the following whiteness-based method in the selection of proofing substrates that matches a printing stock in the ISO 3664 (2009) viewing condition:

1) Assuming there is a database of proofing substrates.

2) Select a printing stock and measure its CIELAB, OBA, gloss, and other paper measurements, including its CIE Whiteness.

3) Sort the proofing substrate database against CIE Whiteness and select substrates having similar CIE Whiteness value as the printing stock.

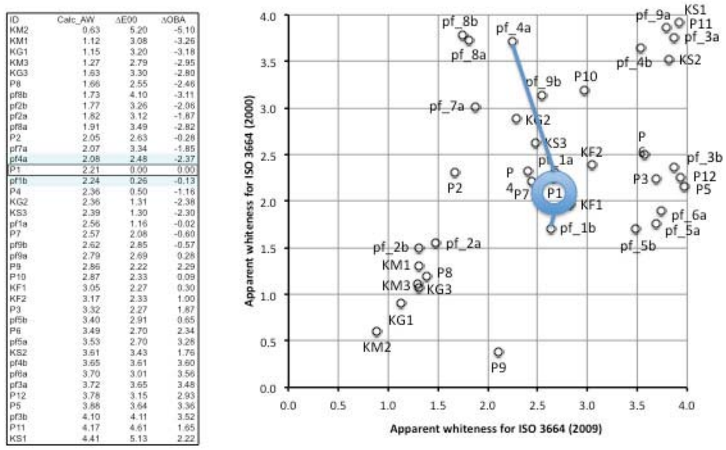
4) Assess the performance metrics, including ΔE00, ΔOBA, ΔCh and select 2-3 substrate candidates.

5) Decide the proofing substrate based on the performance metrics and visual match in ISO 3664 (2009) lighting condition.

Testing the Substrate Selection Performance

We used paper samples within and outside of the database to test the performance of the method. Figure 10 illustrates proofing substrates (pointed), pf_1b and pf_4a, are selected to match the printing stock, P1 (circled).

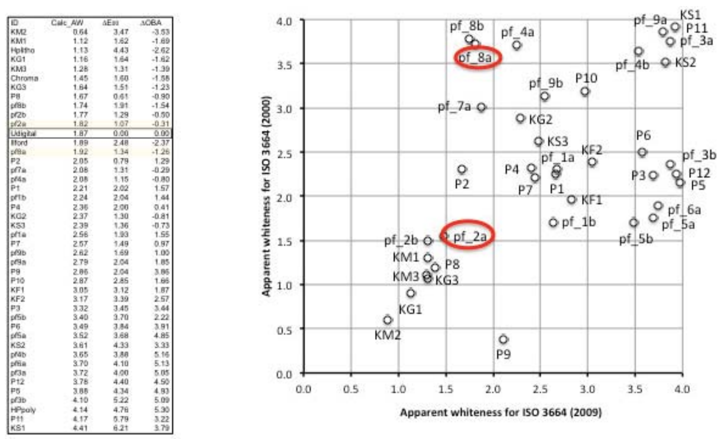
Also included in Figure 10 is a table of Apparent Whiteness (calculated and sorted), ΔE00, and ΔOBA of the database. Samples that are vertically aligned have the same Apparent Whiteness in the ISO 2009 lighting. In addition, the shorter the distance between the reference and the sample is, the smaller the ΔOBA.



ID	Calc_AW	ΔE00	ΔOBA
KM2	0.63	5.20	-5.10
KM1	1.12	3.08	-3.26
KG1	1.15	3.20	-3.18
KM3	1.27	2.79	-2.95
KG3	1.63	3.30	-2.80
P8	1.66	2.55	-2.46
pf8b	1.73	4.10	-3.11
pf2b	1.77	3.26	-2.06
pf2a	1.82	3.12	-1.87
pf8a	1.91	3.49	-2.82
P2	2.05	2.63	-0.28
pf7a	2.07	3.34	-1.85
pf4a	2.08	2.48	-2.37
P1	2.21	0.00	0.00
pf1b	2.24	0.26	-0.13
P4	2.36	0.50	-1.16
KG2	2.36	1.31	-2.38
KS3	2.39	1.30	-2.30
pf1a	2.56	1.16	-0.02
P7	2.57	2.08	-0.60
pf9b	2.62	2.85	-0.57
pf9a	2.79	2.69	0.28
P9	2.86	2.22	2.29
P10	2.87	2.33	0.09
KF1	3.05	2.27	0.30
KF2	3.17	2.33	1.00
P3	3.32	2.27	1.87
pf5b	3.40	2.91	0.65
P6	3.49	2.70	2.34
pf5a	3.53	2.70	3.28
KS2	3.61	3.43	1.76
pf4b	3.65	3.61	3.60
pf6a	3.70	3.01	3.56
pf3a	3.72	3.65	3.48
P12	3.78	3.15	2.93
P5	3.88	3.64	3.36
pf3b	4.10	4.11	3.52
P11	4.17	4.61	1.65
KS1	4.41	5.13	2.22

Figure 10. Matching printing stock, P1

Figure 11 illustrates an external reference, U-digital, as a printing stock. The two samples, having the closest Apparent Whiteness to the stock, are pf_2a and pf_8a. Note that the two samples, pf_2a and pf_8a, happen to have similar Apparent Whiteness as the stock, P2. We should expect a close color match between U-digital and P2 as well. Also notice that the external stock does not have coordinates in the Figure 11.



ID	Calc_AW	ΔE00	ΔOBA
KM2	0.64	3.47	-3.53
KM1	1.12	1.62	-1.69
Hplitho	1.13	4.43	-2.62
KG1	1.16	1.64	-1.62
KM3	1.28	1.31	-1.39
Chroma	1.45	1.60	-1.58
KG3	1.64	1.51	-1.23
P8	1.67	0.61	-0.90
pf8b	1.74	1.91	-1.54
pf2b	1.77	1.29	-0.50
pf2a	1.82	1.07	-0.31
Udigital	1.87	0.00	0.00
Ilford	1.89	2.48	-2.37
pf8a	1.92	1.34	-1.26
P2	2.05	0.79	1.29
pf7a	2.08	1.31	-0.29
pf4a	2.08	1.15	-0.80
P1	2.21	2.02	1.57
pf1b	2.24	2.04	1.44
P4	2.36	2.00	0.41
KG2	2.37	1.30	-0.81
KS3	2.39	1.36	-0.73
pf1a	2.56	1.93	1.55
P7	2.57	1.49	0.97
pf9b	2.62	1.69	1.00
pf9a	2.79	2.04	1.85
P9	2.86	2.04	3.86
P10	2.87	2.85	1.66
KF1	3.05	3.12	1.87
KF2	3.17	3.39	2.57
P3	3.32	3.45	3.44
pf5b	3.40	3.70	2.22
P6	3.49	3.84	3.91
pf5a	3.52	3.68	4.85
KS2	3.61	4.33	3.33
pf4b	3.65	3.88	5.16
pf6a	3.70	4.10	5.13
pf3a	3.72	4.00	5.05
P12	3.78	4.40	4.50
P5	3.88	4.34	4.93
pf3b	4.10	5.22	5.09
HPpoly	4.14	4.76	5.30
P11	4.17	5.79	3.22
KS1	4.41	6.21	3.79

Figure 11. Matching an external reference, U-digital

Overall, the visual match between the selected samples and their references, in the ISO 3664 (2009) viewing booth ranges from reasonable to excellent in comparison to other samples in the database.

Discussions

Apparent Whiteness determination based on visual ranking was deemed difficult by the participants and therefore prone to experimental errors. Factors that contribute to uncertainty include (a) large data set, (b) Apparent Whiteness is one-dimensional while samples differed in many attributes, including shade, brightness, weight, gloss, texture, etc., (c) relatively small visual differences with no ties allowed.

For further research, pairwise comparison of Apparent Whiteness difference for all pair combinations in the database, not just the whitest sample, is expected to provide more accurate data and improve predictive modeling.

The proposed algorithm for selecting a proofing substrate is only applicable to the M1 measurement condition and the ISO 3664 (2009) compliant viewing condition. It will not apply to other measurement and viewing conditions.

Proofing substrates do not need to match printing stocks exactly because we can use ICC color management provided that (a) absolute colorimetric rendering is used for color conversion between the source (printing) color space and the destination (proofing) color space, and (b) there is no clipping in the highlight region of the proofer color gamut. In other words, a proofing stock, with small ΔE_{00} and slightly higher L* and OBA than the print, will do.

Conclusions

We demonstrated that visual ranking the samples in two ISO 3664 lighting conditions are significantly different due to the interaction between UV energy in lighting and OBA in paper substrate in confirmation to the previously reported results (Coppel, 2009).

The high linear correlation between the CIE whiteness and Apparent Whiteness found in the experiment led us to propose a methodology for selecting a proofing substrate for color proofing based on the CIE Whiteness M1 metrics, with the subsequent verification of the selection is verified by measured paper metrics, including ΔE_{00}, ΔOBA, and ΔC_h. The final decision on the proofing substrate-to-printing stock match rests on visual assessment in the ISO 3664 (2009) compliant lighting.

Literature Cited

ASTM E313 Standard Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Color Coordinates (2015) ASTM International, West Conshohocken, PA

Coppel, Ludovic G., iarigai Research Conference (2009) Perception and measurement of the whiteness of papers with different gloss and FWA amount

ISO/DIS 13655 (2009) Graphic technology — Spectral measurement and colorimetric computation for graphic arts images

ISO 3664 (2009) Graphic technology and photography — Viewing conditions

TAPPI T480 (2015) Specular gloss of paper and paperboard at 75 degrees

Thurstone, A Law of Comparative Judgment, Psychological Review (1994) Vol 101, No. 2, 266-270

Acknowledgments

We want to thank the following members of the IDEAlliance Print Properties & Colorimetric Council: Roy Bohnen (Epson) and Steve Dilullo (Kodak) for providing paper samples, Danny Rich (Sun Chemicals), and Bob McCurdy (gti) for their advice and supports. We also want to thank members from RIT: Yingtong Bu (Graduate student, School of Media Sciences) for her laboratory assistances and Dan Clark (Printing Applications Laboratory) for his assistance in gloss measurement. Finally, we want to thank Dave McDowell and Mike Rodriguez for their encouragements and review of the manuscript.