Testing the Validity of Measuring Gray Balance with the GATF Color Circle, Grayness and Hue Error Values

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Abstract: The purpose of this study is to compare L*a*b* Grayness measurement accuracy with that achieved by a proposed new system which uses a re-purposed GATF Color Circle.

It is generally accepted that the visual or instrumental evaluation of gray balance targets is an effective method to control color balance for the four-color printing process. While the various gray balance measurement systems in existence use different instrumentation and quantify grayness in a variety of numeric and graphic formats their ultimate goal is identical. All gray balance measurement systems seek to measure and display grayness variations between a standard and a process grayness.

The results of the study show that both the L*a*b* system and the GATF Color Circle system are effective in quantifying and displaying differences between an actual and a desired grayness.

Introduction

All printing processes rely on the four-color processes to reproduce chromatic originals and as such have to attain a seemingly elusive balance between cyan, magenta, yellow, and black in order to create a facsimile of the original.

A study published by Printing Industries of America Inc. in 2001 (Chadwick, 2001), based on 960 four-color process jobs compiled from 1998 to 2000, gives us a glimpse of the extent of the problem. The study distinguishes between planned and unexpected spoilage, where planned spoilage is the anticipated spoilage inherent in the make-ready of a four-color process job and where unexpected spoilage is caused by not meeting a customer's expectations.

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According to the study planned spoilage for four-color jobs was 185.0%%, 41% 17.8%, 10.6%, and 4.7% for very short runs (<500), short runs (501-2,000), moderate short runs (2,001-5,000), moderate runs (5,0001-10,000) and long runs (>10,000) respectively. The figures for unexpected spoilage listed in the same order as above were 45%, 10.9%, 5.4%, 3.2%, 1.7%. While the study does not implicitly state that spoilage was caused by unacceptable color balance, other studies consistently corroborate that color imbalance is a leading cause for spoilage in four-color process printing. Further indication that the problem is related to color imbalance is the clear correlation between run lengths and spoilage. Color balance is established in the early stages of a press run and can only be achieved by repeated adjustments to the ink feed system of a press while it consumes paper. Once color balance is established it will usually stabilize and therefore, as a percentage of the whole, short runs will be subject to more spoilage.

The balance between process colors has in the distant past (and still often practiced today) been controlled by press operators adjusting the ink feed system of a press in accordance with their visual assessment of the output as compared to an approved standard (OK sheet). The shortcomings of this approach are that the color balance assessment depends on the vagaries of individual press operators' color perception and the slow response time of an operator to required ink feed changes. Given that a reproduction could consist of thousands of colors and shades of colors, press operators are faced with the insuperable task to establish the correct balance between the process colors, and consequently the risk of make-ready spoilage and spoilage due to unacceptable output is high.

The introduction of control strips that could be measured with instrumentations such as densitometers and spectrophotometers greatly improved the efficiency and control of four-color process printing, because print characteristics such as density, dot gain, ink trap, print contrast, grayness, and colorimetric values could be objectively measured for each individual process color, resulting in faster make-readies, better color balance and reduced waste. Additionally, in advanced press systems, the measured data can be compared to pre-set aim points in order to control the ink feed system of a press automatically, thus in a best case scenario, the requirement for press operators to make color balance decisions and the physical action of making the adjustments is eliminated.

Origins of the Gray Balance Concept

One of the first scientists to investigate the mathematical properties of autotypical color synthesis was Hans E. J. Neugebauer. His research culminated with the publication of his seminal paper (Neugebauer, 1937) in which he proposed a series of equations, quantifying the amounts of ink needed to reproduce colors in the four color-printing process. While Neugebauer did not specifically investigate gray balance, he laid the foundation for a mathematical approach to the four-color printing processes. Other color scientists continued this research to specifically compute the cyan, magenta and yellow ink amounts that produce neutral grays, because it was realized, that a primary requirement of four-color reproduction is the ability to create a neutral gray scale throughout a picture's tonal range. If, for example a neutral scale had a greenish colorcast, yellowish color cast, reddish color cast etc., likewise would all other hues in the reproduction be affected by these color casts. Archer (1954), Clapper (1959), Preucil (1964), Pobboravsky (1966) and other researchers contributed to this gray balance research, but their primary area of research was in the realm of internal picture structure for the purpose of improving color separation technology as opposed to the control of color balance during the printing phase.

The Application of Gray Balance Measurements to Controlling Printing Press Ink Feed Systems

In the late 1960s Felix Brunner, a Swiss color scientist and entrepreneur, pioneered the application of the gray balance concept to the control of printing press ink feed systems. One of the earliest commercially available control strips that incorporated color balance elements, which at that time were still assessed visually, was Felix Brunner's 1973 Print Control Strip (Figure 1).

Figure 1.
The 2nd (1973) Print Control strip for checking dot gain, color balance, solid ink density, trapping, high light dots.
Source: System Brunner web site (www.systembrunner.com).

In 1979, a subsequent Brunner control strip generation became the central part of E.I. du Pont de Nemours's well known Eurostandard Cromalin proofing system (Field et. al. 1984). Further developments led to Brunner's Picture Contrast Profile (Brunner, 1987) and Print Expert (Muirhead, 1988) gray balance control systems, which place a high emphasis on dot gain differentials to evaluate gray balance, and furthermore categorize reproductions according to their gray balance sensitivity. Brunner's system has gained acceptance in a number of print control systems foremost of which are QuadTech and MAN Roland. Brunner continues to be a staunch proponent of densitometers as being the most suitable instrument for gray balance measurements (Sonntag et al, 2005).

Other printing press manufacturers, notably Heidelberg Druckmaschinen AG have chosen spectrophotometry as their preferred gray balance measuring system. Similar to the Brunner system, Heidelberg also uses print control strips that incorporate gray patches (Figure 2.) to measure deviations in the gray fields and report them in $\Delta E^*_{a\,b}$ values.

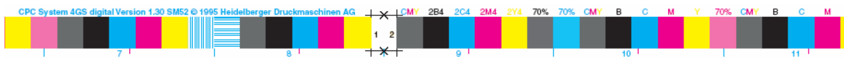


Figure 2.
CPC System 4GS digital Version 1.30 SM52, Heidelberg Druckmaschinen AG.

A further development in printing press color balance control is the spectophotometric measurement of the image itself, rather than control strips. Heidelberg's Prinect Image Control is such system. Measuring the image itself represents a radically different approach to color balance control and is as such not related to the principles of gray balance discussed in this paper.

The Gray Balance Patch

In theory, equal amounts of pure cyan, magenta and yellow inks superimposed over each other will produce black, because pure cyan, magenta and yellow inks each absorb a different third of the spectrum. We know this not to be occurring with real process inks. Equal amounts of actual cyan, magenta and yellow inks will in fact produce a brownish hue, because each process color has unwanted absorptions. In halftone printing a given tone is produced by adjusting the dot areas, which makes it possible to compensate for the impurity of the process inks. A study by Preucil (1963) investigated printed Grayness values produced by various process inks and found that yellow dots require a greater dot size than magenta dots if more bluish magentas are being used, while redder magentas require somewhat smaller yellow dots than magenta. As well, grayer or less saturated cyan inks require larger dot sizes to create neutral grays. As a general rule, to produce a neutral gray, the dot size for cyan must be larger than the dot sizes for magenta and yellow and the dot sizes for yellow and magenta must be similar.

Various standard organizations and producers of commercially available print control elements have defined the screen percentages required to produce neutral grays slightly different. Depending on the printing process they cater to, as well as the paper and inks being used, dot gain and colorimetric values will vary. For example the SWOP standard calls for 50% cyan, 39% magenta and 39% yellow to produce mid-tone neutrals, whereas GRACoL specifies values of 50% cyan, 40% magenta and 40% yellow. SWOP is a standard organization that represents heat-set web offset printers, while GRACoL serves the sheet-fed offset market. Since web offset tends to produce more dot gain than sheet-fed offset, SWOP specifies gray percentages that are 1% smaller for magenta and yellow.

Table 1 shows the gray balance values used by major standard organizations. The black screen patches are typically adjacent to the gray balance patches as a visual reference gray. If both the gray balance and the black patch are indistinguishable from each other, perfect gray balance, and by inference, perfect color balance in the reproduction is achieved.

SWOP (SWOP, 1993)				SNAP Gray Target recommendation (SNAP, 1989)			
Gray Balance Percentages				Gray Balance Percentages			
Black	Cyan	Magenta	Yellow	Black	Cyan	Magenta	Yellow
75	75	63	63		40	34	32
50	50	39	39				
25	25	16	16				
GRACoL (GRACoL, 2002)				Brunner (Brunner, 1987)			
Gray Balance Percentages				Gray Balance Percentages			
Black	Cyan	Magenta	Yellow	Black	Cyan	Magenta	Yellow
75	75	63	63	50	50	41	41
50	50	40	40				
25	25	16	16				
GATF Digital Compact Color Control Strip version 1.0, (Field, 1999)				Ugra/FOGRA Media Wedge CMYK, V2.0 for digital proofs, (Schmitt, 2004)			
Gray Balance Percentages				Gray Balance Percentages			
Black	Cyan	Magenta	Yellow	Black*	Cyan*	Magenta*	Yellow*
40	40	30	30	10	10	6	6
				20	20	12	12
				40	40	27	27
				60	45	45	45
				80	80	65	65
				100	100	85	85
FOGRA ECI/bvd Gray Control Strip for offset printing (ECI, 2005)				DMACS Canadian Specifications, issue 4.9.2, (DMACS, 2005)			
Gray Balance Percentages				Gray Balance Percentages			
Black	Cyan	Magenta	Yellow	Black	Cyan	Magenta	Yellow
70	65	57	50		50	40	40
50	45	36	33				
30	27	20	18				

Table 1.
Gray Balance Patch Screen Percentages. * ISO 12642

Spectrophotometry vs. Densitometry for Gray Balance Measurements

Early investigation of gray balance was driven by a desire to improve color separation techniques, and as such has dominated this field for many years. Although the general principles of gray balance in both the pre-press and press areas are the same, the applications are different. In the former, gray balance is used to balance colors within the picture by adjusting the cyan, magenta and yellow dot sizes, while in the latter gray balance finds application to balance cyan, magenta, and yellow ink flow in order to maintain the color balance that was established in the pre-press stages. Spectrophotometers together with device independent color spaces, such as L*a*b*, are unsurpassed in their ability to quantify color the way the human eye perceives it, because they incorporate the three stimuli of human vision, spectral energy distribution of a light source, spectral reflectance of an object, and spectral response of a detector (standard normal observer). Because modern color management requires the measurement of color patches (IT8 targets) to characterize the output devices in a workflow with device independent color spaces such as L*, a*, b*, spectrophotometers are the only technical option.

Unlike gray balance control in the pre-press area where the possibility for adjustments are extremely flexible with regard to localized color manipulation, the printing process is relatively inflexible in that it can only apply overall amounts of cyan magenta and yellow. For example it is not possible to decide at the printing stages to cause the highlight to be bluer and the mid-tones to be redder. It is only possible to cause both the highlights and the mid-tones to be bluer or redder, or put another way, both tones can not be adjusted independent from each other. This restriction does not apply to prepress procedures and therefore the printing stage requires a different and highly standardized approach to color balance. This is not to say that spectrophotometers and device independent color spaces cannot be used effectively to control color balance during printing, rather it means that densitometers can be used just as effectively.

A rational goal for color acceptability should be closely related to the limits of the human visual system to detect color differences. Because the ability of the human visual system is exceptionally adept at detecting color differences when comparing a standard and a sample side by side, it is standard practice in the printing industry to approve press runs upon visually comparing the printing press output with some type of standard such as a digital proof or a previously printed sample. This approved printing press output is usually called an OK sheet and becomes the standard for the press run. If the Grayness values of the approved printing press output have been measured and recorded, the aim will henceforth be to maintain the Grayness values of the printing press output as closely as possible to the Grayness values of an OK sheet, which virtually assures color balance in the printed image.

Grayness deviations can be measured by spectrophotometers and quantified in ΔE^*_{ab} units, with adequate accuracy (Stokes et al, 1992). However densitometers are also effective because of the sufficiently good correlation between optical density units and ink amounts (Field, 1999). Given that optical densities are a good measure of ink amounts, it stands to reason that the proportions of cyan, magenta and yellow inks, that produce Grayness, can be monitored and controlled with densitometers.

An analogy from the world of cooking will be pertinent to this line of reasoning. In cooking the aim is to satisfy the sense of taste, which is not unlike the world of printing where the objective is the sense of sight. If, for instance a particularly tasteful dish was prepared from a recipe that calls for three ingredients of known weights, one could reconstitute the dish by making a complete chemical analysis of the dish. Although this approach would probably work, it would be an excessively complex method to accomplish a relatively simple task. The obvious and more sensible approach would be to use the exact same weights as specified in the recipe for each of the three ingredients. The former approach is akin to the technologically complex spectophotometric analysis of gray balance, while the latter approach is akin to using the much simpler densitometric technology for the same task.

The GATF Color Circle

The GATF Color Circle was first introduced in 1957 in *GATF Research Report No. 38* (Cox, 1970) and is as such the oldest of the GATF color diagrams. All of the GATF diagrams, including the GATF Color Hexagon and the GATF Color Triangle are adaptations from other color notational systems using cyan, magenta, yellow solid ink density units as their basic input values. They were primarily developed to show hue and chroma variations induced by printing process related phenomena, such as ink trapping, color sequence, ink strength, and substrate gloss or absorbency.

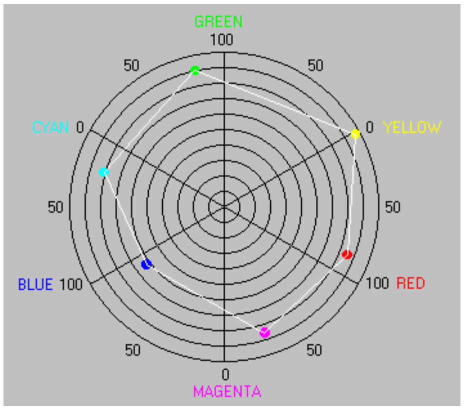
The GATF Color Circle (Figure 3) displays two color dimensions called Hue Error and Grayness, where Hue Error is plotted in the circumferential direction and Grayness is plotted in the axial direction of the circle. The input (densities) and output (Hue Error and Grayness) values are shown in Table 2. Similar to most color spaces, colors found near the periphery of the circle are more saturated than colors found toward the center of the circle. The circle is transected by three axis, which represent the perfect primary and secondary color coordinates with regard to their hues. Each axis is shared by a primary and its secondary color complement. Thus cyan and red, magenta and green, and yellow and blue share the same axis.

Densitometers are made specifically for process colors and will measure the light absorption of a process color through a filter color that is complementary to the color measured. Thus cyan, magenta, and yellow are measured through red, green, and blue filters respectively. The complementary filter color of the process color measured will always yield a higher density value than the other two filters, but the other two filter values are almost never zero. This means process colors have unwanted absorptions or are, in other words, colorimetrically impure.

The formulas to calculate Hue Error and Grayness are as follows:

$$\text{Hue Error} = \left(\frac{\text{Mid Density - Low Density}}{\text{High Density - Low Density}}\right) \text{x } 100 \quad (1)$$

$$\text{Grayness} = \left(\frac{\text{Low Density}}{\text{High Density}}\right) \text{x } 100 \quad (2)$$



Filters	R	G	B	Hue Error	Gray
Cyan	1.40	0.53	0.27	23.01	19.29
Magenta	0.21	1.45	0.58	29.84	14.48
Yellow	0.03	0.05	1.10	1.87	2.73
Red	0.22	1.35	1.55	84.96	14.19
Green	1.44	0.14	1.18	80	9.72
Blue	1.51	1.62	0.61	89.11	37.65

Figure 3.
GATF Color Diagram.

Table 2.
Density, Hue Error and Grayness.

A color will fall on its axis only if the two unwanted absorptions are equal. If a color has unequal absorptions, as is invariably the case, it will have a Hue Error. Consider the example in Figure 3 and Table 2 where a cyan has density values of 1.40, 0.53 and 0.27 for the red, green, and blue filters respectively. The Hue Error is determined by the middle value, which in this case is 0.53.

In the diagram the color would then be plotted in the radial direction that is closest to the process color with which the measured color is contaminated. In the foregoing example this would mean that the cyan, having a middle value (0.53) for the green filter value, has a magenta Hue Error and will therefore be plotted in the radial direction that is closest to magenta.

Secondary colors are plotted similarly, but since in the four-color process, they are produced by two primary colors their Hue Errors are a measure of the equality of both primary colors that produce it. For example, if a red has density values of 0.22, 1.35, 1.55 in the red green and blue filter positions respectively, then the red will be more yellowish by virtue of its higher blue filter value (1.55) and will therefore be plotted toward the radial direction of yellow.

Grayness values are a function of the lowest density reading, because equal absorptions of red green and blue light, which is indicative of a neutral gray, are possible only when measured relative to the lowest filter value. This gray component in the color will tend to de-saturate the color, causing the plot to move in the axial direction toward the center of the circle.

Adaptation of the GATF Color Circle to Intrinsic Grayness Measurements

Using the GATF Color Circle for the purpose of controlling gray balance during the printing process is a rather novel application for this color space (Breede, 2004), because it was originally developed for the measurement and display of the saturated primary process colors cyan, magenta, and yellow, as well as their secondary color derivates red, green and blue. Grayness in the context of the original color circle's application means the dulling or de-saturation of a measured color, and not the measurement of Grayness itself. To make the GATF Color Circle useful for intrinsic Grayness measurements the red, green and blue axis have to be reassigned a modified function. Unlike the original purpose of the color circle, which is to plot the three primary and secondary colors, intrinsic Grayness measurements require only the measurement of the three primary colors. Therefore, the red, green and blue axis are no longer input values but specifically indicate the output or hue shifts of a given Grayness. Otherwise, the Hue Error and Grayness values are calculated as per equations (1) and (2) and likewise the circle's interpretation remains unchanged. Figure 4 shows the position of a Grayness measurement that yielded 0.66, 0.56 and 0.46 for the red, green and blue filters respectively, while Table 3 shows the input (density) and output (Hue Error and Grayness) values. Using equations (1) and (2) we will get a Hue Error of 50% and a Grayness of 69.7%. Since the highest value was found for the red filter density the dominant hue of the gray patch is cyan.

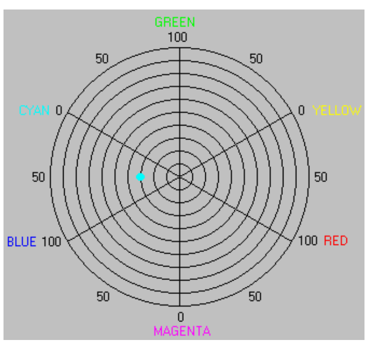


Figure 4.
GATF Color Circle Grayness plot having a cyan color cast.

Filters	R	G	B	HE	Grayness
Cyan	0.66	0.56	0.46	50	69.7

Table 3.
Density, Hue Error and Grayness.

Using the GATF Color Circle for Press Run Color Balance Control

Suppose an approved (OK sheet) four-color process job was measured for Grayness, and yielded 0.62, 061, and 0.60 densities for the red, green and blue filter values. The resulting Hue Error and Grayness values are therefore 50% and 96.77% respectively. At this point it must be remembered that the job was not approved because of its Grayness, although it is reasonably good, but because of the visual acceptability of the reproduction. Henceforth, the aim will be to control the ink flow in such a way that the above red, green and blue filter densities are maintained as close as possible, which in turn infers that the initially accepted quality is maintained because of the Grayness/color balance correlation discussed earlier. In essence, the Grayness reading of the initially

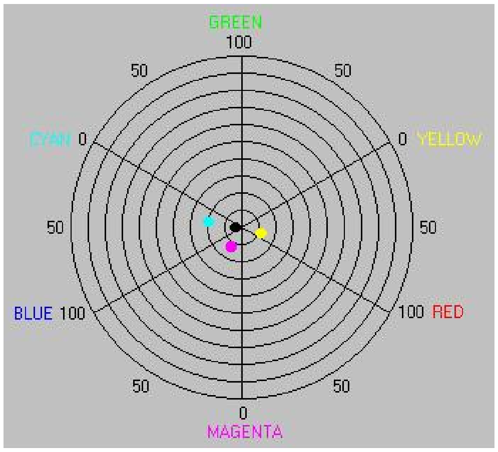


Figure 5.
GATF Color Circle Grayness plots clustered around a standard Grayness.

Filters	R	G	B	HE	Gray	ΔGray	ΔR	ΔG	ΔB
Gray (standard)	0.62	0.61	0.60	50	96.77				
1. Gray (cyan hue)	0.62	0.54	0.50	33.33	80.65	-16.12	0	-0.07	-0.1
2. Gray (mag. hue)	0.65	0.70	0.61	44.44	87.14	-9.63	0.03	0.09	0.01
3. Gray (yell. hue)	0.66	0.73	0.75	77.78	88	-8.77	0.04	0.12	0.15

Table 4.
Density, Hue Error, Grayness and Δ values.

approved press sheet serves as a benchmark for the entire press run. In Figure 5, the initial Grayness of the OK sheet is shown as a black plot, while three press sheets' Grayness readings taken during the press run are shown by plots that are colored according to their colorcasts. Table 4 lists the corresponding density, Hue Error, Grayness and Delta values.

Grayness values express the magnitude of the deviation from the approved standard, both numerically and graphically, while the ΔR, ΔG and ΔB values are used to control the ink flow of the press. In concrete terms, this means press sheet No. 1 requires more magenta and yellow, press sheet No. 2 requires the ink flow to be reduced to all colors but mostly to magenta and least to yellow, and press sheet No. 3 requires also less ink flow in all colors but especially less yellow and magenta, to reestablish the approved color balance.

Experimental Method

The aim of the study was to measure Grayness values sampled from an experimental press run and to determine whether a correlation with $\Delta E^*_{a\,b}$ exists. The experimental press run was conducted under normal print conditions for sheet-fed offset lithographic printing of four-color process reproductions, while simultaneously aiming for nominally perfect gray balance. In the context of this study normal print conditions means the measurable print characteristics as defined by GRACoL (General Requirements for Applications in Commercial Offset Lithography, 2004), and nominally perfect gray balance means equal reflection densities through the red, green and blue filters of a densitometer. The overriding emphasis however, was to achieve nominally perfect gray balance, even if print conditions deviated from those stipulated in GRACoL.

A test form (Figure 6) incorporates the following critical components:

1. A gray balance strip composed of 50% cyan, 41% magenta and 41% yellow extending across all ink zones of the press.
2. An image containing memory colors, in particular skin tones, an image that is less sensitive to color shifts (i.e. a profusion of many colors) and an image that is highly sensitive to color shifts (i.e. very neutral colors).
3. Solid and 50% tint screen strips for all four process colors extending across all ink zones of the press, in order to measure and control solid ink density and dot gain.

The test form was printed on a Heidelberg Quickmaster DI, waterless offset press, using 148 g/m^2, M-Real, Euro, Art Gloss, D.I., coated offset paper. The inks used, were waterless inks by Rycoline and the lay down sequence was K,C,M,Y.

Nominally perfect gray balance was achieved in one ink zone, against which all other readings were compared. The same press sheet on which nominally perfect gray balance was found had sufficient gray balance variation to produce 40 readings of continuously diminishing Grayness values and will for the purpose of this study be referred to as Uncontrolled Grayness Variation (UGV). Subsequent to finding a nominally perfect Grayness and its L*a*b equivalent, the Uncontrolled Gray Balance Variation was measured as close as possible to 0.20 ΔE^*_{ab} intervals.

The same press run also produced gray balance differences that were caused by gradually increasing the ink flow to the magenta plate only. This resulted in 15 readings from 15 different press sheets and will henceforth be called Controlled Grayness Variation (CGV).

All measurements were made with an X-Rite 530 spectrodensitometer. Every location measured was simultaneously recorded in both L*a*b*, D50/10, and the three filter densities (Status T), which were subsequently converted to Hue Error and Grayness values. The raw data can be seen in Appendices A and B.

-------Trailing Edge------

---------Leading Edge--------

Figure 6.
Test Form.

Evaluation Method

In view of the fact that spectrophotometric measurements are generally recognized to be an accurate method of quantifying color differences, the proposed Grayness measurement system will be evaluated by its nearness to it. Therefore, Grayness values will be statistically evaluated using linear regression analysis, where $\Delta E^*_{a\ b}$, is the independent and ΔGrayness is the dependent variable. Additionally, an ANOVA analysis will determine whether the association between $\Delta E^*_{a\ b}$ and Grayness is statistically significant. Grayness and Hue Errors will also be compared to a* and b* to determine if similarities exist in the way the $L^*_{a\ b}$ and GATF Color Circle color spaces register color shifts. The equations used are defined as follows:

$$\Delta L^* = L^*_{\text{Sample}} - L^*_{\text{Standard}} \tag{3}$$

$$\Delta a^* = a^*_{\text{Sample}} - a^*_{\text{Standard}} \tag{4}$$

$$\Delta b^* = b^*_{\text{Sample}} - b^*_{\text{Standard}} \tag{5}$$

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{6}$$

$$\Delta \text{Grayness} = (\text{Grayness}_{\text{Sample}} - \text{Grayness}_{\text{Standard}}) \times -1^* \tag{7}$$

* ΔGrayness is converted to a positive value in order to create the quantitative equivalent of $\Delta E^*_{a\ b}$.

Print Quality Analysis

For this experimental press run, the densities and the 50% mid tone dot gain values producing nominally perfect gray balance were as follows:

	Solid Ink Density	Dot Gain
Cyan	1.31	32%
Magenta	1.26	31%
Yellow	0.91	39%

whereas the gray bar produced the following densitometer readings:

Visual filter reading	0.84
Red filter reading	0.78
Green filter reading	0.78
Blue filter reading	0.78

thus using equation (2), a nominally perfect Grayness of 100% was achieved.

The L* a* b* equivalents are:

L* = 45.61
a* = -1.75
b* = -3.61

The unusually high dot gain value for yellow can be explained by the fact that Heidelberg's direct imaging system uses a yellow halftone line screen ruling that is significantly finer than the 175 lines/inch used in cyan and magenta. This is done, to prevent banding, which can otherwise occur at the relatively low image resolution of 1,270 dots per inch. Since finer line screen rulings are known to cause more dot gain, yellow's dot gain must necessarily be high. For this and other reasons, that are beyond the scope of this study, densities and dot gain values are deviating from those recommended in GRACoL. Nonetheless, given the aforementioned definitions, nominally perfect Grayness was achieved by virtue of equal red, green, and blue filter readings. The equivalent L*a*b* values are however showing that the gray is not perfectly neutral. Here again, an explanation is in order.

In the printing process it is a near impossibility to produce a perfectly neutral gray with the three process colors, but in some other processes that are more easily controlled, such as photographic imaging, near perfect neutral grays can be produced. For example a 24-step Kodak Reflection Density Guide (continuous tone), if measured at the approximate density step of the experimental press run's gray density, produces the following densitometer readings:

Visual filter reading	0.83
Red filter reading	0.83
Green filter reading	0.83
Blue filter reading	0.83

and the L* a* b* equivalents are:

L* = 42.42
a* = 0.08
b* = 0.66

The Kodak Reflection Guide L* a* b* values indicate clearly a more neutral gray than the gray produced by the experimental press run, because its a* and b* values are closer to zero, yet this difference is not recorded using Grayness equation (2), which calculates 100% Grayness for both. Spectrophotometric measurements converted to the L*a*b* color space are therefore more accurate than densitometric measurements converted to Grayness values. The reason is however, not necessarily an indication of inherently less accurate densitometric measurements, but that this densitometer displays densities only to two decimal places of accuracy. Had the densitometer a three decimal place accuracy, it probably would have registered the difference between the two grays. This discussion should be born in mind for a better understanding of some forthcoming test data.

Results and Discussion of Uncontrolled Grayness Variation (UGV) Data

To describe the relationship between the ΔE^*_{ab} and ΔGrayness both sets of data were plotted on a scatter diagram fitted with a regression line. There are 40 pairs of data points ranging from 0.1 ΔE^*_{ab} vs. 0 ΔGrayness, to 7.87ΔE^*_{ab} vs. 15.56 ΔGrayness. An important consideration was the selection of an interval for the independent variable ΔE^*_{ab}, because it would be pointless to use ΔE^*_{ab} intervals that are beyond the human visual system's ability to perceive color.

A NPIRI Task Force on Color Measurement (Basimir et al, 1995) testing human subjects found that color difference perception is highly dependent on the color viewed. According to the NIPIRI study, 70% of subjects perceived just noticeable color differences from a low ΔE^*_{ab} value of 0.3 for grays to a high ΔE^*_{ab} value of 5.0 for yellows. For this reason, aiming for intervals of 0.20 ΔE^*_{ab} seems reasonable. The actual achieved intervals for this study ranged from a low of 0.05 to a high of 0.49 ΔE^*_{ab} resulting in an overall average of 0.211.

Examining the data in Table 5, and the scatter diagram in Figure 7, it can be seen that a clear relationship between ΔE^*_{ab} and ΔGrayness exists. The regression line fits the data reasonably well and therefore in general, as ΔE^*_{ab} increases, ΔGrayness increases too. The strength of this relationship can be determined by calculating the coefficient of determination, shown in Table 6 as the value of $r^2 = 0.979106$. This value, ranges always from 0 to 1, and tells us what proportion of the change in ΔGrayness can be explained by a change in ΔE^*_{ab}. Expressed as a percentage, we can therefore state that 97.91% of a change in ΔGrayness is attributable to a change in ΔE^*_{ab}.

The statistical significance of a test statistics can be determined by performing an ANOVA analysis of the data, seen in Table 6. Accordingly, the result of the F-test produces a Significance F value of 1.56E-33. (Table 6). Since Significance F is <0.01 the null hypothesis, or the assertion that no statistical association between ΔE^*_{ab} and ΔGrayness exists, can therefore be rejected at a 99% confidence level.

The overall results show a strong ΔE^*_{ab} and ΔGrayness statistical association, but seen also on the scatter diagram are periodic data points that are not randomly distributed above and below the regression line. These clusters of horizontal bands are an indication that the densitometer does not register Grayness variations at the same level of sensitivity as the spectrophotometer, because of the aforementioned lack of accuracy beyond a 2nd decimal place.

No.	Δ E	Δ Grayness	No.	Δ E	Δ Grayness
1	0.1	0	21	4.06	8.33
2	0.43	1.27	22	4.29	8.33
3	0.66	2.53	23	4.52	9.41
4	0.82	2.53	24	4.75	9.41
5	1.1	2.53	25	5.04	10.59
6	1.27	2.53	26	5.31	10.34
7	1.47	2.53	27	5.5	9.3
8	1.52	3.75	28	5.68	10.59
9	1.65	2.53	29	5.91	10.59
10	1.82	3.8	30	6.21	10.59
11	2.07	5	31	6.39	11.63
12	2.22	5	32	6.55	11.76
13	2.42	5	33	6.69	12.5
14	2.69	6.25	34	6.87	12.5
15	2.84	6.25	35	7.11	12.5
16	3.07	6.17	36	7.26	13.5
17	3.3	7.41	37	7.4	14.61
18	3.52	7.41	38	7.64	14.61
19	3.67	6.1	39	8.13	15.56
20	3.93	8.33	40	8.33	16.48

Table 5.
ΔE^*_{ab} vs. ΔGrayness ("UGV").

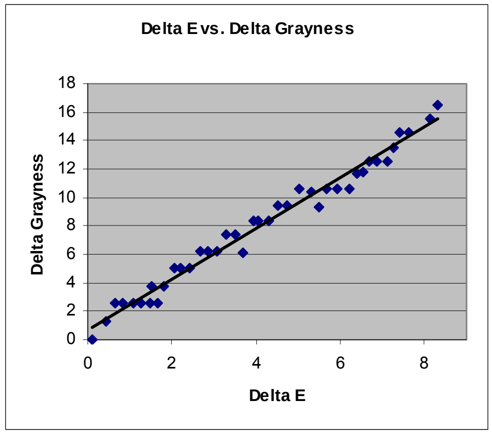


Figure 7.
Scatter diagram and regression line of ΔE^*_{ab} vs. ΔGrayness ("UGV").

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.989498					
R Square	0.979106					
Adjusted R Square	0.978556					
Standard Error	0.637164					
Observations	40					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	722.9373	722.9373	1780.732	1.56E-33	
Residual	38	15.42715	0.405978			
Total	39	738.3644				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.683859	0.200544	3.41001	0.001552	0.277878	1.08984
X Variable 1	1.782447	0.042239	42.19872	1.56E-33	1.696938	1.867956

Table 6.
Regression Statistics and ANOVA Table (UGV).

Results and Discussion of Controlled Grayness Variation (CGV) Data

A further objective of this study was to evaluate the relationship between a known cause of color shifts and the corresponding effects on the L*a*b* and GATF Color Circle color spaces. To this end, the experimental press run included a period in which the magenta ink feed was increased, thus causing an intentional color imbalance. Whereas the ΔE intervals for the previously described tests were selected on the basis of just noticeable color differences, in this series of tests the intervals were selected on the basis of color acceptability. In 1990, Heidelberg Druckmaschinen AG demonstrated the use of spectrophotometry for gray balance measurements of press sheets at DRUPA (Field, 1999) and later categorized ΔE units according to their acceptability (Table 7).

ΔE between 0 and 1	In general, this deviation cannot be perceived
ΔE between 1 and 2	Very small deviation; only perceivable by an experienced eye.
ΔE between 2 and 3.5	Medium deviation; perceivable even by an inexperienced eye.
ΔE between 3.5 and 5	Large deviation.
ΔE exceeding 5	Massive deviation.

Table 7.
ΔE Categories (Heidelberg Druckmaschinen AG, 1995).

An extensive study of color variation involving 9 web offset and 9 gravure press runs ranging from 50,000 to 450,000 copies proposed ΔE tolerances shown in Table 8. (Schläpfer et al, 1995).

	Gravure	Web Offset
Within production run deviation	3.0 ΔE	5.5 ΔE
Average deviation from the OK sheet	1.8 ΔE	3.3 ΔE

Table 8.
Proposed ΔE tolerances for Gravure and Web Offset.

To echo these acceptability tolerances, this part of the study uses 1.0 ΔE^*_{ab} intervals (Table 9-10 and Figure 8). The actual achieved intervals for this study ranged from a low of 0.56 to a high of 1.66 ΔE^*_{ab} resulting in an overall ΔE^*_{ab} average of 1.078.

No.	Delta E	Delta Grayness
1	2.23	3.75
2	3.28	4.94
3	4.51	6.02
4	5.21	7.06
5	6.87	7.95
6	7.85	8.89
7	9.13	10
8	10.53	11.71
9	11.57	12.5
10	12.55	15.46
11	13.76	15.84
12	14.61	16.83
13	15.17	17.48
14	16.16	18.27
15	17.33	19.44

Table 9.
ΔE^*_{ab} vs. ΔGrayness (CVC).

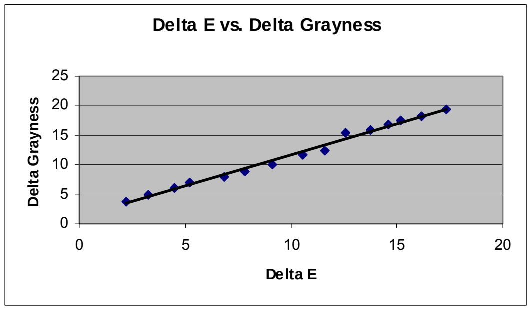


Figure 8.
Scatter diagram and regression line of $\Delta E^*_{a\,b}$ vs. ΔGrayness (CGV)

SUMMARY OUTPUT					
Regression Statistics					
Multiple R	0.994963				
R Square	0.989952				
Adjusted R Square	0.989179				
Standard Error	0.543531				
Observations	15				
ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	378.388	378.388	1280.823	2.25E-14
Residual	13	3.840535	0.295426		
Total	14	382.2285			
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	1.089446	0.329094	3.310439	0.005633	0.378482
X Variable 1	1.059952	0.029617	35.78858	2.25E-14	0.995968

Table 10.
Regression Statistics and ANOVA Table (CGV).

High $\Delta E^*_{a\,b}$ values are typical early in the four-color process make-ready phase, because color balance has not yet been established. Consequently, an accurate method to measure gray balance is particularly critical at this stage, when the risk for spoilage is highest.

This set of data has a somewhat higher r^2 value than the "Uncontrolled Gray Balance Variation" data. Also the clusters of horizontal bands are no longer apparent. Overall, these results show that an interval increase from 0.30 to 1.0 ΔE^*_{ab} units, causes the correlation between ΔE^*_{ab} and ΔGrayness to become even stronger.

The marginally higher Significance F value is for all intents and purpose still zero, and can be explained by the smaller sample size, but the statistical significance of the test statistics is still maintained at a 99% confidence level, because the Significance F value 2.25E-14 < 0.001.

When a*b* and Grayness and Hue Errors are plotted in their respective color spaces it can clearly be seen that both color spaces indicate color shifts similarly (Figures 9-10). The a*b* color space indicates mainly a shift toward red and somewhat toward the blue direction, which is indicative of a magenta shift, while the GATF Color Circle indicates a strong magenta shift increasing drifting toward red. Furthermore, both color spaces accurately register the process related occurrence which led to the color imbalance in the first place. It will be recalled that during the experimental press run, ink flow to the magenta plate was intentionally increased. It follows that gray balance corrections in reverse, i.e. from a gray with a color cast toward a neutral gray standard, can also be controlled with the GATF Color Circle.

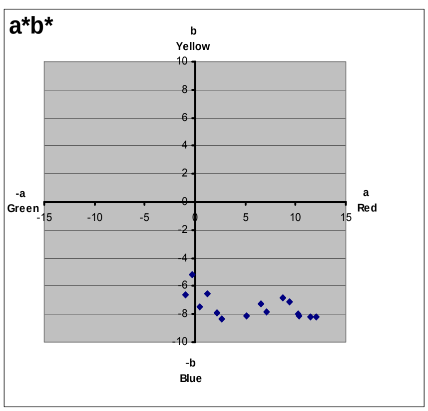


Figure 9.
a*b* (CGV)

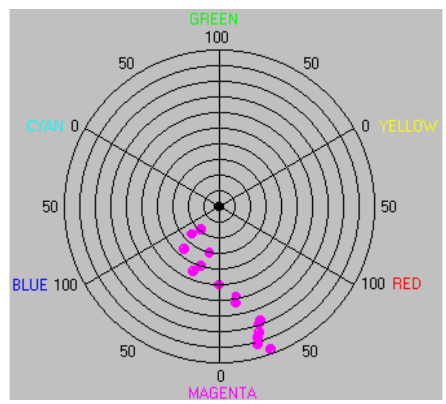


Figure 10.
Grayness and Hue Error (CGV)

Conclusion

Linear regression analysis of $\Delta E^*_{a\,b}$ vs. ΔGrayness shows a strong correlation, but at an approximate sampling interval of 0.20 $\Delta E^*_{a\,b}$, $\Delta E^*_{a\,b}$ has a greater sensitivity to color variation than ΔGrayness. Increasing the sampling intervals from 0.20 to 1.0 $\Delta E^*_{a\,b}$, results in both $\Delta E^*_{a\,b}$ and ΔGrayness having about the same sensitivity to color variation. The color variation sensitivity of Grayness units could probably be improved if densitometers with 3rd decimal place accuracy are used, but from a color acceptability point of view, a 1.0 ΔE^*_{ab} accuracy is adequate for the great majority of four-color process work.

The fundamental purpose of ΔE^*_{ab} and ΔGrayness, in the context of this study, is to quantify color variation rather than influence the process. When a process related event such as an increased ink flow to one particular plate occurs, both measurement systems record the resulting color shifts similarly in their respective color spaces, but both systems can influence or change the process only by reverting to the original data from which ΔE^*_{ab} and ΔGrayness are derived.

Densitometric values ΔR, ΔG, and ΔB could be used effectively in closed loop "on press" measurement systems to correct undesirable color casts.

The reliance of the GATF Color Circle on optical density as its basic input value is advantageous for controlling the ink flow of a press because, unlike L*a*b*, optical density bears a close relationship to ink film thickness.

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Note: Figure 3 is a screen capture of a software published by PIA/GATF*Press* under the name Abacus version 2. Figures 4, 5, and 10 are screen captures of a computer program under development. Both applications were developed by the author.

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Appendix A

Raw Data for Uncontrolled Grayness Variation (UGV):

ΔE^*_{ab}	L*a*b*	Densities	Grayness Hue Error	ΔE^*_{ab}	L*a*b*	Densities	Grayness Hue Error
Standard	L 45.61 a -1.75 b -3.61	V 0.84 C 0.78 M 0.78 Y 0.78	Grayness 100 ΔGrayness 0 HE 100	No.16 3.07	L 45.10 a -2.21 b -6.60	V 0.85 C 0.81 M 0.79 Y 0.76	Grayness 93.83 ΔGrayness 6.17 HE 60.00
No.1 0.10	L 45.67 a -1.83 b -3.59	V 0.84 C 0.78 M 0.78 Y 0.78	Grayness 100 ΔGrayness 0 HE 100	No.17 3.30	L 45.06 a -2.33 b -6.80	V 0.86 C 0.81 M 0.79 Y 0.75	Grayness 92.59 ΔGrayness 7.41 HE 66.67
No.2 0.43	L 45.35 a -1.88 b -3.92	V 0.84 C 0.79 M 0.79 Y 0.78	Grayness 98.73 ΔGrayness 1.27 HE 100	No.18 3.52	L 45.01 a -2.29 b -7.03	V 0.86 C 0.81 M 0.79 Y 0.75	Grayness 92.59 ΔGrayness 7.41 HE 66.67
No.3 0.66	L 45.51 a -1.90 b -4.24	V 0.84 C 0.79 M 0.78 Y 0.77	Grayness 97.47 ΔGrayness 2.53 HE 50	No.19 3.67	L 44.04 a -0.93 b -6.82	V 0.87 C 0.82 M 0.82 Y 0.77	Grayness 93.90 ΔGrayness 6.10 HE 100
No.4 0.82	L 45.64 a -1.84 b -4.42	V 0.84 C 0.79 M 0.78 Y 0.77	Grayness 97.47 ΔGrayness 2.53 HE 50	No.20 3.93	L 44.03 a -3.16 b -6.91	V 0.88 C 0.84 M 0.81 Y 0.77	Grayness 91.67 ΔGrayness 8.33 HE 57.14
No.5 1.10	L 45.60 a -1.79 b -4.70	V 0.84 C 0.79 M 0.78 Y 0.77	Grayness 97.47 ΔGrayness 2.53 HE 50	No.21 4.06	L 43.99 a -3.23 b -7.01	V 0.88 C 0.84 M 0.81 Y 0.77	Grayness 91.67 ΔGrayness 8.33 HE 57.14
No.6 1.27	L 45.35 a -1.68 b -4.85	V 0.85 C 0.79 M 0.79 Y 0.77	Grayness 97.47 ΔGrayness 2.53 HE 100	No.22 4.29	L 43.80 a -3.59 b -7.02	V 0.89 C 0.85 M 0.81 Y 0.78	Grayness 91.67 ΔGrayness 8.33 HE 42.86
No.7 1.47	L 45.38 a -1.89 b -5.05	V 0.85 C 0.79 M 0.79 Y 0.77	Grayness 97.47 ΔGrayness 2.53 HE 100	No.23 4.52	L 43.90 a -3.70 b -7.31	V 0.88 C 0.85 M 0.81 Y 0.77	Grayness 90.59 ΔGrayness 9.41 HE 50.00
No.8 1.52	L 45.15 a -1.72 b -5.06	V 0.85 C 0.80 M 0.79 Y 0.77	Grayness 96.25 ΔGrayness 3.75 HE 66.67	No.24 4.75	L 43.97 a -3.65 b -7.64	V 0.88 C 0.85 M 0.81 Y 0.77	Grayness 90.59 ΔGrayness 9.41 HE 50.00
No.9 1.65	L 45.27 a -1.65 b -5.22	V 0.85 C 0.79 M 0.79 Y 0.77	Grayness 97.47 ΔGrayness 2.53 HE 100	No.25 5.04	L 43.94 a -3.91 b -7.84	V 0.89 C 0.85 M 0.81 Y 0.76	Grayness 89.41 ΔGrayness 10.59 HE 55.56
No.10 1.82	L 45.40 a -2.02 b -5.39	V 0.85 C 0.79 M 0.78 Y 0.76	Grayness 96.20 ΔGrayness 3.8 HE 66.67	No.26 5.31	L 43.35 a -4.55 b -7.51	V 0.90 C 0.87 M 0.82 Y 0.78	Grayness 89.66 ΔGrayness 10.34 HE 44.44
No.11 2.07	L 45.29 a -2.20 b -5.60	V 0.85 C 0.80 M 0.79 Y 0.76	Grayness 95.00 ΔGrayness 5.00 HE 75.00	No.27 5.50	L 42.93 a -2.73 b -8.30	V 0.91 C 0.86 M 0.83 Y 0.78	Grayness 90.70 ΔGrayness 9.30 HE 62.50
No.12 2.22	L 45.19 a -2.21 b -5.74	V 0.85 C 0.80 M 0.79 Y 0.76	Grayness 95.00 ΔGrayness 5.00 HE 75.00	No.28 5.68	L 43.64 a -2.83 b -8.82	V 0.89 C 0.85 M 0.82 Y 0.76	Grayness 89.41 ΔGrayness 10.59 HE 66.67
No.13 2.42	L 45.49 a -2.54 b -5.89	V 0.85 C 0.80 M 0.78 Y 0.76	Grayness 95.00 ΔGrayness 5.00 HE 50.00	No.29 5.91	L 43.50 a -2.99 b -8.98	V 0.89 C 0.85 M 0.82 Y 0.76	Grayness 89.41 ΔGrayness 10.59 HE 66.67
No.14 2.69	L 45.42 a -2.67 b -6.13	V 0.85 C 0.80 M 0.78 Y 0.75	Grayness 93.75 ΔGrayness 6.25 HE 60.00	No.30 6.21	L 43.55 a -2.78 b -9.37	V 0.89 C 0.85 M 0.82 Y 0.76	Grayness 89.41 ΔGrayness 10.59 HE 66.67
No.15 2.84	L 45.24 a -2.26 b -6.37	V 0.85 C 0.80 M 0.79 Y 0.75	Grayness 93.75 ΔGrayness 6.25 HE 80.00	No.31 6.39	L 43.38 a -2.73 b -9.51	V 0.90 C 0.86 M 0.82 Y 0.76	Grayness 88.37 ΔGrayness 11.63 HE 60.00

No.32 6.55	L 43.47 a -2.77 b -9.71	V 0.90 C 0.85 M 0.82 Y 0.75	Grayness 88.24 ΔGrayness 11.76 HE 70.00	No.37 7.40	L 42.82 a -4.40 b -9.92	V 0.91 C 0.89 M 0.83 Y 0.76	Grayness 85.39 ΔGrayness 14.61 HE 53.85
No.33 6.69	L 42.73 a -3.48 b -9.39	V 0.91 C 0.88 M 0.84 Y 0.77	Grayness 87.50 ΔGrayness 12.50 HE 63.64	No.38 7.64	L 42.67 a -4.90 b -10.14	V 0.92 C 0.89 M 0.83 Y 0.76	Grayness 85.39 ΔGrayness 14.61 HE 53.85
No.34 6.87	L 42.55 a -3.81 b -9.40	V 0.92 C 0.88 M 0.84 Y 0.77	Grayness 87.50 ΔGrayness 12.50 HE 63.64	No.39 8.13	L 42.66 a -4.82 b -10.53	V 0.92 C 0.90 M 0.83 Y 0.76	Grayness 84.44 ΔGrayness 15.56 HE 50.00
No.35 7.11	L 42.83 a -4.40 b -9.59	V 0.91 C 0.88 M 0.83 Y 0.77	Grayness 87.50 ΔGrayness 12.50 HE 54.55	No.40 8.33	L 42.66 a -5.99 b -10.14	V 0.92 C 0.91 M 0.83 Y 0.76	Grayness 83.52 ΔGrayness 16.48 HE 46.67
No.36 7.26	L 42.57 a -4.57 b -9.57	V 0.92 C 0.89 M 0.84 Y 0.77	Grayness 86.52 ΔGrayness 13.50 HE 58.33				

Appendix B

Raw Data for Controlled Grayness Variation (CGV):

ΔE^*_{ab}	L*a*b*	Densities	Grayness Hue Error	ΔE^*_{ab}	L*a*b*	Densities	Grayness Hue Error
Standard	L 45.61 a -1.75 b -3.61	V 0.84 C 0.78 M 0.78 Y 0.78	Grayness 100 ΔGrayness 0 HE 100	No.8 10.53	L 40.23 a 6.53 b -7.27	V 0.95 C 0.83 M 0.94 Y 0.85	Grayness 88.29 ΔGrayness 11.71 HE 18.18
No.1 2.23	L 45.01 a -0.28 b -5.18	V 0.85 C 0.79 M 0.80 Y 0.77	Grayness 96.25 ΔGrayness 3.75 HE 66.67	No.9 11.57	L 39.52 a 7.13 b -7.85	V 0.96 C 0.84 M 0.96 Y 0.86	Grayness 87.50 ΔGrayness 12.50 HE 16.67
No.2 3.28	L 44.58 a -0.93 b -6.61	V 0.86 C 0.80 M 0.81 Y 0.77	Grayness 95.06 ΔGrayness 4.94 HE 75.00	No.10 12.55	L 39.57 a 8.76 b -6.86	V 0.96 C 0.82 M 0.97 Y 0.87	Grayness 84.54 ΔGrayness 15.46 HE 33.33
No.3 4.51	L 44.58 a 1.26 b -6.57	V 0.87 C 0.79 M 0.83 Y 0.78	Grayness 93.98 ΔGrayness 6.02 HE 20.00	No.11 13.76	L 38.31 a 9.36 b -7.15	V 0.98 C 0.85 M 1.01 Y 0.90	Grayness 84.16 ΔGrayness 15.84 HE 31.25
No.4 5.21	L 43.00 a 0.52 b -7.50	V 0.90 C 0.83 M 0.85 Y 0.79	Grayness 92.94 ΔGrayness 7.06 HE 66.67	No.12 14.61	L 38.40 a 10.24 b -7.98	V 0.98 C 0.84 M 1.01 Y 0.89	Grayness 83.17 ΔGrayness 16.83 HE 29.41
No.5 6.87	L 41.92 a 2.14 b -7.90	V 0.92 C 0.83 M 0.88 Y 0.81	Grayness 92.05 ΔGrayness 7.95 HE 28.57	No.13 15.17	L 37.70 a 10.38 b -8.12	V 1.00 C 0.85 M 1.03 Y 0.90	Grayness 82.52 ΔGrayness 17.48 HE 27.78
No.6 7.85	L 41.21 a 2.66 b -8.38	V 0.93 C 0.85 M 0.90 Y 0.82	Grayness 91.11 ΔGrayness 8.89 HE 37.50	No.14 16.16	L 37.57 a 11.49 b -8.20	V 1.00 C 0.85 M 1.04 Y 0.90	Grayness 81.73 ΔGrayness 18.27 HE 26.32
No.7 9.13	L 41.69 a 5.17 b -8.11	V 0.92 C 0.81 M 0.90 Y 0.81	Grayness 90.00 ΔGrayness 10.00 HE 0	No.15 17.33	L 36.18 a 12.04 b -8.19	V 1.03 C 0.87 M 1.08 Y 0.94	Grayness 80.56 ΔGrayness 19.44 HE 33.33