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The relationship between white ink coating weight and color fidelity when blocking chromatic contents in compostable flexible packaging

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Abstract

As leaders in the consumer goods industry embrace compostable flexible packaging, the challenge lies in maintaining the fidelity of the design colors printed on it. When printing transparent flexible substrates, a white ink underlayer is necessary to reproduce saturated colors. Nevertheless, to comply with American and European compostability standards, white ink coating weight (Ctg Wt) cannot exceed 1 % of the total weight of the package, a limitation that restricts the amount of white ink used in reverse printed compostable packaging to as little as 25 % of the Ctg Wt used today. The objective of this study is to investigate the influence of background color, design color, and Ctg Wt on resulting design color deviations (ΔE_{00}). A supermarket survey was conducted to identify problematic design and background colors used in retail packages. The supermarket survey confirmed that maintaining the fidelity of design colors on reverse printed flexible packages is a problem, even for packages using today's standard Ctg Wt. The survey identified 91 collation packages where design color fidelity was compromised by the background color. For these packages, blue (in 40 % of the packages), black (in 34 %), and red/brown (in 14 %) were the most commonly encountered background colors. The most commonly compromised design colors were white (41 %), yellow (15 %), green (11 %), orange (11 %), and red (9 %). To analyze the influence of background color, design color, and Ctg Wt on design color deviations (ΔE_{00}), a designed experiment (DOE) was conducted. The DOE explored the relationship between design color deviations and six levels of background color, six levels of design color, and two levels of Ctg Wt. The DOE showed that all three main effects (background color, design color, Ctg Wt) are significant at the .001 level. The DOE also showed that all of the interactions (three two-way interactions and one three-way interaction) are significant at the 0.05 level. After adjusting for the number of degrees of freedom, Ctg Wt had the most pronounced influence on design color deviations (ΔE_{00}), followed by design color, and, more distantly, by the background. The strongest interaction was shown to be design color cross background color. Finally, the psychophysical causes of this interaction were identified for several design color cross background color pairs (e.g. yellow design color cross bright red background color).

Keywords: white ink underlayer, ΔE_{00}, rotogravure, design color, background color, chromatic backing, supermarket survey

1. Introduction

Compostable packaging has been embraced by brand owners as a way to make their packages more environmentally friendly (Cahillane, 2018; Parker, 2020; Furneaux, 2006). Standards for compostable packaging (ASTM, 2021; European Committee for Standardization, 2000) limit the amount of white ink to less than 1 % of the total weight of the package. In these packages white ink is required to achieve acceptable chromaticity (Flexographic Technical Association, 2020). Today, the weight of the white ink layer (1.95 g/m² in a typical package) exceeds 1 % of the total package weight in many applications. For example, the weight of the white ink layer in a widely used flexible package structure (18 µm oriented polypropylene film / ink / adhesive / 30 µm sealant film) is 3.9 % of the total package weight (1.95 g/m^2 white ink weight divided by 50 g/m^2 total package weight).

This research investigates ways to reduce white ink coating weight while maintaining acceptable color fidelity. It studies the relationship between the amount of white ink used in a flexible package and the fidelity of its design colors. A previous paper (Eller and D'Amico, 2022) investigated the impact of reducing white ink Ctg Wt when blocking a black background. While black backgrounds are found in commercial packaging, a supermarket survey (described below) revealed a variety of other background colors that resulted in visible color shifts. The objective of this research is to investigate the relationship between Ctg Wt and the fidelity of design colors when blocking chromatic background colors.

2. Methods

Figure 1 summarizes the methodology used to answer the research question: "What is the relationship between Ctg Wt and the fidelity of design colors when blocking chromatic background colors?"

A supermarket package survey was first conducted to identify potential critical background colors responsible for design color deviations in today's packaging. This information was used to select the problematic design colors to be investi- gated in a color fidelity experiment. Next, a designed experiment was conducted to 1) assess the color deviations observed in a variety of simu- lated packages, and 2) identify the main effects and interactions responsible for this deviation. Finally, observed color differences were assessed to deter-mine which simulated packages are acceptable, and which packages would be rejected due to lack of color fidelity.

2.1 Supermarket Package Survey

The population of reverse printed flexible packages (including reverse printed labels) was sampled by surveying the food and toy departments of Walmart, Wegmans and Costco (all USA). These retailers were chosen because they represent three facets of the retail market. Walmart is the largest retailer in the United States (Johnson, 2023), Wegmans is a high-end grocery retailer found in many states of the USA (Wegmans, 2023), and Costco is a large low-cost retailer selling bulk products to consumers using a membership model (Costco, 2023). The supermarket package survey was conducted during the period from September 2022 through February 2023. The survey was limited to stores in the Rochester, N.Y. area. Packages were identified wherethe fidelity of a design color was compromisedby the presence of the background color during the survey. For each compromised design color, the hues (e.g. red, green, yellow, etc.) of the color pair (design color and background color) were collected. The background colors in this sample were identi-fied as "problematic background colors" because they were strong enough to contaminate the design color despite the presence of a typical (~2 g/m^2) white ink layer. Finally, the most frequently encountered problematic background colors were chosen for further study.

2.2 Measuring the CIELAB values of problematic background colors on actual packages

To select CIELAB values for the background colors used in the color fidelity experiment, packages representing the most commonly encountered problematic background colors were purchased. The color of each package was measured using a TECHKON SpectroDens spectrodensitometer, and the CIELAB values of these colors were used to define the background colors used in the experiment. All measurements were made using the following conditions: D50 illuminant, 2° viewing angle, M1 mode (D50), white background.

2.3 Color Fidelity Experiment

To answer the question, "What is the relationship between Ctg Wt and the fidelity of design colors when blocking a problematic background color?", a designed experiment was conducted. The experiment assessed the influence of Ctg Wt (two levels), background color (six levels), and design color (six levels) on the fidelity of the measured design color. The methodology

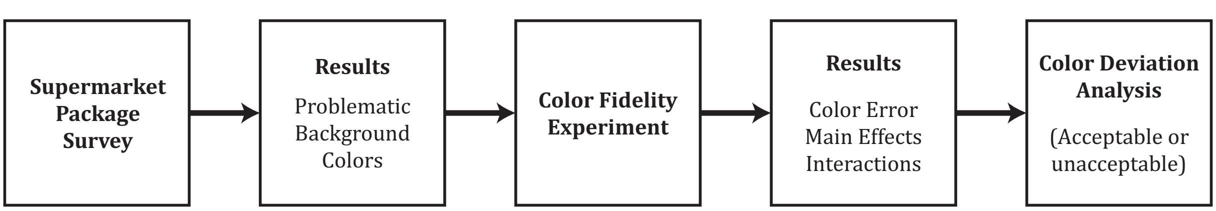

Figure 1: Methodology used to answer the research question

used by Eller and D'Amico in their earlier paper was adopted (Eller and D'Amico, 2022). The primary difference between the methodology used by Eller and D'Amico and the methodology used in this paper is that the black background color was replaced by chromatic background colors in the present research. Highlights of the methodology are repeated for the convenience of the reader.

2.4 Materials

Solvent-based gravure inks provided by Flint Group were used in the experiment. The inks were formulated to have a viscosity of 15 cP (±2 cP) at 25º C before printing. Test swatches of each ink were printed on 19 µm clear oriented polypropylene (OPP) (>97 % transparency). Inks and films used in the experiment are summarized in Table 1.

White ink samples were printed on 19 µm OPP film using a commercial gravure press and cylinders engraved to apply nominal weights of 1.95 g/m^2, 0.98 g/m^2, and 0.49 g/m^2. Coating weights were chosen to represent full-thickness, half-thickness and quarter-thickness prints of a typical white underlayer used in commercial packaging today.

2.4.1 Data generation

Figure 2 shows the research problem. A consumer views a collation package (clear film / design color / white ink) with single packs of product inside it. In this situation, the white ink layer is supposed to prevent the background color of the single packs from contaminating the design color printed on the collation pack. The most demanding test of the white ink's blocking power occurs when the collation package touches the single pack.

Figure 3 shows the sandwich structure used to simulate the research problem in the experiment. The left side of Figure 3 (a) shows the individual components of this structure:

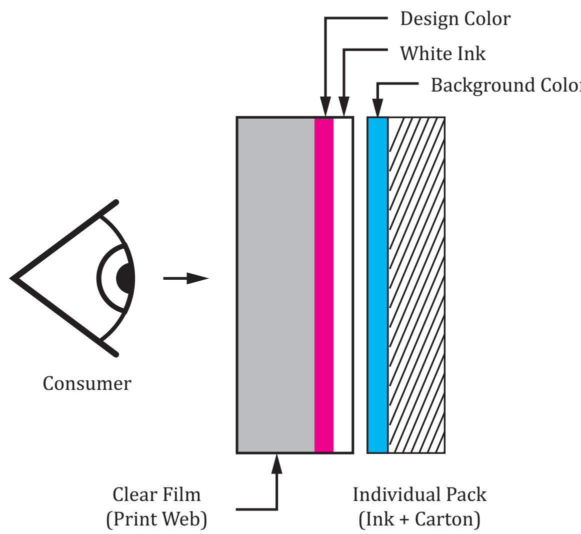

Figure 2: Consumer viewing an individual product pack inside a collation package

1) a swatch of clear film printed with a design color,

2) a swatch of clear film printed with a layer of white ink, and

3) a swatch of GMG high gloss proofing paper printed with a background color.

The right side of Figure 3 (b) shows the assembled sandwich (simulating the structure in the research problem) being measured on sheet of white backing using a Techkon SpectroDens spectrophotometer.

All color measurements were collected using the same measurement conditions as for actual pack- ages: D50 illuminant, 2° viewing angle, M1 (D50), white backing. The CIELAB value for a sandwich structure was calculated by sampling thestructure using a 3x3 grid of measurement points,and averaging these measurements to obtain a singleCIELAB triplet-value for the structure.

Table 1: Inks and films used in the experiment

Inks			Films	
Ink Color	**Supplier**	**Grade**	**Film Type**	**Supplier**
Cyan	Flint Group[1]	XCEL GS CF Blue	19 µm OPP	Tagleef Inc.[2]
Magenta	Flint Group[1]	2.2234R37CRLA2027 Bon Rubine		
Yellow	Flint Group[1]	PluriBase V1 HS NC Yellow		
Black	Flint Group[1]	PluriBase Black		
Orange	Flint Group[1]	PluriStar RTV 37078 Orange		
Violet	Flint Group[1]	XCEL Carb Violet		

[1] Flint Group, Anniston, Al, USA (Flint Group, 2022)

[2] Tagleef Industries, Newark, DE, USA (Tagleef Industries, 2022)

Color fidelity was defined as the color difference (ΔE_{00}) between the measured CIELAB values of two test samples. The first sample represented today's packaging (using a 1.95 g/m^2 Ctg Wt). The second sample represented a package incorporating a reduced white ink Ctg Wt (either 0.49 or 0.98 g/m^2). The difference between the CIELAB values of these samples represented the color deviation introduced by reducing the white ink Ctg Wt.

3. Results and Discussion

The supermarket package survey was conducted and analyzed as described in Section 2.1 prior to the color fidelity experiment. Thus, the results of the survey are described first, followed by the results of the Experiment.

3.1 Packages with problematic background colors

During the survey, thousands of flexible pack-ages in the food and toy departments of the target retailers (Walmart, Wegmans, and Costco) were examined. From this sample, packages where the background color compromised fidelity of the design colors were identified. In total, 111 packages with problematic background colors were identified. This total was further divided into packages where the source of the background color was an individual pack in a multipack wrapper (a collation pack), and packages where the source was the product being packaged. Collation packs dominated the population, accounting for 91 of the 111 packs identified.

As described in section 2, the study focused exclusively on collation packs. The background colors in the reduced database were grouped by hue.

Table 2 shows the number of collation packs in each hue group. The final column shows the percentage of problematic collation packs associated with each hue group.

3.2 Hues of problematic design colors

Table 3 summarizes hues of the design colors found in the sample of collation packages. The design colors used in the experiment (cyan, magenta, yellow, orange, and violet) were chosen because they represent inks used in extended gamut printing. In addition, white was treated as a design color. White data was collected by simulating the way design white is printed in the packages under study (i.e. by measuring a white underlayer through a clear film).

Compared to Table 3, in the experiment cyan (a greenish blue) stands in for the blue and green, magenta (a bluish red) stands in for red and pink, yellow represents yellow, orange represents orange, violet represents purple, and white represents white.

Table 2: Hues of problematic background colors encountered in the supermarket survey

Background	Count	Percent
Blue	40	43.96 %
Black	31	34.07 %
Red	7	7.69 %
Brown	6	6.59 %
Green	5	5.49 %
Yellow	1	1.10 %
Orange	1	1.10 %
Total	91	100.00 %

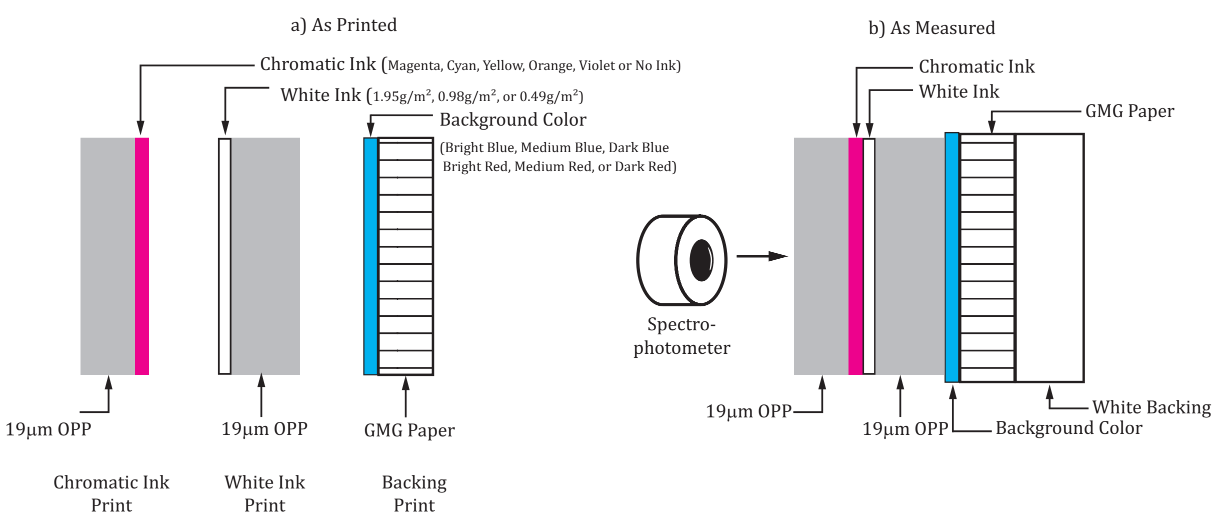

Figure 3: Test samples as printed (a) and as assembled for measurement (b)

Table 3: Hues of problematic background colors encountered in the supermarket survey

Design color	Count	Percent
White	37	40.66 %
Yellow	14	15.38 %
Green	10	10.99 %
Orange	10	10.99 %
Red	8	8.79 %
Pink	5	5.49 %
Purple	2	2.20 %
Blue	1	1.10 %
Cream	1	1.10 %
Black	1	1.10 %
Grey	1	1.10 %
Silver	1	1.10 %
Total	91	100.00 %

3.3 Background color CIELAB values used in the color fidelity experiment

As previously discussed, the focus was on the blue and red/brown hue sectors. Samples of packages in these sectors were purchased and measured. The L^*-values of the blue samples ranged from 17 (for dark blues) to 46 (for bright blues). Similarly, the L^*–values of the red/brown samples ranged from 15 (for browns = dark reds) to 47 (for bright reds). As a result, each hue sector was divided into bright, medium, and dark colors. Table 4 summarizes the range of CIELAB values for the bright, medium, and dark colors in each sector. CIELAB targets were selected for the background colors used in the experiment based on this data. While the survey contained packages with bright red and brown background colors, packages containing medium red backgrounds were absent. Nevertheless, a medium red was required for the color fidelity experiment, so a CIELAB value halfway between the bright red and brown was chosen to represent medium red. Finally, backing sheets matching the CIELAB target colors shown in Table 4 were printed.

The sheets were printed on an Epson SureColor P5000 inkjet printer using Epson inks, GMG High Gloss 250 paper, and Esko proofing software. After drying, the printed sheets were measured for color conformance and spatial uniformity. All measurements were within 1 ΔE_{00} of the target CIELAB value.

3.4 Color Fidelity Experiment

The experiment was conducted in accordance with the methodology described in Section 2.3. Two replicates of 72 individual treatments (design color / Ctg Wt / background color) were assembled and measured. The resulting CIELAB values were used to calculate color deviations (ΔE_{00}). This effort resulted in 144 datapoints, which were analyzed as a full factorial Design of Experiment (DOE). Analysis of Variance (ANOVA), main effect plots, and interaction plots were used to analyze the results of the experiment as being discussed in the following sections.

3.4.1 Analysis of variance (ANOVA)

Analysis of variance was used to assess the statistical significance of the relationships between sources of variation (design color, background color, and Ctg Wt, together with their interactions) and the response variable (ΔE_{00}). Table 5 presents the results of the analysis of variance.

Throughout the experiment, sources of random variation were minimized. The success of this effort is evident as less than 1.5 % of the total variation can be attributed to random error. As the ANOVA table shows, the primary sources of observed variation are white ink Ctg Wt and design color. Nevertheless, the probabilities of obtaining the observed results through random chance were all between 0.000 and 0.023, indicating the main effects and all interactions are significant at the 0.05 level. The P-values of 0.000 should be interpreted as meaning that the probability of obtaining the observed results through random chance is >0 but <0.0005.

Table 4: Background colors selected for the color fidelity experiment

Background Color	Retail Example	CIELAB Range						CIELAB Target		
		L^* Range		a^* Range		b^* Range		L^*	a^*	b^*
Bright Blue	Great Value	34	46	-3	-7	-40	-55	37	-4	-50
Medium Blue	Snapple	22	34	-5	16	-42	-53	31	8	-49
Dark Blue	Welch’s	16	17	13	14	-31	-32	17	13	-31
Bright Red	Skittles	39	48	63	68	33	41	45	63	38
Medium Red	Required for DOE	n/a	n/a	n/a	n/a	n/a	n/a	29	42	25
Brown	Hershey	15	16	20	23	7	13	16	22	11

3.4.2 Main effects plots

Main effects plots display the relative impact of each factor. Figure 4 shows the impact of background color, design color, and white ink Ctg Wt on color deviations (ΔE_{00}). design color has the largest range of ΔE_{00} values, white ink Ctg Wt has the next largest, and background color has the smallest.

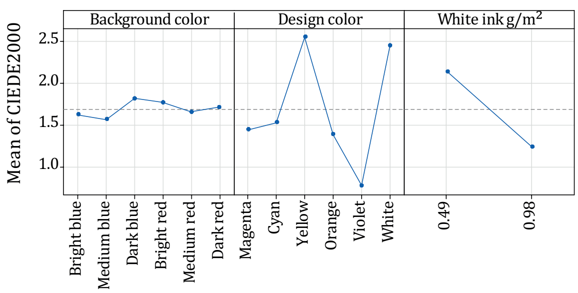

Figure 4: Main effects plot for ΔE_{00} vs background color, design color, and white ink Ctg Wt

The relative contribution of each factor to color deviation was determined by dividing the observed ranges by the number of degrees of freedom associated with each factor. Using this metric, white ink Ctg Wt has the largest impact (0.9 ΔE_{00}/DF), design color has the next largest (0.36 ΔE_{00}/DF), and background color has the least impact (0.05 ΔE_{00}/DF). This is consistent with the results obtained by Eller and D'Amico (2022).

3.4.3 Interaction plots

Interactions between factors are present when the observed response (ΔE_{00} in this experiment) differs significantly from the sum of the effects of the individual factors. In this experiment, an ANOVA demonstrated that observed differences are significant at the 0.05 level for all interactions. Interaction plots show these differences graphically. In this experiment, there are three possible 2-way interactions: 1) design color deviation cross white ink Ctg Wt, 2) background color cross white ink Ctg Wt, and 3) design color cross background color. Figures 5 through 8 show where interacting factors contribute to the significance of the associated interaction.

Figure 5 is a plot of the design color cross white ink Ctg Wt interaction when no interactions are present. The starting point for creating this plot is the design color main effect plot. There are two interaction lines, one depicting the interaction between the design colors and the low level of white ink Ctg Wt (0.49 g/m^2), and another depicting the interaction between the design colors and the high level of white ink Ctg Wt (0.98 g/m^2). Both lines mirror the shape of design color main effect plot. The gap between the lines is constant and equal to 0.90 ΔE_{00} (the difference between the 0.49 g/m^2 and 0.98 g/m^2 on the white ink Ctg Wt main effects plot).

Figure 6 is compares the "no interaction" case shown in Figure 5 to the actual design color cross white ink Ctg Wt interaction observed in the experiment. Three

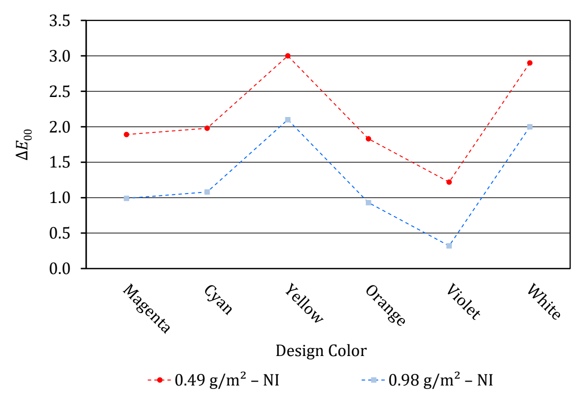

Figure 5: Interaction plot for design color cross white ink Ctg Wt when no interaction is present

Table 5: Analysis of variance for ΔE_{00} vs background color, design color, and white ink Ctg Wt

Source	**DF**	**Adj SS**	**Adj MS**	***F*-Value**	***P*-value**
Model	71	96.94	1.37	70.06	0.000
Linear	11	86.67	7.88	404.29	0.000
Background color	5	1.06	0.21	10.86	0.000
Design color	5	56.41	11.28	578.95	0.000
White ink Ctg Wt	1	29.20	29.20	1498.19	0.000
2-Way Interactions	35	9.29	0.27	13.63	0.000
Background color × Design color	25	5.44	0.22	11.16	0.000
Background color × White ink Ctg Wt	5	0.27	0.05	2.79	0.023
Design color × White ink Ctg Wt	5	3.59	0.72	36.82	0.000
3-Way interactions	25	0.97	0.04	2.00	0.012
Background × Design × White ink	25	0.97	0.04	2.00	0.012
Error	72	1.40	0.02		
Total	143	98.34			

design colors (white, yellow, and violet) stand out as being major contributors to the significance of this interaction. White and yellow have difficulty blocking background colors and exhibit larger than expected gaps (1.29 ΔE_{00} for yellow and 1.32 ΔE_{00} for white versus 0.90 ΔE_{00} when no interaction is present). Violet, on the other hand, obscures the background colors and, exhibits a smaller than expected gap (0.47 ΔE_{00} versus 0.90 ΔE_{00}).

Figure 7 is a plot of the background color cross white ink Ctg Wt interaction. Compared to Figure 6, this plot indicates a weaker interaction (four background colors show almost no difference in gap size and the remaining two gaps are small).

Figure 8 is a plot of the design color cross background color interaction when no interactions are present. Each line represents one design color. The lines all mirror the shape of the background color main effect plot. The lines are parallel but the gaps vary in size (yellow and white are subject to large color deviations, cyan, magenta, and orange are subject to medium size color deviations, and violet is subject to small color deviations).

Figure 9 compares the actual design color cross background color interactions to the "no interaction" case shown in Figure 8. All six design colors show large differences when compared the "no interaction" lines, indicating the presence of a strong interaction. There are clear psychophysical reasons for several of these differences. In the case of yellow, for example, color deviations (ΔE_{00}) jumps when blue background colors are replaced by red ones. Blue background colors have only one effect on color deviations: they reduce the chromaticity of yellow (making it appear "dirty" and less colorful). Red background colors, on the other hand, have two effects. They reduce chromaticity and produce a large hue shift (yellow + red = orange).

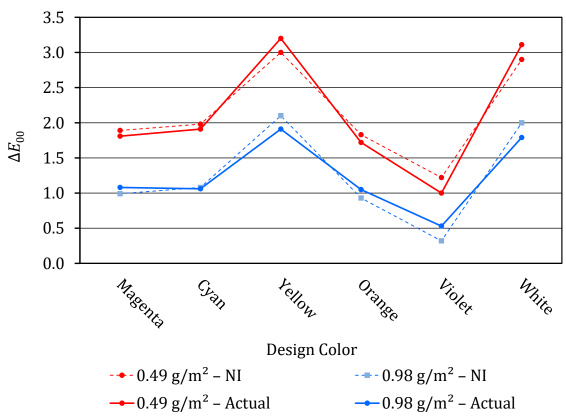

Figure 6: Interaction plot comparing the actual design color cross white ink Ctg Wt interaction (as observed in the experiment) to the "no interaction" case

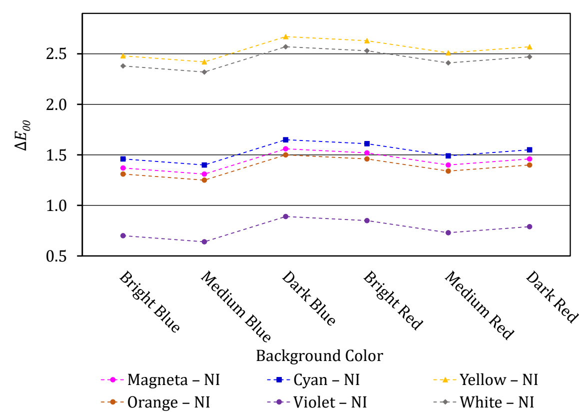

Figure 8: Interaction plot for design color cross background color when no interaction is present

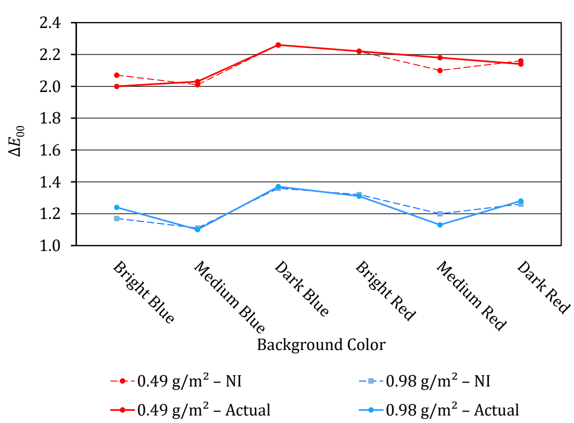

Figure 7: Interaction plot comparing the actual background color cross white Ctg Wt interaction to the appearance of the plot when no interaction is present

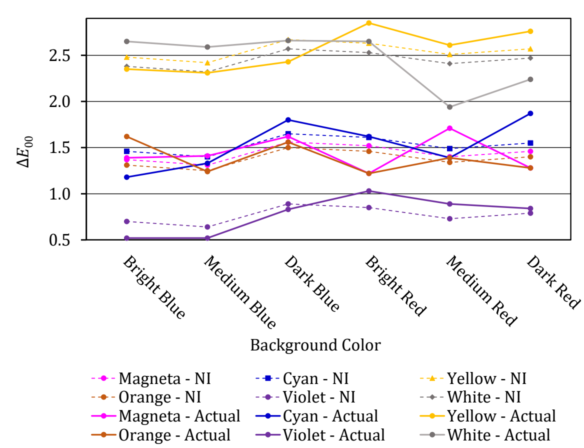

Figure 9: Interaction plot comparing the actual background color x design color interactions to the appearance of the plot when no interaction is present

Because, the human visual system is more sensitive to differences in hue than chroma (Habekost, 2013), the presence of this hue shift accounts for the jump in color deviation.

3.5 Total color deviation – using a limited white ink budget

In the packaging and labels industry, brand owners typically required printed colors to match their targets within a tolerance of 2 ΔE_{00} (Labels and Labeling, 2018). Thus, total color deviation is the metric that determines if a color match is acceptable or unacceptable. Figures 10–15 show the color deviation resulting from each design color / Ctg Wt / background color combination explored in the color fidelity experiment. When interpreting these figures, it is important to realize that total color deviation is the sum of color deviation due to the conditions explored in the experiment plus color deviation due to press repeatability. An extensive search of the literature identified sources listing maximum acceptable repeatability on press (e.g. Martin (2015) states that 4 ΔE_{00} is the upper threshold for acceptable machine repeatability), but failed to identify a source stating typical press repeatability in packaging. Based on the researcher's 30 years of industry experience, 1.0 ΔE_{00} repeatability represents excellent performance for a packaging printing press. Thus, an experimental result of <1.0 ΔE_{00} is acceptable, results between 1.0 ΔE_{00} and 2.0 ΔE_{00} will likely result in some rejects for color deviations, and results >2.0 ΔE_{00} are unacceptable.

Figure 10 shows color deviations for design colors measured on a bright blue background. The black bar shows the color deviations associated with today's standard white ink Ctg Wt (1.95 g/m^2). This is always 0.0 ΔE_{00} since today's Ctg Wt is the standard against which reduced Ctg Wts were judged. The lighter bright blue bars represent the color deviation associated with reducing white ink Ctg Wt by 50 % (to 0.98 g/m^2). The darker bright blue bars show color deviations when white ink Ctg Wt was reduced by 75 % (to 0.49 g/m^2). Lighter colors (yellow, orange, and white) will experience rejects for color deviations when white ink Ctg Wt is cut in half. When white ink Ctg Wt is cut by 75 %, color deviations for yellow and white are unsatisfactory. The remaining colors, with the exception of violet, will all experience some rejects for color deviations.

Figure 11 shows color deviations associated with medium blue backgrounds. Result mirror Figure 10, with the exception that the orange / 50 % reduced white ink combination is acceptable.

Color deviations on dark blue backgrounds are presented in Figure 12. Notice that the reduced L^* of this background color makes it harder to hide. Now a 50 % reduction in white ink Ctg Wt will result in some rejects for all colors except violet. When white ink Ctg Wt is reduced by 75 %, all colors (including violet) will experience some rejects, and cyan is added to the list of colors with unsatisfactory performance.

Figure 13 shows color deviations associated on bright red backgrounds. Reducing white ink Ctg Wt by 50 % results in unacceptable results for yellow and white. Reducing white ink Ctg Wt by 75 % results in unacceptable results for cyan, yellow, and white.

Figure 14 shows color deviations associated with medium red backgrounds. Results mirror bright red except for the facts that yellow and white are no longer unsatisfactory when white ink Ctg Wt is reduced by 50 %, and that magenta replaced cyan as the third color having an unacceptable deviation when white ink Ctg Wt is reduced by 75 %.

Figure 15 shows color deviations associated with dark red (brown) backgrounds. Results mirror the results

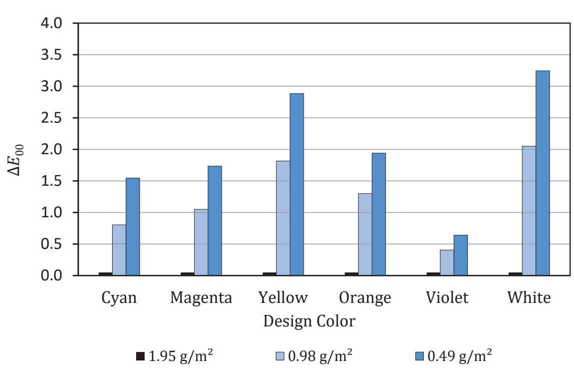

Figure 10: Design guide for bright blue background colors

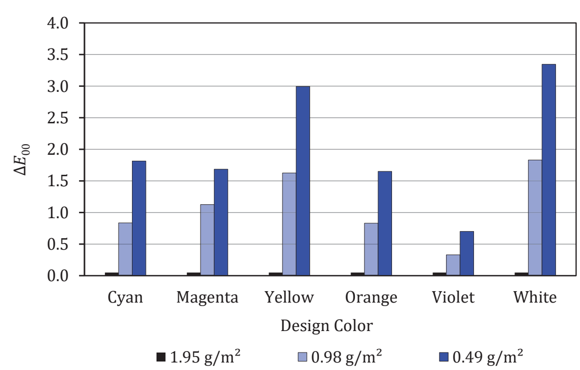

Figure 11: Design guide for medium blue background colors

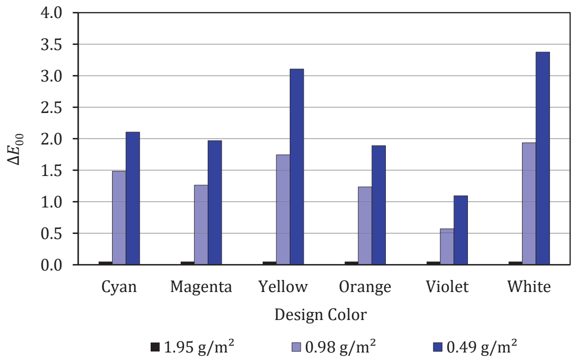

Figure 12: Design guide for dark blue background colors

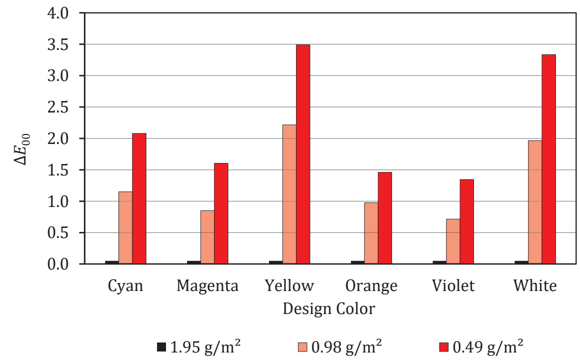

Figure 13: Design guide for bright red background colors

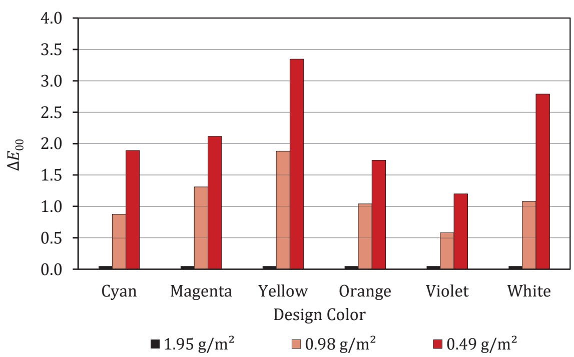

Figure 14: Design guide for medium red background colors

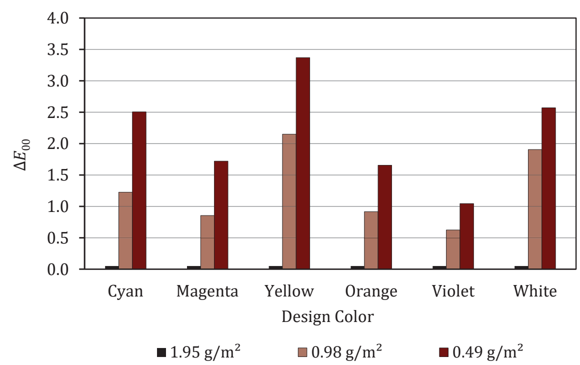

Figure 15: Design guide for dark red (brown) background colors

for bright red except that white with 50 % white ink reduction is no longer unacceptable.

For designers, these figures suggest a way to use a limited white ink budget more effectively. Instead of underlaying the entire design with a uniform coating of white ink, a designer has the option of applying heavier Ctg Wts under design colors where the background color will create large color deviation, and lighter Ctg Wts under colors where there is less risk of compromising color fidelity.

4. Conclusion

A supermarket package survey found that today's standard white ink coating weight occasionally fail to prevent background colors from contaminating design colors. Blue (40 %), black (34 %), and red/brown (14 %) are the most problematic background colors. A designed experiment investigating the effect of background color (six levels), design color (six levels), and white ink g/m^2 (two levels) on design color deviation (ΔE_{00}) found that white ink coating weight had the largest impact on color deviations. This conclusion is consistent with Eller and D'Amico (2022). background color cross design color and design color cross white ink coating weight showed the strongest interactions. An analysis of total color deviation resulting from the design color / coating weight / background color combinations explored in the color fidelity experiment showed that: 1) white and yellow were the most easily compromised design colors, 2) violet was most resistant, and 3) a 75 % reduction in white ink coating. weightresulted in completely or partially unacceptable color deviations for all design colors except violet.

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