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Color Studies Curriculum: Re-Envisioning Josef Albers' Interaction of Color in the Digital Age

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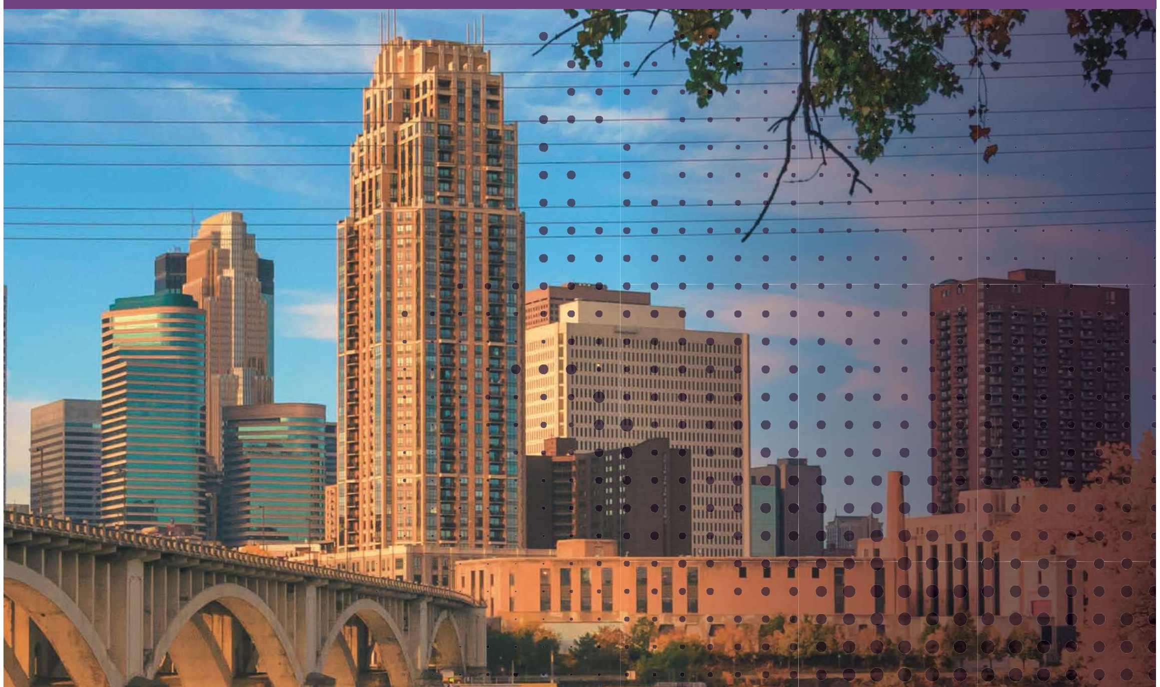

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Color Studies Curriculum: Re-Envisioning Josef Albers' Interaction of Color in the Digital Age

Yue (Julia) Cao and Bruce Leigh Myers, Ph.D.

Keywords: Josef Albers, simultaneous contrast, spectrophotometer, color studies, color management

Abstract

This study considers the possibility of using digital technologies to improve established color studies teaching methods, which are largely based on visual evaluation. Experiments utilized in this study are based on work outlined in Josef Albers' *Interaction of Color* (2009). Albers, a famous artist and art educator, has made significant contributions to the field of color studies. In this paper, the researchers conduct two experiments to assess the efficacy of two different approaches to Albers' traditional methods of color studies pedagogy by seeking to replicate examples from *Interaction of Color*.

In the first approach, modern ICC-profile-based color management tools are used with an inkjet printer to determine if two illustrations featured in *Interaction of Color* can be faithfully reproduced. In the second approach, color measurement technologies are used to ascertain if colorimetry can be useful in selecting optimal paper samples from a set of Color-aid papers, a collection of 314 screen printed papers especially utilized by students studying color in curricula prescribed by Albers.

The illustrations selected from I*nteraction of Color* for the study are based on the visual phenomena described as 'Two Colors as One' and 'One Color as Two'; these phenomena are otherwise termed 'simultaneous contrast' (e.g.: Long, 2015; Fairchild, 2005, Berns, 2000).

The results of this study reveal limitations of these digital methods as compared to visual evaluation when replicating the visual effects of illustrations from *Interaction of Color* and provide insights that may enhance future curricula in color study fields.

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Introduction and Background

For decades, art educators teaching color studies have utilized the pedagogy pioneered by Josef Albers, which is articulated and illustrated in his landmark treatise *Interaction of Color*. The first version of Interaction of Color was published in 1963 by Yale University Press, and included screen-printed, precisely produced color reproductions of Albers' work. The edition featured impressive color reproductions replicating many of the color phenomena as Albers had originally conceived for teaching. Rare booksellers now advertise these original volumes for thousands of dollars. In 1971, an inexpensive, mass-produced version of *Interaction of Color* became widely available; these do not feature the precise color reproduction of the 1963 volume. Nonetheless, this mass-produced edition, retailing for under $20, has sold over 250,000 copies ("*Interaction of Color*," 2019). This edition is extensively used by students and educators in color studies courses. In 2009, Yale University Press re-published a carefully produced edition of the 1963 edition of *Interaction of Color* to the original 1963 standards: these sell for approximately $250 and are endorsed by the Josef and Anni Albers Foundation. This 2009 volume, otherwise known as *Interaction of Color: New Complete Edition*, offers a relatively affordable, finely reproduced version of *Interaction of Color*.

In color studies classes based on Albers' curricula, students are typically shown examples of the relative nature of color, and then asked to reproduce the phenomena using colored papers. Students are asked to use visual analysis to compare and select the papers that would best replicate the respective effect. Despite color measurement devices and software products now being widely available, a review of the relevant literature revealed no studies that utilized colorimetry or a color-managed workflow to explore other methods to approach color studies curricula. The present study proposes bringing these exercises into the digital and color measurement age; the objective is to quantify select exercises and determine the efficacy color-managed workflow and color measurement technologies in this context.

Critical to the framing of the present study is the recognition that in Albers' curriculum, he recommends that students use color papers in their exercises, rather than paints or other media. According to Albers, color papers provide innumerable colors in a range of shades and tints ready for immediate use. The papers are therefore simple and efficient, making them highly practical and enabling students to compare neighboring and contrasting colors. Other reasons for using color papers are cited by Albers (2009):

- Color paper avoids the difficult, time-consuming, and tedious mixing of paints.
- Students sustain interest and save time and materials without discouraging failures from mixing or imperfectly matching of spoiled paints and papers.
- Color paper permits repeated use of precisely the same color without any slight change in tone, light, or surface quality.
- Working with color paper is simple, inexpensive, and orderly, mostly requiring adhesive and a razor blade; tools and equipment for handling paints are unnecessary.
- Texture, which often hides a poor conception, is avoided; students need not worry about brush marks and strokes, incalculable changes from wet to dry, or other circumstances.

In the late 1940s, Albers began using a specific commercially-available set of color papers in his classes, known as Color-aid brand papers (Horowitz, 2006). According to the Color-aid corporation website: “Since 1948 Color-aid Corp. has been manufacturing the Color-aid system of colored paper. Initially developed as a backdrop for photographers, Color-aid was soon thereafter discovered by Josef Albers and has since then become an indispensable teaching tool in art and design classes” (“Color-aid,” 2019). Today, Color-aid papers consist of 314 color papers sold in kits intended for color study.

Research Questions

This study sought to answer the following questions:

1. Can a color managed inkjet printer effectively recreate examples from *Interaction of Color* (2009)?
2. Can colorimetry be used to effectively select optimal Color-aid papers to recreate the visual effects illustrated in the new complete edition of Interaction of Color (2009)?

Materials

The materials utilized in the present study include the 2009 edition of *Interaction of Color*, Color-aid papers, color measurement hardware, software including Adobe Photoshop, standardized color viewing, a computer monitor display optimized for critical color evaluation, and an inkjet printer. In addition, knowledge of the criteria conducive to the visual phenomenon known as simultaneous contrast is a critical component of the present study, therefore it is listed and explained here.

1. *Interaction of Color: New Complete Edition* (2009). As previously indicated, this carefully produced edition offers faithful color reproduction of Albers' original work. For this study, two examples were selected: one illustrated "one color as two," in which the same color appears as two contingent upon the adjacent and surrounding colors, and "two colors as one," in which two different colors appear to be more similar due to the effect of adjacent and surrounding colors.

2. Color-aid Papers, a commercially available set of 314 color papers commonly used by students in color studies classes, and recommended by Albers himself (Horowitz, 2006).

3. Color Measurement Hardware including:
   a. X-Rite i1 Pro 2 Spectrophotometer
   b. X-Rite SpectroEye Spectrophotometer

4. Software
   a. X-Rite i1 Profiler (otherwise known as i1 Publish) for ICC-Profile based color management
   b. X-RiteColor Master QA Master II, a color database
   c. Adobe Photoshop
   d. Microsoft Excel

5. Standardized color viewing: A GTI Color Matcher Standardized Viewing Booth

6. Computer monitor display: color-managed NEC PA242 Monitor for soft proofing

7. Inkjet Printer: Epson SureColor P5000

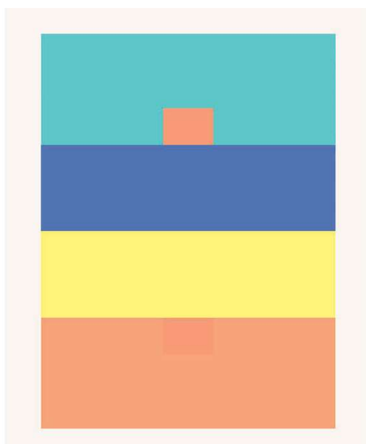
8. Knowledge about simultaneous contrast. Long (2015) defined simultaneous contrast as "[what] happens when a color is touching or, especially, is surrounded by another color. In this phenomenon, vision helps interpret and differentiate what is seen, by heightening or exaggerating the difference between colors, and the adjustments are made in hue, value, and chroma to both colors" (p. 47). In addition, Hoskin (2019), outlined the following criteria regarding simultaneous contrast:
   - Adjacent colors shift toward the complement of the other;
   - Mixed hues are more influenced than pure hues;
   - Dull colors change more easily than bright;
   - Light values are easier to change;
   - Strong contrast will create more extreme change (value); and
   - Less contrast results in less change.

Methods

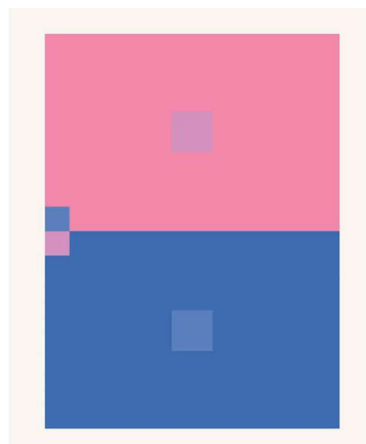
The first research question evaluates the ability of a color managed inkjet printer to effectively recreate examples from *Interaction of Color* (2009). The following steps were taken:

- Select and measure illustrations from Interaction of Color
- Recreate the illustrations using Adobe Photoshop
- Profile the inkjet printer
- Output the Photoshop illustrations on the color-managed inkjet printer
- Visually evaluate the results in standardized viewing condition
- Adjust and re-output the results if needed

An example illustrating "two colors as one" and an example illustrating "one color as two" were selected from *Interaction of Color* (2009), representations of these are illustrated in Figure 1.



'One Color as Two': Colors in small squares are the same but appear different because of their different backgrounds and other relative conditions.

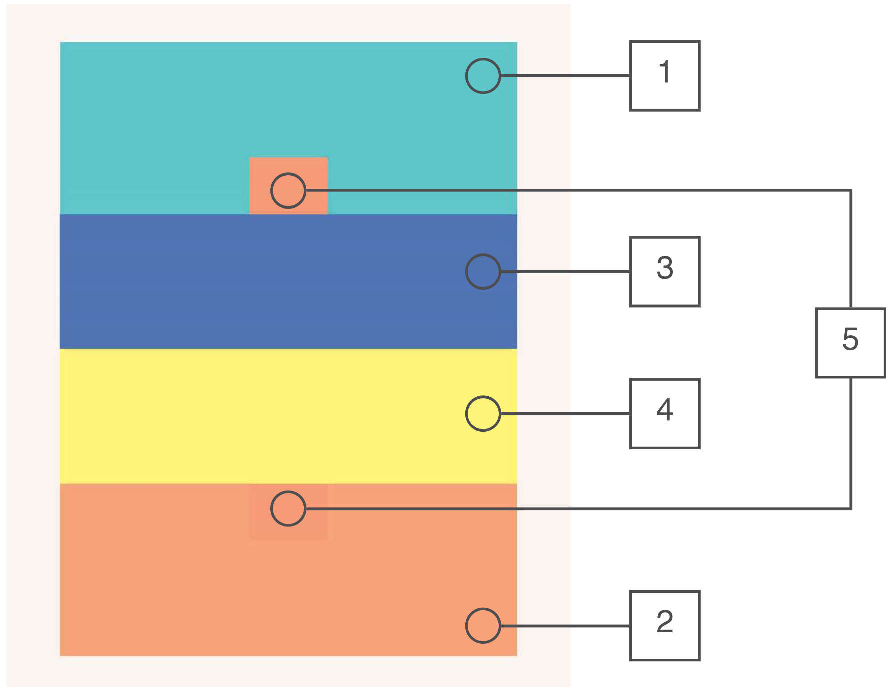


'Two Colors as One': Colors in small squares are different but appear similar because of their different backgrounds and other relative conditions.

Figure 1. *Illustrations from Interaction of Color (2009) used in the present study.*

Using the X-Rite SpectroEye, CIELAB colorimetric values at D50/2° were measured from the illustrations in *Interaction of Color* (2009) and the values were recorded.

The researcher measured the dimensions of elements which comprise the illustrations. Using Adobe Photoshop, wire frame outlines were created at the same size as the original illustrations, which were subsequently filled with colors at the same CIELAB values as were measured, as illustrated in Table 1.

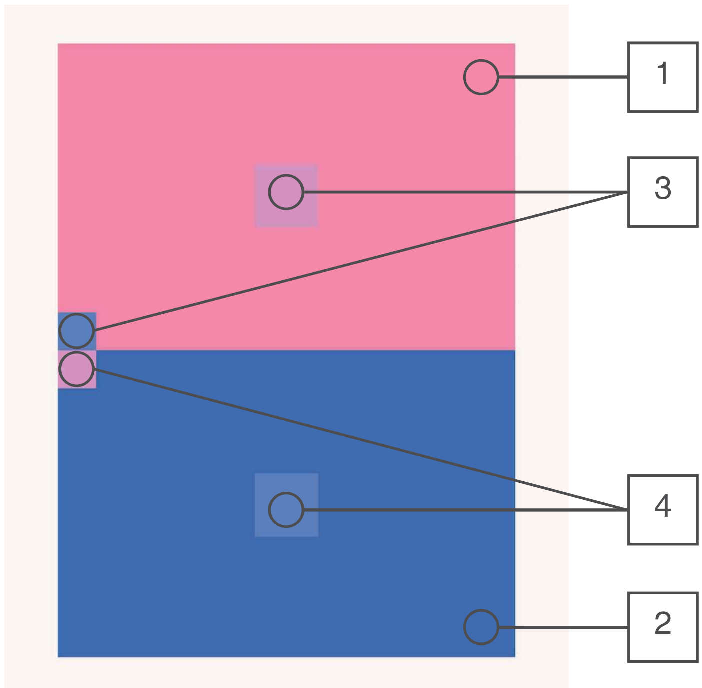


	L*	a*	b*	C*	h°
1.	64.67	-28.10	-14.13	31.45	206.69
2.	69.06	24.67	49.36	55.19	63.45
3.	40.31	6.77	-31.67	32.38	282.07
4.	90.78	-8.3	63.13	63.68	97.49
5.	63.29	15.54	29.37	33.22	62.14

Table 1. *Colorimetric Readings from Interaction of Color (2009)*

'One Color as Two': When separated by the highly chromatic, contrasting yellow and blue (#3 and #4), and placed against different backgrounds (#1 and #2), color #5 appears to be two different colors. Note that color #5 can be described as "mixed" and "achromatic."

‘Two Colors as One’



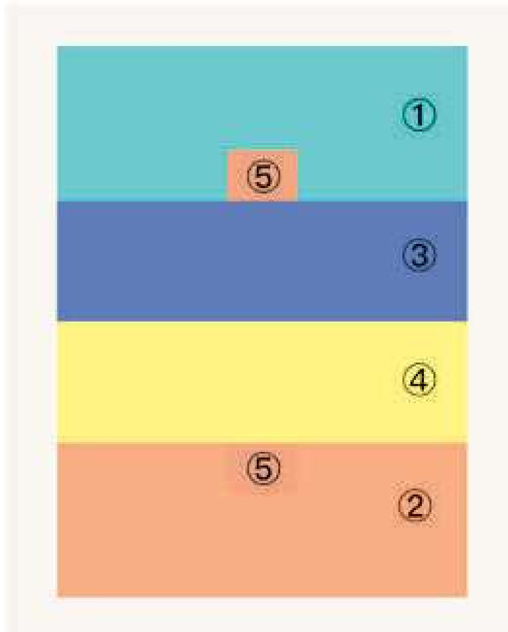
	L*	a*	b*	C*	h°
1.	67.87	36.79	2.00	36.85	3.12
2.	34.44	7.75	-29.48	30.48	284.73
3.	66.78	24.64	-6.97	25.60	344.21
4.	45.10	2.50	-27.24	27.34	275.23

‘Two Colors as One’: When looking at the middle of the illustration, the small squares (#3 and #4) appear similar. On the far left, these same colors are placed next to each other where the differences are more noticeable. Note that colors #3 and #4 can be described as “mixed” and “achromatic.”

A limitation is noted here: Adobe Photoshop is not intended to be used for precise colorimetric applications. CIELAB values in Photoshop are input in whole numbers only, whereas the SpectroEye reports colorimetric values in two decimal places. In addition, Photoshop does not support the selection of illumination and observer values.

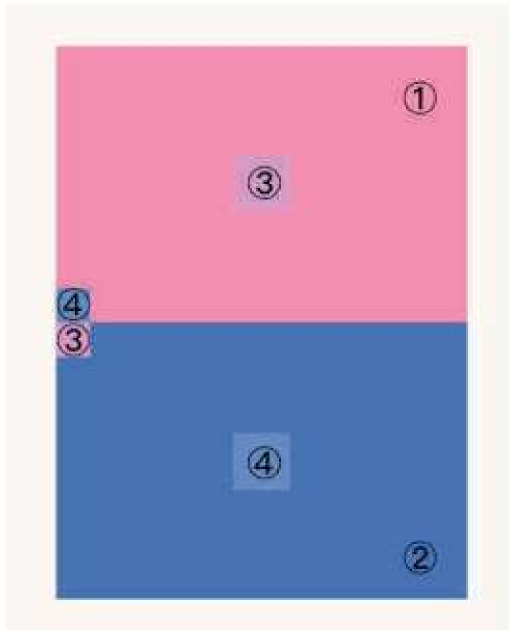
To profile the inkjet printer, a method described by Ashe (2014) was employed using the X-Rite i1 Profiler software and the i1 Pro 2 spectrophotometer. All of the output in the present study was completed using the printer driver only, as such, an RGB profile was built. While it is recognized that a Raster Image Processor (RIP) may have offered more accurate color management, the researchers chose to utilize lower-cost options as they will be more accessible in many classroom environments.

Once the Photoshop illustrations were output on the profiled inkjet printer and allowed to dry, they were evaluated in the standardized viewing condition. It was noted that some of the colors were visually good matches to the original from Interaction of Color (2009), while others exhibited more difference. As these examples represent a limited number of solid colors, the respective target CIELAB values in Photoshop were adjusted to obtain a better match. After two such iterations for each illustration, the results provided a good visual match to the originals. Colorimetric data from the resulting prints are compared to data from in Interaction of Color (2009) is reproduced in Tables 2 and 3.



Color			*Interaction of Color (2009)*		
	L*	a*	b*	C*	h°
1.	64.67	-28.10	-14.13	31.45	206.69
2.	69.06	24.67	49.36	55.19	63.45
3.	40.31	6.77	-31.67	32.38	282.07
4.	90.78	-8.3	63.13	63.68	97.49
5.	63.29	15.54	29.37	33.22	62.14
Color			Optimized Inkjet		
	L*	a*	b*	C*	h°
1.	63.35	-28.25	-15.99	32.47	209.51
2.	68.20	25.68	48.92	55.25	62.3
3.	39.05	0.53	-29.58	29.58	271.03
4.	88.14	-4.33	67.58	67.71	93.67
5.	62.48	15.38	29.02	32.84	62.08
Color			Difference		
	ΔL*	Δa*	Δb*	ΔC*	Δh°
1.	-1.23	0.15	-1.86	1.02	2.82
2.	-0.86	1.01	-0.44	0.06	-1.15
3.	-1.26	-6.24	2.09	-2.8	-11.04
4.	-2.64	3.97	4.45	4.03	-3.82
5.	-0.81	-0.16	-0.35	-0.38	-0.06

Table 2. *Colorimetric readings from 'One Color as Two' from Interaction of Color (2009)*



Color	Interaction of Color (2009)				
	L*	a*	b*	C*	h°
1.	67.87	36.79	2.00	36.85	3.12
2.	34.44	7.75	-29.48	30.48	284.73
3.	66.78	24.64	-6.97	25.60	344.21
4.	45.10	2.50	-27.24	27.34	275.23
Color	**Optimized Inkjet**				
	L*	a*	b*	C*	h°
1.	65.86	35.64	7.82	36.49	12.37
2.	33.81	7.45	-35.65	36.42	281.80
3.	66.79	24.78	-4.10	25.11	350.61
4.	44.36	5.13	-25.04	25.56	281.58
Color	**Difference**				
	ΔL*	Δa*	Δb*	ΔC*	Δh°
1.	2.01	1.15	5.82	0.36	9.25
2.	0.63	0.30	6.17	5.94	-2.93
3.	0.01	0.14	2.87	0.49	6.40
4.	0.74	2.63	2.20	1.78	6.35

Table 3. *Colorimetric readings from 'Two Colors as from Interaction of Color (2009)*

Turning to the second research question, which applies colorimetry to the selection of Color-aid papers, the same colorimetric target values from *Interaction of Color* (2009) as used for the first research question were employed. In addition, colorimetric values from each of the 314 Color-aid paper samples were measured with the X-Rite SpectroEye and input into the X-RiteColor Master QA Master II database. These values were also exported to Microsoft Excel for analysis.

Two strategies were employed to use the colorimetric values to select the optimum Color-aid papers. The first involves simply selecting the lowest ΔE_{00} Color-aid paper from the target colorimetric values for each color in the respective illustrations, this is referred to as the "lowest ΔE" method. The second method involves selecting "anchor color(s)" for each illustration from the Color-aid, and then selecting the other colors based on the colorimetric relationship of those "anchors" to the other colors, consistent with the colorimetric relationships in *Interaction of Color*. This is referred to as the "anchor color" method. Once the Color-aid papers were selected for each method, the colorimetric values of the respective Color-aid papers were input into the Photoshop wireframes, and the results were evaluated as soft proofs on the color managed NEC monitor.

Lowest ΔE_{00} Method

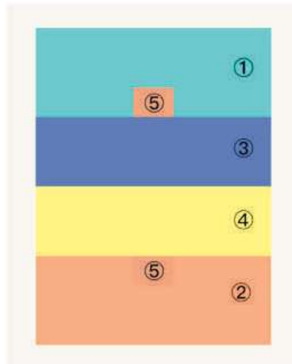
The general steps of the lowest ΔE_{00} method were as follows:

Step 1: Search the X-RiteColor Master QA Master II database for the lowest ΔE_{00} (i.e., the colorimetric values obtained from the illustrations in *Interaction of Color* (2009) were used to search for the closest Color-Aid in the Color Master database); in this instance, Color-aid papers within ten ΔE_{00} are reported;

Step 2: Add the obtained L*a*b* colorimetric values from the respective lowest ΔE_{00} Color-aid into Photoshop wireframes.

Step 3: Soft-proof and analyze results (i.e., calibrate NEC Monitor using i1 Profiler and i1 Pro 2, compare soft proof of Photoshop wireframes containing colorimetric values of selected Color-aid to those from the 2009 new complete edition of *Interaction of Color*).

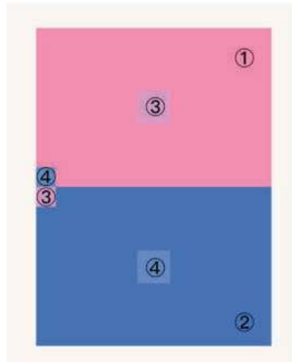
Data collected in this experiment appear in Tables 4 and 5



	IoC* Color #1	Color-aid BG-T3	Δ	C-T3 Color-aid	Δ	Color-aid	
L*	34.67	70.73	6.06	71.45	6.78		
a*	-28.1	-33.83	-5.73	-28.95	-0.85		
b*	-14.13	-14.61	-0.48	-19.81	-5.68		
C*	31.45	36.86	5.41	35.08	3.63		
h°	206.69	203.36	-3.33	214.38	7.69		
ΔE_{00}			5.43		6.21		
	Color #2	**O-P1-1**	**Δ**				
L*	69.06	70.36	1.3				
a*	24.67	26.77	2.1				
b*	49.36	50.74	1.38				
C*	55.19	57.37	2.18				
h°	63.45	62.18	-1.27				
ΔE_{00}			1.44				
	Color #3	**V-P1-1**	**Δ**	**B-P1-1**	**Δ**		
L*	40.31	42.37	2.06	42.16	1.85		
a*	6.77	8.51	1.74	-1.07	-7.84		
b*	-31.67	-26.08	5.59	-36.59	-4.92		
C*	32.38	27.44	-4.95	36.61	4.23		
h°	282.07	288.07	6	268.32	-13.75		
ΔE_{00}			4.84		8.10		
	Color #4	**YC-T1**	**Δ**	**Y-T1**	**Δ**		
L*	90.78	89.95	-0.83	89.55	-1.23		
a*	-8.3	-9.15	-0.85	-0.78	7.52		
b*	63.13	61.87	-1.26	65.9	2.77		
C*	63.68	62.54	-1.14	65.9	2.22		
h°	97.49	98.41	0.92	90.68	-6.81		
ΔE_{00}			0.86		4.81		
	Color #5	**O-P2-2**		**ROP22**		**YOP31**	
L*	63.29	65.49	2.17	62.59	-0.7	55.97	-7.32
a*	15.54	17.1	1.56	23.3	7.76	9.66	-5.88
b*	29.37	33.35	3.98	25.57	-3.8	30.43	1.06
C*	33.22	37.48	4.26	34.59	1.37	31.92	-1.3
h°	62.14	62.86	0.72	47.65	-14.49	72.39	10.25
ΔE_{00}			2.46		6.61		7.99

IoC* refers to *Interaction of Color (2009)*

Table 4. *Closest Color-aid in Color Master Database ('One Color as Two').*



	*IoC** Color #1	Color-aid RC-T3	Δ	Color-aid RC-T4	Δ	Color-aid	
L*	67.87	70.95	3.08	75.24	7.37		
a*	36.79	45.56	8.77	35.07	-1.72		
b*	2	7.29	5.29	6.7	4.7		
C*	36.85	46.14	9.29	35.7	-1.15		
h°	3.12	9.09	5.79	10.81	7.69		
ΔE_{00}		4.72		6.33			
	Color #2	**V-S1**	**Δ**	**V-P1-1**	**Δ**		
L*	34.44	32.01	-2.43	42.37	7.93		
a*	7.75	9.17	1.42	8.51	0.76		
b*	-29.48	-22.2	7.28	-36.08	-6.6		
C*	30.48	24.02	-6.46	27.44	-3.04		
h°	284.73	292.45	7.72	288.07	3.34		
ΔE_{00}		5.83		7.29			
	Color #3	**MP-1-2**	**Δ**	**MP-2-2**	**Δ**		
L*	66.78	73.75	6.97	61.02	-5.76		
a*	24.64	21.17	-3.47	22.2	-2.37		
b*	-6.97	0.65	7.62	0.92	7.89		
C*	25.6	21.18	-4.42	22.29	-3.31		
h°	344.21	1.76	342.45	2.37	-341.84		
ΔE_{00}		7.64		7.3			
	Color #4	**V-P1-1**	**Δ**	**BP1-1**	**Δ**	**BP2-1**	**Δ**
L*	45.1	42.37	-2.73	42.16	-2.94	38.7	-6.4
a*	2.5	8.51	6.01	-1.07	-3.57	-3.26	5.76
b*	-27.24	-26.08	1.16	-36.59	-9.35	-20.22	7.02
C*	27.34	27.44	0.1	36.61	9.27	20.48	-6.86
h°	275.23	288.07	12.84	268.32	-6.91	260.84	-14.39
ΔE_{00}		6.15		6.99		7.38	

IoC* refers to *Interaction of Color (2009)*

Table 5. *Closest Color-aid in Color Master Database ('Two colors as one')*

Anchor Color Method

The next steps involved selecting an "anchor" color or colors from the Color-aid set, and then selecting the rest of the colors based on the relationships of the other colors to those "anchors" in the original illustration from *Interaction of Color* (2009).

The general steps of the anchor color method were as follows:

Step 1: Examine the lowest ΔE_{00} colorimetric data collected to select anchor color(s) for the respective illustrations.

Step 2: Examine the relationships between the anchor color(s) and other colors displayed in *Interaction of Color* (2009). Knowledge of simultaneous contrast from Hoskin (2019) and Long (2015) are used in to guide these selections.

Step 3: Search the Color-aid database for samples that best represent the relationship to the anchor color(s). In this step, the colorimetric relationships (i.e.: ΔL^*, Δa^*, Δb^*) from *Interaction of Color* (2009) are applied to the selected anchor color to obtain a theoretical colorimetric standard representing the measured relationship to the selected anchor color. This theoretical colorimetric standard is then used to search the Color-aid database for the Color-aid samples that best represent the relationship to the selected anchor color.

Step 4: The selected colorimetric values from the Color-aid database are added into Photoshop wireframes.

Step 5: The resulting Photoshop wireframe is soft-proofed and analyzed results (i.e., NEC Monitor calibrated and profiled using i1 Profiler and i1 Pro 2, the resulting soft proof of the Photoshop wireframes containing colorimetric values of selected Color-aid are compared to those from the 2009 new complete edition of *Interaction of Color*).

These general steps are illustrated in Figure 2.

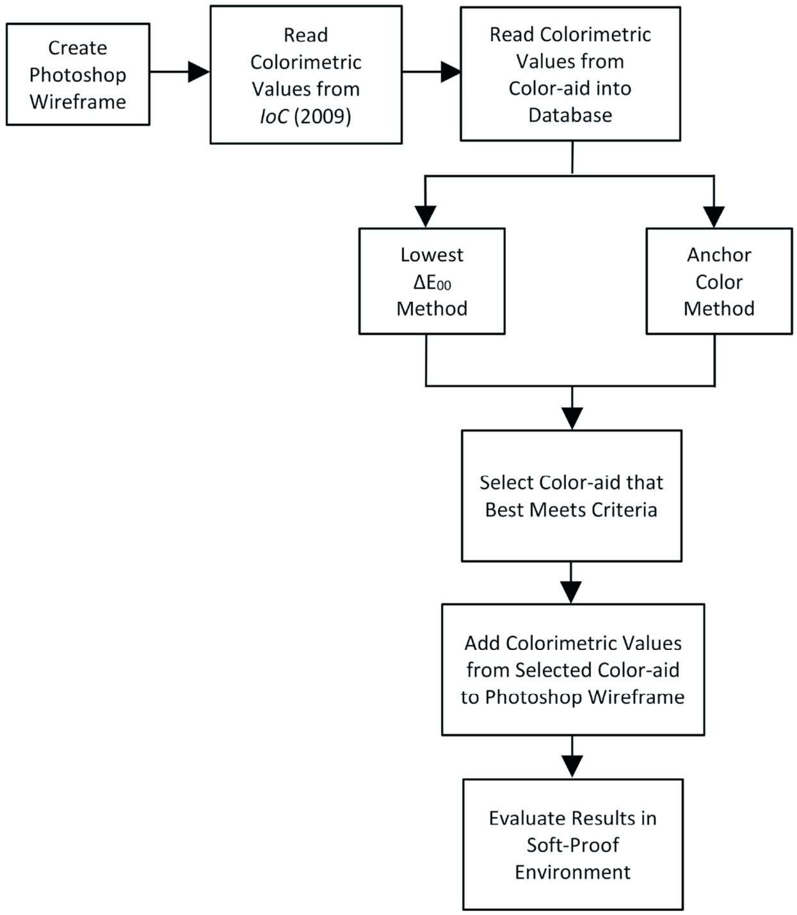
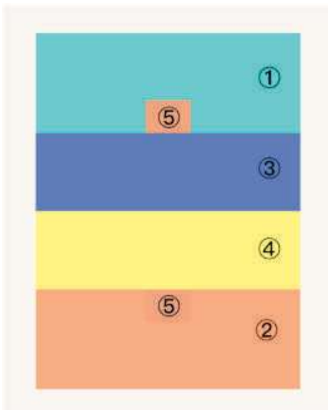


Figure 2. *General Procedure for Colorimetric Selection of Color-aid Papers*

Anchor Color Method: 'One Color as Two'

In the case of 'One Color as Two,' the decision to select three anchor colors from the Color-aid set was made. This was due to the nature of the highly chromatic blue and yellow (colors #3 and #4 in the present illustration, as reproduced in Table 6). The function of these two colors in the present illustration was to separate and influence color that appears as two (#5 in the present illustration). The yellow, in particular, had a Color-aid sample that was nearly identical to the *Interaction of Color* (2009) illustration in the Color-aid set (ΔE_{00} = 0.86). Of the two Color-aid blues within ten ΔE00 of the Interaction of Color (2009) illustration, the one perceived as the purest blue was chosen (ΔE_{00} = 04.84, Color-aid VP1-1 L*=42.37, a*=8.51, b*=-26.08, C*=27.44, h°= 288.07). Color-aid #O-P1-1 was selected to represent the orange (#2 in the illustration), as it exhibited the lowest ΔE_{00}-of the remaining Color-aid choices when compared to *Interaction of Color* (2009), as illustrated in Table 4.



	IoC Color #2	O-P1-1	Δ
L*	69.06	70.36	1.3
a*	24.67	26.77	2.1
b*	49.36	50.74	1.38
C*	55.19	57.37	2.18
h°	63.45	62.18	-1.27
ΔE_{00}			1.44

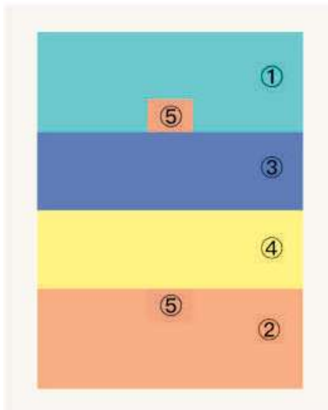
	IoC Color #3	V-P1-1	Δ
L*	40.31	42.37	2.06
a*	6.77	8.51	1.74
b*	-31.67	-26.08	5.59
C*	32.38	27.44	-4.95
h°	282.07	288.07	6
ΔE_{00}			4.84

	IoC Color #4	YC-T1	Δ
L*	90.78	89.95	-0.83
a*	-8.3	-9.15	-0.85
b*	63.13	61.87	-1.26
C*	63.68	62.54	-1.14
h°	97.49	98.41	0.92
ΔE_{00}			0.86

Table 6. *Anchor Colors Selected for 'One Color as Two'*

To search for the remaining potential Color-aid colors, the original color relationships were needed. These figures were based on the relationship between Color #1 and Color #3; Color #2 and Color #5, and Color #1 and Color #5.

Using the colorimetric Color-aid anchor color O-P1-1 (representing Color #2) and the Color-aids selected for colors #3 and #4 (V-P1-1 and YC-T1, respectively), the colorimetric relationships were used to create a theoretical colorimetric standard, which was subsequently used to search the Color-aid database for those Color-aid samples for the closest that exhibit the colorimetric relationships illustrated in *Interaction of Color* (2009). These are illustrated in Table 7.



The highly chromatic blue (#3) and yellow (#4) were selected from the Color-aid set, the orange (#2) was selected as an anchor color using Color-aid #O-P1-1. Once selected, the colorimetric relationships between colors #1 and #3; #2 and #5; and #1 and #5 were be determined and implemented. The relationship from *Interaction of Color* (2009) is then applied to the Color-aid anchor colorimetric values, which was used as a theoretical standard with which to search the Color-aid database for the closest papers to that theoretical standard. Matches within ten ΔE_{00} are reported.

Colorimetric Relationships from *IoC*, Colors #1 and #3			
	IoC **Color #1**	***IoC*** **Color #3**	**Relationship**
L*	64.67	40.31	-24.36
a*	-28.10	6.77	34.87
b*	-14.13	-31.67	-17.54

	#3 Anchor Color-aid V-P1-1	**Relationship**	**Theoretical Standard**	**Color-aid BGP 2-2**
L*	66.73	-24.36	42.37	62.34
a*	-36.36	34.87	8.51	-21.89
b*	-8.54	-17.54	-26.08	-4.54

Colorimetric Relationships from *IoC*, Colors #2 and #5			
	IoC **Color #2**	***IoC*** **Color #5**	**Relationship**
L*	69.06	63.29	-5.77
a*	24.67	15.54	-9.13
b*	49.36	29.37	-19.99

	#2 Anchor Color-aid O-P1-1	**Relationship**	**Theoretical Standard**	**Color-aid O-P2-2**	**Color-aid YOP2-1**	**Color-aid RO-P2-2**
L*	70.36	-5.77	64.59	65.46	64.04	62.59
a*	26.77	-9.13	17.64	17.10	12.47	23.30
b*	50.74	-19.99	30.75	33.35	40.21	25.57

Colorimetric Relationships from *IoC*, Colors #1 and #5			
	IoC **Color #1**	***IoC*** **Color #5**	**Relationship**
L*	64.67	63.29	1.38
a*	-28.10	15.54	43.64
b*	-14.13	29.37	43.50

	#1 Anchor Color-aid BGP2-2	**Relationship**	**Theoretical Standard**	**Color-aid O-P2-2**	**Color-aid YOP2-1**
L*	62.34	1.38	63.72	65.46	64.04
a*	-21.89	43.64	21.75	17.10	12.47
b*	-4.54	43.50	48.04	33.35	40.21

Table 7. *Searched Potential Color-aid, 'One Color as Two'*

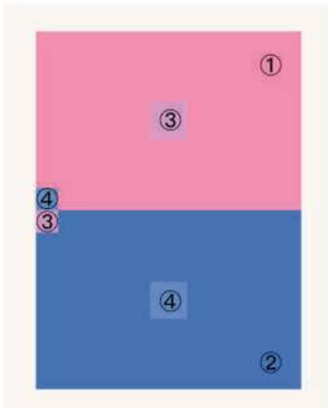
As indicated in Table 7, the relationship between colors #1 and #3 in *Interaction of Color* (2009) along with the previously selected anchor Color-aid representing color #3 were used to create a theoretical colorimetric standard to search the database and select a Color-aid best representing this relationship. In this case, only one Color-aid was within ten ΔE_{00}, namely BGP2-2. This color was therefore selected to represent color #1.

Looking at the relationship between colors #2 and #5 from *Interaction of Color* (2009), a similar procedure was used based on the previously selected Color-aid representing color #2. In this case, three examples were within ten ΔE_{00}: Color-aid numbers O-P2-2, YOP2-1, and RO-P2-2. As color #5 is the most critical, the next step examined the relationship between colors #1 and #5, using the previously selected Color-aid BGP2-2 for color #1. Here, two samples were within ten ΔE_{00}: O-P2-2 and YOP2-1. The decision was therefore made to select Color-aid O-P2-2 to represent color #5, as this color exhibited the closest relationships between colors #1 and #2 as expressed in *Interaction of Color* (2009) given the selected anchor Color-aid selections.

Anchor color method: ‘Two Colors as One’

Turning to the ‘Two Colors as One’ illustration, a similar procedure was followed except in this case only one anchor color was selected. As shown in Table 5, the closest ΔE_{00} match to any of the colors in this illustration from *Interaction of Color*(2009) was Color-aid RCT3 as matched to Color #1, this therefore became the anchor.

To search for potential Color-Aid colors, the original color relationships were needed. These relationships were based on those between colors #1 and #2, colors #2 and #3, and colors #2 and #4.



The Color-aid with the lowest ΔE00 to any of the four colors in this illustration was selected as the anchor, namely Color-aid RCT3 as color #1. Once selected, the colorimetric relationships between colors #1 and #2; #1 and #3; and #2 and #4 were be determined and implemented. The relationship from *Interaction of Color* (2009) is then applied to the Color-aid anchor colorimetric values, which was used as a theoretical standard with which to search the Color-aid database for the closest papers to that theoretical standard. Matches within ten ΔE_{00} are reported.

Colorimetric Relationships from *IoC*, Colors #1 and #2			
	IoC **Color #1**	***IoC*** **Color #2**	**Relationship**
L*	67.87	34.44	-33.43
a*	36.79	7375	-29.04
b*	2.00	-29.48	-31.48

	#1 Anchor Color-aid RCT3	**Relationship**	**Theoretical Standard**	**Color-aid V-S1**
L*	70.95	-33.43	37.52	32.01
a*	45.56	-29.04	16.52	9.17
b*	7.29	-31.48	-24.19	-22.20

Colorimetric Relationships from *IoC*, Colors #1 and #3			
	IoC **Color #1**	***IoC*** **Color #3**	**Relationship**
L*	67.87	66.78	-1.09
a*	36.79	24.64	-12.15
b*	2.00	-6.97	-8.97

	#1 Anchor Color-aid RCT3	**Relationship**	**Theoretical Standard**	**Color-aid RCT4**
L*	70.95	-1.09	69.86	75.24
a*	45.56	-12.15	33.41	35.07
b*	7.29	-8.97	-1.68	6.70

Colorimetric Relationships from *IoC*, Colors #2 and #4			
	IoC **Color #2**	***IoC*** **Color #4**	**Relationship**
L*	34.44	45.10	10.66
a*	7.75	2.50	-5.25
b*	-29.48	-27.24	-2.24

	#2 Anchor Color-aid V-S1	**Relationship**	**Theoretical Standard**	**Color-aid V-P1-1**
L*	32.01	10.66	42.67	42.37
a*	9.17	-5.25	3.92	8.51
b*	-22.20	-2.24	-24.44	-26.08

Table 8. *Searched Potential Color-aid, 'One Color as Two'*

As illustrated in Table 8, once Color-aid RCT3 was selected representing color #1, and the relationship between colors #1 and #2 from *Interaction of Color* (2009) was calculated and applied to create a theoretical standard with which to search the database, only one Color-aid was within ten ΔE_{00}, namely V-S1. This color was therefore selected to represent color #2.

Similar procedures were then applied to select color #3, where the relationship between colors #1 and #3 yielded only one Color-aid sample within ten ΔE_{00} to represent color #3: Color-aid # RCT-4. Likewise, with Color-aid #V-S1 representing color #2, factoring the differences from *Interaction of Color* (2009) to search the database resulted in one Color-aid sample to represent color #4, which was V-P1-1. The next step was to add the colorimetric values from the selected Color-aid samples to the respective Photoshop wireframes, and to soft proof and analyze the outcome, as discussed in the Results section.

Results

For the first research question, after two iterations with a profiled inkjet printer good visual matches were obtained for both the "one color as two" and "two colors as one" illustrations. Relevant colorimetric values are shown in Tables 2 and 3. This indicates that color managed inkjet printers can be used to effectively replicate the simultaneous contrast phenomena displayed in Interaction of Color.

To address the second research question, the methods described were utilized to select representative Color-aid samples to represent the colors in *Interaction of Color* (2009), namely, by selecting the lowest ΔE_{00} for each color and alternatively by selecting Color-aid anchor color or colors and then selecting the remaining Color-aid samples based on the relationships

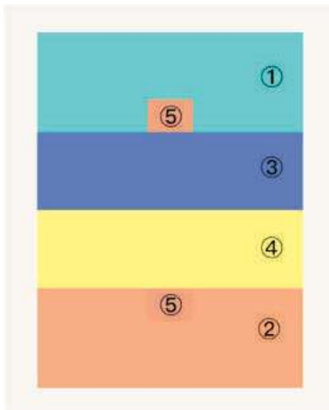
expressed in the original volume. The resulting selected Color-aid numbers for each method are illustrated in Tables 9 and 10.

One Color as Two

Upon comparing the lowest ΔE_{00} method and 'anchor color with relationships' method in the 'One Color as Two' case, the lowest ΔE00 Color-aid selections better represented simultaneous contrast as seen in *Interaction of Color* (2009).

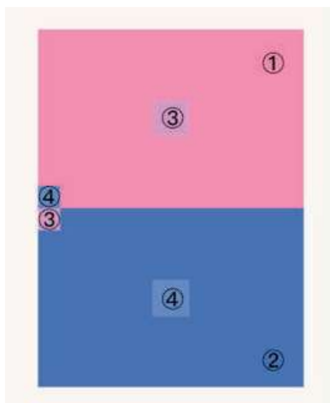
Two Colors as One

Upon comparing the lowest ΔE_{00} method and 'anchor color with relationships' method in the 'Two Colors as One' case, the 'anchor color with relationships' method Color-aid selections better represented simultaneous contrast as seen in *Interaction of Color* (2009).



Color #	Lowest ΔE_{00} method	Anchor color method
1	BG-T3	BG-P2
2	O-P1-1	O-P1-1
3	V-P1-1	V-P1-1
4	Yc-T1	Yc-T1
5	O-P2-2	O-P2-2

Table 9. *Resulting Color-aid selections for lowest ΔE_{00} and anchor-color method: One Color as Two*



Color #	Lowest ΔE_{00} method	Anchor color method
1	RC-T3	RC-T3
2	V-S1	V-S1
3	M-P1-1	Rc-T4
4	V-P1-1	V-P1-1

Table 10. *Resulting Color-aid selections for lowest ΔE_{00} and anchor-color method: Two Colors as One*

Conclusions

Research question one asked: "Can a color managed inkjet printer effectively recreate examples from *Interaction of Color* (2009)? The present study indicates that, indeed, today's inkjet printing technology and widely available color management tools can be used to effectively to reproduce the simultaneous contrast examples in *Interaction of Color*.

The second research question asked: "Can colorimetry be used to effectively select optimal Color-aid papers to recreate the visual effects illustrated in *Interaction of Color* (2009)?" The results of the present study here do not support that using colorimetry to select color papers to represent simultaneous contrast is a substitute for visual analysis. Colorimetry, therefore, seems to be limited in its application in this context. The well-documented visual non-uniformity of the CIELAB colorspace is likely a factor here.

However, the results suggest that, as students can use color managed inkjet printers to replicate illustrations from *Interaction of Color*, they can effectively output colors to supplement gaps in the Color-aid assortment. This means that they do not need to turn to paint mixing when an ideal Color-aid sample is not available. This finding therefore supports the some goals of Albers' color studies curricula, namely that solutions should be simple, quick, practical and allow more choices.

Limitations and Further Study

In this experiment, the researcher did not compare the size and proximity of simultaneous contrast colors from the illustrations; however, it is documented these factors may influence the effects of simultaneous contrast. The present study only examined direct replications of Albers' work, in color studies classes students are typically shown these as examples only, and asked to replicate the effect using their own color combinations, shapes and proximities.

Therefore, as in the present study the researcher focused on quantitative color evaluation, subsequent research could include experiments related to the size and proximity of simultaneous contrast colors using psychophysical experiments and visual evaluation. Moreover, as previously noted, Photoshop is not a truly scientific colorimetric tool, and represents an important limitation, and the experiments in this study considered the printer driver exclusively, and no raster image processor was considered. Lastly, the selected illustrations were duplicated using Color-aid papers; no paint mixing or other emissive color methods (e.g., monitor, tablet, or phone) were considered. Finally, it is suggested that classroom studies could be developed to ascertain the efficacy of various applied teaching methods in real teaching environments. It is suggested that future researchers consider these factors in designing experiments in this domain.

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