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Comparison of Chromatic Assimilation Effects Depending on Printing Substrate in the Munker-White Model

Katja Milković*, Damir Vusić, Martina Hajdek

Abstract: Understanding the influence of paper surface structures on color perception is crucial for the printing industry. This research investigates the impact of horizontal and vertical parallel lines on chromatic assimilation using the Munker-White grid model. The study employs the perceived ΔE_{00} metric to quantify color differences and determine whether these textures affect perceived color accuracy and consistency differently. Results reveal variations in color perception due to surface textures. The biggest color difference (ΔE_{00}) occurred at 60% RTV coverage for cyan, where the vertical structure showed a significantly lower value than the horizontal. For the yellow primary stimulus, the greatest difference was observed at 20% RTV coverage, with both structures showing high initial values that decrease with increased coverage. These findings provide valuable insights for improving color management practices and enhancing the quality and reliability of color reproduction on various substrates, contributing to advancements in printing technology and color science.

Keywords: chromatic assimilation; color perception; Munker-White model; paper texture; printing surface; printing technology; subtractive synthesis

1 INTRODUCTION

The study of color perception and reproduction is a crucial aspect of the printing industry. One of the significant challenges in this field is understanding how different surface structures of printing substrates influence the perceived color of printed materials. Chromatic assimilation, a phenomenon where the surrounding colors affect the perception of a given color, is particularly relevant in this context. The effects of chromatic induction and assimilation are based on the principle of surface light induction [1]. Visual effects are considered undesirable due to the unwanted shift in the perceived color tone by the observer or consumer, which cannot be detected using instrumental colorimetric methods [2].This article focuses on the impact of paper surface structures, specifically horizontal and vertical lines, on chromatic assimilation in the context of subtractive synthesis.

CMYK subtractive synthesis is the process used in color printing where cyan, magenta, yellow, and black inks are combined to produce all other colors. The quality and accuracy of color reproduction in this process depend significantly on the interaction between the inks and the substrate. Different surface textures can alter the way light is reflected and absorbed by the printed material, leading to variations in color perception. In 2005 Spitzer et al discusses a computational model for chromatic induction that includes mechanisms for both local and remote contrast effects. It provides insights into how different spatial frequencies and orientations affect chromatic assimilation [2]. Trends in graphic reproduction increasingly demand the use of non-standard, structured materials to further enhance the product experience. This can cause problems during the printing reproduction process and result in different color perception compared to materials that do not have structural irregularities. According to the research by Motoyoshi et al., it has been established that increasing the structural irregularity of the material enhances the perception of the brightness of a certain color. It has also been found that adapting to the structure can lead to altered color perception and experience [3, 4].

To investigate these effects, this study employs the Munker-White grid, a well-known visual illusion model. The Munker-White grid is used to illustrate how different background patterns and structures can significantly influence the perceived color of objects [5]. By applying this model, we can better understand the mechanisms of chromatic assimilation and how they are affected by the surface structure of the substrate.

Previous studies have indicated that surface roughness and texture can cause noticeable differences in the final appearance of printed colors. Betz et al. extended White's research by adding horizontal and vertical interferences, i.e., lines, to the Munker-White grid. They discovered that visual adaptation to edges that are positioned parallel to the White grid enhances the brightness of the observed area, while adaptation to horizontal edges has the opposite effect on the observer, resulting in a lower perception of brightness, or even its cancellation [6].

However, there is limited research specifically comparing the effects of horizontal and vertical structures on color perception using the ΔE metric, which quantifies the difference between two colors. To colorimetrically describe and compare the mentioned effects using recognized methods, Milković investigated the color differences using ΔE_{00} [7]. In his work, Helson stated that thinner lines create a narrowing effect that causes assimilation, while thicker lines result in inhibition, leading to greater contrast [8]. Chen et al. investigated the Munker-White effect and chromatic induction, establishing that the brightness of a color can be altered if it is surrounded by different structures within the observer's visual field [9]. This article aims to fill this gap by providing a detailed analysis of how these two distinct surface structures affect the perceived color accuracy and consistency in printed materials.

The objective of this study is to determine whether the horizontal and vertical paper structures differently influence the ΔE values and thus the color perception by observers. Bresan et al. studied the effect of simultaneous contrast on structured and unstructured image backgrounds and concluded that a structured image background enhances this effect [10]. By conducting controlled experiments and thorough analysis using the Munker-White grid model, this research seeks to provide insights that could lead to improved color management practices in the printing industry. The findings of this study will be valuable for printers and material scientists looking to enhance the quality and reliability of color reproduction on different substrates.

The use of the Munker-White grid allows for a controlled comparison [11] of how these surface structures influence color perception under standardized conditions. This approach not only highlights the practical implications for the printing industry but also contributes to the broader understanding of visual perception and color science.

In summary, this article explores the relationship between the surface structure of printing substrates and chromatic assimilation in CMYK printing. By focusing on horizontal and vertical linear textures and utilizing the Munker-White grid model, it aims to provide a deeper understanding of the factors influencing color perception. This study ultimately contributes to advancements in printing technology and color science, offering potential improvements in color management and reproduction quality.

2 EXPERIMENTAL PART

The experimental part of this study determines whether the direction of lines in the lineature structure of the printing surface affects the occurrence of chromatic assimilation effects in the graphic reproduction process. It also investigate of the intensity of psychophysical visual effects of chromatic assimilation on the Munker-White grid under the influence of the following parameters: different printing surface structures (2 regular geometric structures of the printing substrate that differ only in the direction of the lines were observed), different combinations of primary and secondary stimulus colors (combinations of primary colors of subtractive and additive synthesis) and different percentages of printed surface coloring (20%, 40%, 60%, 80% coverage).

2.1 Methodology of the Experiment

A printing substrate was selected for the study that is identical in its psychophysical characteristics and possesses a final surface finish (horizontal "Linea" and vertical "Fili" lines structure). In addition to its surface finish, the printing substrate has identical parameters and properties in its basic technical specifications, including the same weight, brightness, thickness, and stiffness. The chosen paper is a wood-free offset paper made of 100% cellulose, marketed under the artistic name Astroprint, produced by Cordenons, with a weight of 280 g/m². The technical characteristics of the paper, as defined by the manufacturer, are shown in the Tab. 1.

After selecting the printing substrate, test forms were designed and printed on the chosen substrates using identical technique under unchanged conditions. The obtained prints and reference atlases were subjected to spectrophotometric measurement of CIE $L^*a^*b^*$ values, followed by visual binocular matching with a test group of 20 participants.

Table 1 Technical Characteristics of the Paper

Technical Characteristics	Unit of Measurement	Target	Measurement Method
Weight	g/m²	280	MCM-003 (ISO 536)
Thickness	mm	0.355	MCM-004 (ISO 534)
Brightness	%	105	MCM-078 (ISO 2470)
Stiffness (Taber 15°) MD	mN	175	MCM-023 (ISO 2493)
Stiffness (Taber 15°) CD	mN	80	MCM-023 (ISO 2493)

To observe the background effect of chromatic assimilation, a Munker-White line grid was constructed, within which the left and right rectangular elements have the same brightness. This design was used specifically to define the influence of the geometric design of the line grid, which is often used in graphic solutions when it interpolates with a structure that is also geometrically regularly arranged like the Munker-White grid but with different structure direction. The grid has geometrically identical lines and spacings with variations in the observed color (primary stimulus) and the background surrounding that color (secondary stimulus) in the basic colors used in graphic reproduction (Tab 2). The printing substrate also has geometrically identical lines and spacings, but with differing directions.

Table 2 Color Pairs of Test Sample Primary and Secondary Stimuli

Primary Stimulus	Secondary Stimulus Left	Secondary Stimulus Right
Cyan	Blue	Green
Magenta	Red	Blue
Yellow	Red	Green

The primary stimulus was varied in ranges of 20%, 40%, 60%, and 80% coverage, while the secondary stimulus was always 100% coverage (Fig. 1).

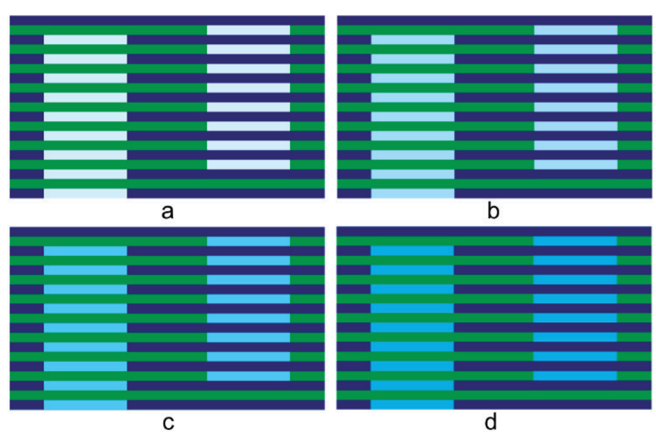

Figure 1 Test Form for Primary Stimulus Cyan (a - 20% RTV, b - 40% RTV, c - 60% RTV, d - 80% RTV)

The size of the test cards was made in accordance with the standard viewing conditions prescribed by ISO 3664:2009 (viewing conditions for graphic technology). The color atlas was constructed such that the RTV range is defined by fields differing by 2% RTV, where the first field has a surface coverage percentage of 2% RTV and the last 100% RTV, which gives a total of 50 fields with a 2% increment step. It was constructed to cover the entire area of perception (Fig. 2).

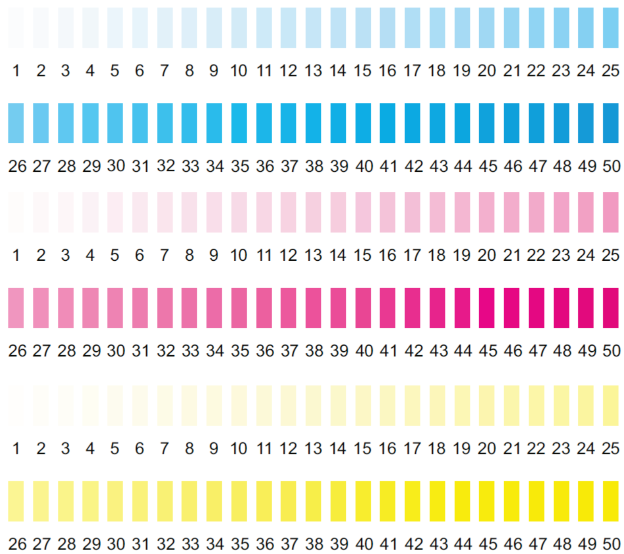

Figure 2 Reference Color Atlas for Primary Stimuli Cyan, Magenta, and Yellow

The described test form was printed on a calibrated digital printing machine, Ricoh C7100 XPRO, with a resolution of 1200 × 4800 dpi without the use of ICC profiles, directly from Adobe Illustrator CS6. Powder toner was used for the printing. Before printing, the paper was conditioned in a room under prescribed standard environmental conditions (temperature of 23 °C and relative humidity of 55%) for 48 hours.

2.2 Instrumental and Visual Analysis

The quantification of reference fields was performed using an Xrite Exact Standard 1 reflective spectrophotometer. The wavelength range used for measurement was from 400 to 700 nm, with a gas light source at a temperature of 2850 K. The measurement step was 10 nm, and the illumination geometry was set to 45°/0°. The measurement accuracy of the device, or the average deviation in terms of reflectance, is up to 0.5% per wavelength step (the calibration reference was measured by the Munsell laboratory with an accuracy of $\Delta E^* = 0.25$, using a D50 light source and a viewing angle of 20 degrees).

To improve the precision of the statistical results, the measurement was repeated 10 times for each type of paper, after which the average values of the measurements for the atlas and test forms were calculated (Tab. 3).

For conducting the visual analysis, 20 participants were selected who underwent the Farnsworth-Munsell 100 Hue Test (FM-100 test). Only the participants who successfully passed the test were included in further analysis. The average age of the participants was 21 years, with an equal representation of male and female participants.

Table 3 Measured $L^*a^*b^*$ Values

	%	"Fili"			"Linea"		
		C	M	Y	C	M	Y
L	20	92,36	90,49	98,33	91,03	89,26	97,48
a		–7,48	10,38	–3,52	–7,73	11,86	3,73
b		–7,06	–2,84	13,37	–7,31	–3,29	16,19
L	40	82,51	76,77	96,81	79,37	77,83	95,49
a		–17,4	30,99	–6,43	–19	28,97	–6,6
b		–18,34	–6,61	37,4	–19,77	–6,35	38,99
L	60	72,85	63,3	94,79	71,94	63,32	93,94
a		–25,67	51,95	–7,24	–25,04	50,91	–7,06
b		–25,3	–6,75	54,96	–25,74	–6,12	56,59
L	80	66,93	57,41	94,74	63,63	53,96	93,33
a		–30,78	61,37	–7,46	–32,64	65,81	–7,78
b		–29,15	–3,94	66,06	–31,51	–3,37	71,59

The psychophysical part of the experiment for visual evaluation was conducted under actual graphic production conditions, allowing participants to evaluate the samples under the following conditions: a viewing angle of 10°, a distance of 50 cm between the participant and the test sample, an environment with a neutral matte gray surface, illumination of 2000 lux with a light temperature of 5000 K in accordance with the ISO 3664:2017 standard.

During the experiment, the test sample and the atlas were placed parallel to each other within the full visual field of the participant. Each participant's task was to identify the field in the atlas that most closely matched the observed line (primary stimulus) located between the two observed secondary stimuli on the left and right sides of the test form. Participants had to carefully observe and compare the samples and select the best match between the test cards and the fields in the atlas to correctly complete their task (Fig. 3).

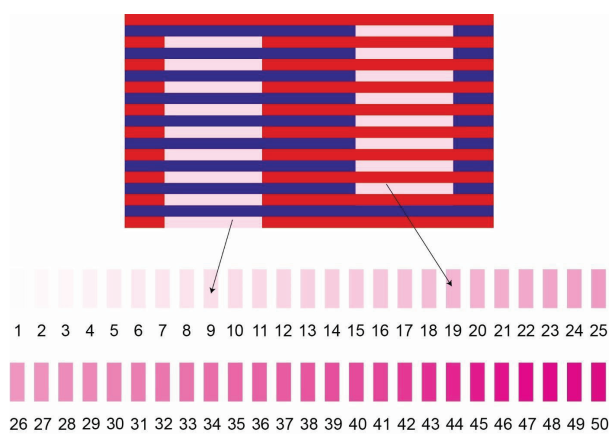

Figure 3 Visual Analysis Based on the Color Atlas

3 RESEARCH RESULT AND DISCUSSION

Statistical analysis of the obtained data was performed using the GraphPad Prism 9.5.1 software package. The results of the statistical analysis were tested using the Mann-Whitney statistical method to examine the impact of the psychophysical visual effect of chromatic assimilation depending on the secondary stimulus with the combination of colors of all primary stimulus at all percentages of coverage (20%, 40%, 60%, 80%) on the observed printing substrates ("Fili" and "Linea").

The following hypotheses were tested using the specified method: H_0: The medians of the two samples are equal, H_1: The medians of the two samples are not equal. The formulas used for the calculations are as follow [12] :

$$U_x = n_x n_y + \frac{n_x(n_x+1)}{2} - R_x \tag{1}$$

$$U_y = n_x n_y + \frac{n_y(n_y+1)}{2} - R_y \tag{2}$$

Where: U_x is the Mann-Whitney U statistic for sample x, U_y is the Mann-Whitney U statistic for sample y, n_x is the sample size of sample x, n_y is the sample size of sample y, R_x is the sum of the ranks for sample x, R_y is the sum of the ranks for sample y. The expected values of U are calculated using the following formulas:

$$\mu_U = \frac{n_x n_y}{2} = \frac{\left(U_x + U_y\right)}{2} \tag{3}$$

$$\sigma_U = \sqrt{\frac{n_x n_y (N+1)}{12}} \tag{4}$$

The total number of samples is denoted by N, where $N = (nX + nY)$. The mean value of the U distribution is denoted by μ_U, while σ_U represents the standard deviation. Through the process of normalizing the U variable, we obtain a new variable Z that follows a standard normal distribution. In other words, after normalization, the Z variable is distributed according to the standard normal distribution.

$$Z = \frac{\left[U - \left(\frac{n_x n_y}{2}\right)\right]}{\sigma_U} \tag{5}$$

At a significance level of $\alpha = 0.05$, the null hypothesis H_0 will be accepted if the statistical measure "z" falls within the interval from –1.959964 to 1.959964. In this context, "z" represents the standardized value of the test statistic used to test the null hypothesis. If the "z" value falls within this interval, it will be considered that the results do not provide sufficient statistical basis to reject the null hypothesis at the 0.05 significance level.

According to the Mann-Whitney test (Tab. 4), among the primary colors of subtractive synthesis, a significant deviation was present only for the yellow primary stimulus. In the tested combinations of primary stimulus colors, surface coverage, and paper structure, the research findings indicate that the smallest effect of simultaneous contrast was observed at the edge values of surface coverage, specifically at 20% and 80% coverage. On the other hand, the greatest differences were observed at the mid-range values of surface coverage, specifically at 40% and 60% coverage.

Table 4 Mann Whitney test results

Structure	%	Primary Stimulus	Secondary Stimulus	Mann Whitney	
				Z	p
"Fili"	20	C	B/G	1.432137	0,1556
		M	R/B	1.089024	0,2825
		Y	R/G	1.181454	0,2431
"Linea"		C	B/G	1.210160	0,2316
		M	R/B	0.397615	0,6991
		Y	R/G	0.367458	0,7251
"Fili"	40	C	B/G	1.618924	0,1074
		M	R/B	0.938259	0,3555
		Y	R/G	2.499181	0,0116
"Linea"		C	B/G	2.049117	0,0402
		M	R/B	1.447711	0,1511
		Y	R/G	2.630522	0,0077
"Fili"	60	C	B/G	0.573402	0,5749
		M	R/B	0.747816	0,4630
		Y	R/G	2.389955	0,0160
"Linea"		C	B/G	0.176866	0,8665
		M	R/B	0.993640	0,3276
		Y	R/G	1.317129	0,1923
"Fili"	80	C	B/G	0.474334	0,6437
		M	R/B	1.955048	0,0507
		Y	R/G	0.108552	0,9199
"Linea"		C	B/G	1.273207	0,2078
		M	R/B	0.951451	0,3488
		Y	R/G	0.379593	0,7123

Table 5 ΔE_{00} Primary Stimulus Cyan Median on Secondary Stimulus Blue

ΔE_{00} Cyan Median / Blue				
%	20	40	60	80
"Fili"	7,7	7,5	3,2	3,1
"Linea"	8,3	8	4,5	4,5

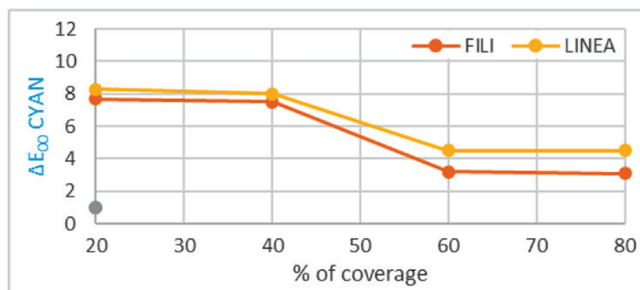

Figure 4 Colorimetric Difference ΔE_{00} for Primary Stimulus Cyan Color and Secondary Stimulus Blue Color on the Left

Based on the obtained results, the calculation of median values was performed to describe and correspond to the perception of individual test cards (left and right) as seen and observed by the CIE standard observer. The deviation in perception caused by the manifestation of the psychophysical visual effect of chromatic assimilation was expressed by the total color difference ΔE_{00} (Tabs. 5-10) and are graphically represented (Figs. 4-9) and commented according to following criteria from the perspective of a standard observer: A ΔE_{00} value of less than 1 indicates a not noticeable difference. A ΔE_{00} value between 1 and 2 indicates a very slight difference, noticeable only to an experienced observer. A ΔE_{00} value between 2 and 3.5 indicates a moderate difference, noticeable even to an inexperienced observer. A ΔE_{00} value between 3.5 and 5 indicates a significant difference. A ΔE_{00} value greater than 6 indicates a very significant difference [13].

Table 6 ΔE_{00} Primary Stimulus Cyan Median on Secondary Stimulus Green

ΔE_{00} Cyan Median / Green				
%	20	40	60	80
"Fili"	6,6	4,3	3,2	3,7
"Linea"	8,3	5,1	4,4	4,5

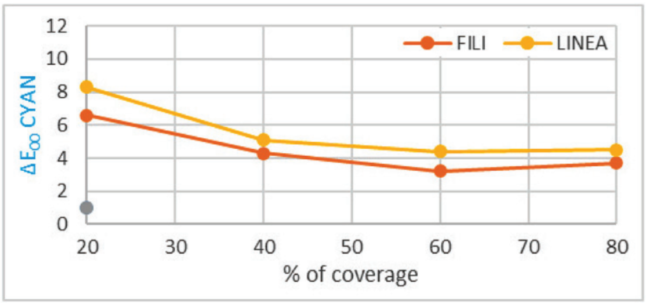

Figure 5 Colorimetric Difference ΔE_{00} for Primary Stimulus Cyan Color and Secondary Stimulus Green Color on the Right

Table 7 ΔE_{00} Primary Stimulus Magenta Median on Secondary Stimulus Red

ΔE_{00} Magenta Median / Red				
%	20	40	60	80
"Fili"	4,8	3,2	4,2	2,7
"Linea"	4,1	4	3,4	3,1

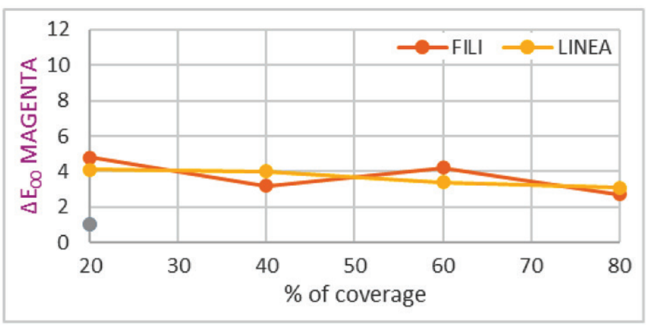

Figure 6 Colorimetric Difference ΔE_{00} for Primary Stimulus Magenta Color and Secondary Stimulus Red Color on the Left

The ΔE_{00} values for the cyan primary stimulus (Tabs. 5-6) show a general decreasing trend as the percentage of coverage increases. At 20% coverage, both "Fili" and "Linea" have similar ΔE_{00} values, approximately 7.7 and 8.3, respectively. As the coverage increases to 40%, the values decrease slightly to around 7.5 for "Fili" and 8.0 for "Linea". A significant drop in ΔE_{00} values is observed at 60% coverage, with "Fili" showing a much lower value compared to "Linea". At 80% coverage, the ΔE_{00} values stabilize around 3.1 for "Fili" and 4.5 for "Linea". The greatest difference in ΔE_{00} values is observed at 60% coverage, where "Fili" demonstrates a notably lower value than "Linea".

Table 8 ΔE_{00} Primary Stimulus Magenta Median on Secondary Stimulus Blue

ΔE_{00} Magenta Median / Blue				
%	20	40	60	80
"Fili"	5	4,3	3,6	4,9
"Linea"	4,9	4,3	5,3	3,8

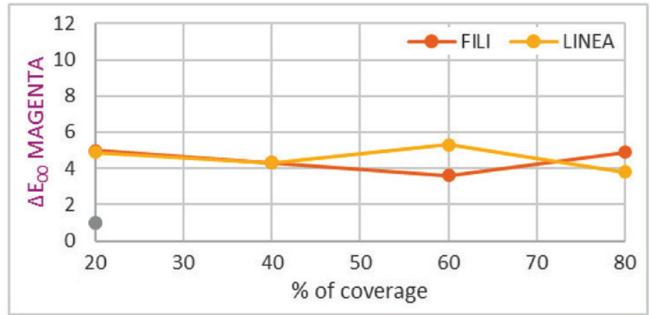

Figure 7 Colorimetric Difference ΔE_{00} for Primary Stimulus Magenta Color and Secondary Stimulus Blue Color on the Right

The ΔE_{00} values for the magenta primary stimulus (Tabs. 7-8) exhibit minimal variation across different coverages. At 20% coverage, both "Fili" and "Linea" show similar ΔE_{00} values around 4.0. This consistency persists across 40% and 60% coverage, with only slight fluctuations observed. By 80% coverage, the values stabilize again for both "Fili" and "Linea". There are minimal differences across all coverage percentages, indicating a stable chromatic assimilation effect for the magenta primary stimulus.

Table 9 ΔE_{00} Primary Stimulus Yellow Median on Secondary Stimulus Red

ΔE_{00} Yellow Median / Red				
%	20	40	60	80
"Fili"	8,2	5,5	3,9	3
"Linea"	9,4	5,7	2,6	2,6

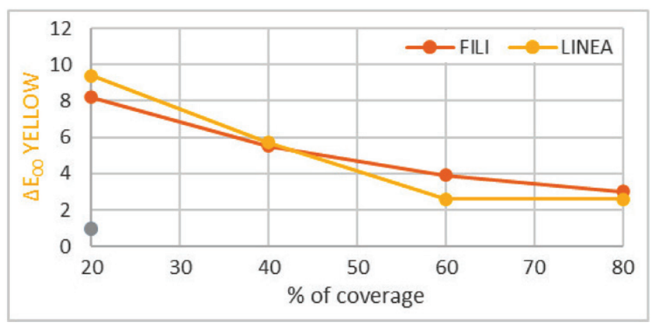

Figure 8 Colorimetric Difference ΔE_{00} for Primary Stimulus Yellow Color and Secondary Stimulus Red Color on the Left

Table 10 ΔE_{00} Primary Stimulus Yellow Median on Secondary Stimulus Gren

ΔE_{00} Yellow Median / Green				
%	20	40	60	80
"Fili"	5,3	3,5	3	3,2
"Linea"	9,4	4,1	2,4	2,8

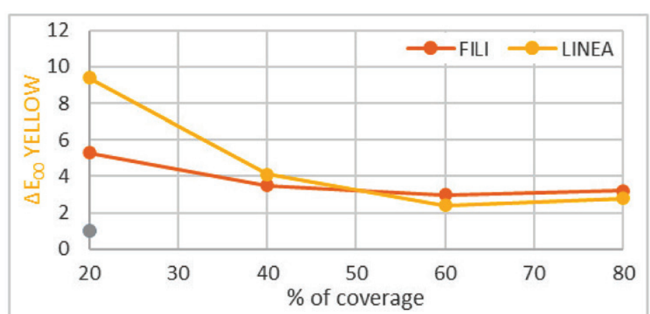

Figure 9 Colorimetric Difference ΔE_{00} for Primary Stimulus Yellow Color and Secondary Stimulus Green Color on the Right

The ΔE_{00} values for the yellow primary stimulus (Tabs. 9-10) show a distinct trend depending on the percentage of RTV coverage. At 20% coverage, there is a notable difference between the two structures, with "Fili" having a ΔE_{00} value of 5.3 and "Linea" having a significantly higher value of 9.4. As the coverage increases to 40%, both structures exhibit a decrease in ΔE_{00} values; "Fili" drops to 3.5, and "Linea" decreases to 4.1. This decreasing trend continues at 60% coverage, where "Fili" shows a ΔE_{00} value of 3.0 and "Linea" further drops to 2.4. At 80% coverage, the values slightly increase for "Fili" to 3.2, while "Linea" shows a slight increase to 2.8. The greatest difference in ΔE_{00} values is observed at 20% RTV coverage, where "Linea" exhibits a significantly higher value compared to "Fili." As the coverage percentage increases, the difference between the two structures diminishes, with "Linea" showing lower ΔE_{00} values than "Fili" at 60% and 80% coverage. The graphs depict the variation in ΔE_{00} values for different primary stimuli (Cyan, Magenta, Yellow) under various coverage percentages for two paper structures, "Fili" and "Linea".

4 CONCLUSION

The key observations are as follows: For the cyan primary stimulus, the greatest ΔE_{00} difference is at 60% RTV coverage, with "Fili" showing a significantly lower value compared to "Linea". For the magenta primary stimulus, minimal variation is observed across all coverage percentages, indicating stable chromatic assimilation effects. For the yellow primary stimulus, the greatest ΔE_{00} difference is at 20% coverage, with both "Fili" and "Linea" showing high initial values that decrease with increased coverage.

These findings highlight the importance of considering paper structure and coverage percentages in printing applications to manage and predict chromatic assimilation effects. The results are significant for optimizing color accuracy and consistency in graphic reproduction, especially for specific color stimuli and coverage levels.

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Authors' contacts:

Katja Milković, PhD
Jurja Dobrila University of Pula,
Zagrebačka 30, 52100 Pula, Croatia
katja.milkovic@unipu.hr

Damir Vusić, PhD, Full Professor
University North,
104. brigade 3, 42000 Varaždin, Croatia
damir.vusic@unin.hr

Martina Hajdek, PhD
Faculty of Graphic Arts, University of Zagreb,
Getaldićeva ulica 2, 10000 Zagreb, Croatia
martina.hajdek@grf.unizg.hr