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Scientific article

Evaluation of the visual perception of crispening effect on desaturated samples on uncoated substrate

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Abstract:

This study investigates the effect of crispening on desaturated samples printed on uncoate substrate, focusing on primary stimuli of 45%, 50% and 55% RTV. The crispening effect is described as an enhanced perception of contrast between an object and its background when there are minimal differences in brightness or color. In the experimental part, 20 participants were tasked with "matching" the values based on the ratio rating scale (Stevens) for each of the previously defined primary stimuli, so that the stimuli, regardless of their background (RTV range from 0% to 100%), are perceived as identical. The results of this study may have significant implications for optimizing printing processes and improving the quality of color reproduction on different substrates.

Keywords:

desaturated reproduction, crispening, printing substrate, visual psychophysics

1. Introduction

Visual psychophysics is a branch of psychology that studies how the physical properties of visual stimuli, such as color, contrast, lightness, and motion, influence human perception and how these perceptions are shaped in the context of everyday experiences. The science of visual perception links the subjective interpretation of stimuli with the objective physical characteristics of those stimuli [1,2]. The goal is to understand the human visual system and apply these insights to various industries, including graphic design, printing, digital media, architecture, and even medical applications [3,4].

One of the most well-known visual phenomena is the crispening effect, which is described as an enhanced perception of contrast between an object and its background when there are minimal differences in lightness or color. These differences become psychologically amplified under certain conditions [5]. For example, two squares of the same gray color may appear significantly different when placed on a background of similar lightness because the human visual system interprets minimal contrast as a greater difference [1,6]. This effect plays a crucial role in printed materials and digital design, as it allows for the optimization of visual readability and attractiveness [3,7]. The crispening effect enables designers to create vivid, dynamic contrasts with minimal physical differences between objects and their backgrounds.

Besides the crispening effect, another important phenomenon in visual perception is simultaneous contrast. This describes the change in the perception of an object's color or lightness depending on the surrounding background [8,9]. For example, a gray square may appear brighter or darker when placed on a lighter or darker background, even though its objective lightness remains unchanged. This effect is essential in many visual fields as it allows designers to manipulate contrast and colors to create the desired visual impression [2,8]. Similar to the crispening effect, simultaneous contrast influences the interpretation of color and lightness by creating a subjective sense of difference that is greater than it actually is [9–11].

In graphic design and printing, the application of simultaneous contrast and crispening effects can significantly enhance color perception and the clarity of printed materials. For example, manipulating contrasts between objects and their backgrounds helps create a stronger impression by emphasizing certain design elements [3,12]. Since printing processes involve different levels of color and lightness on various types of paper, understanding these visual effects can help optimize final results and achieve precise color reproduction [13].

Simultaneous contrast and crispening also play a key role in digital design by optimizing the visual experience on websites and mobile devices. For instance, web and app designers use these effects to improve text readability and recognition of visual elements [14,15]. Manipulating color contrast based on these principles ensures that content remains clear even in conditions where lightness differences are minimal. This approach is used to create pleasant and functional user interfaces [16]. The effects of simultaneous contrast and crispening can enhance interactivity by making applications more visually appealing and easier to use.

In virtual and augmented reality (VR/AR), understanding how contrast and crispening manifest in visual displays can significantly improve immersive experiences. In technologies such as VR and AR—where depth perception and clarity are crucial—applying psychophysical principles like simultaneous contrast and crispening helps create clearer and more natural representations of objects in 3D space [17]. Visual precision and clarity in virtual environments allow users to better perceive interactions with objects while reducing visual discomfort [18].

Additionally, in medical applications such as vision diagnostics or assistive devices for visually impaired individuals, understanding simultaneous contrast and the crispening effect enables better testing and customization of optical devices for precise visual perception. Using psychophysical principles in vision assessment tests allows for better adaptations for individuals with contrast perception issues [19].

Furthermore, in art and design fields, artists often utilize the crispening effect and simultaneous contrast to achieve emotional impact by creating images that evoke strong visual reactions. These effects can create illusions of depth and space while making images visually exciting and dynamic [20,21]. Additionally, understanding these effects in light of new technologies such as generative design opens new possibilities for innovative artistic projects [22]. Along with the simultaneous contrast effect, the background creasing effect is one of the most researched effects, and this is a continuation of research published in scientific papers investigating the occurrence of the creasing effect depending on the display medium, the printing substrate, and its color characteristics [23–26].

2. Experimental part

The experimental part of the evaluation of the crispening effect is based on test samples created according to the following principle: the first type of samples was designed to stimulate the manifestation of desaturated crispening with a central field value of 25% RTV, which is also the reference (starting) field, surrounded by fields of 20% RTV (left) and 30% RTV (right), with an outer field of 25% RTV surrounding all three mentioned fields (background), in steps of increasing each subsequent outer field by an additional 25% RTV (i.e., 0%, 25%, 50%, 75%, and 100% RTV – see Figure 1up).

The next type of sample was created in the same manner, with the difference being that the reference field has a value of 50% RTV,

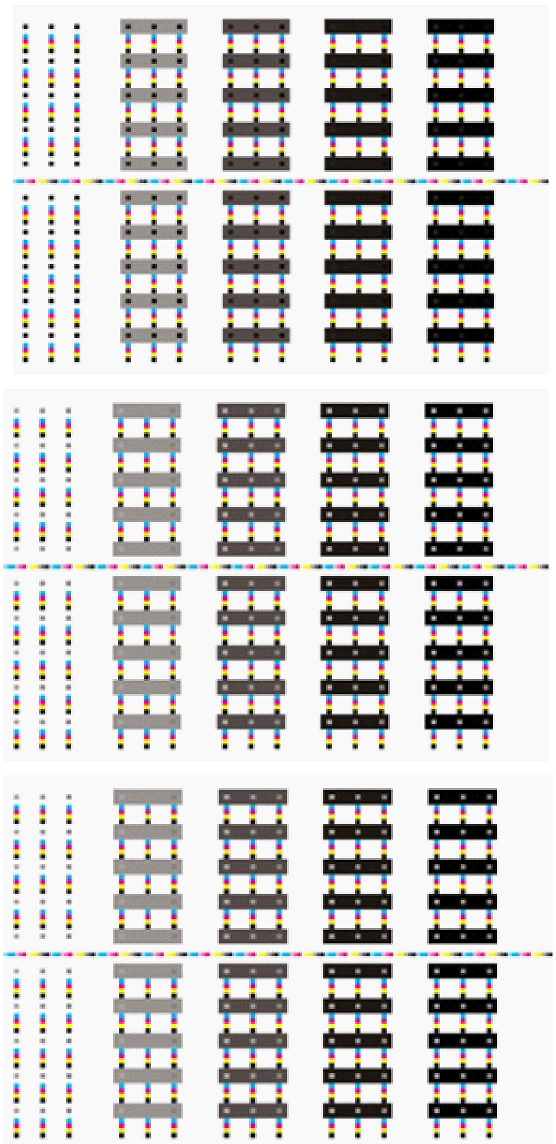

Figure 1. Design of test samples for the desaturated crispening effect (up - 25% RTV; middle –50% RTV; bottom –75% RTV)

surrounded by fields of 45% RTV and 55% RTV, with outer fields ranging from 0%, 25%, 50%, 75%, and 100% RTV (see Figure 1 middle). The third type of sample has a reference field with a value of 75% RTV, surrounded by fields with values of 70% RTV and 80% RTV, with a background range of values from 0%, 25%, 50%, 75%, and 100% RTV (see Figure 1 bottom).

In the experiment, which involves identical evaluation (simultaneous binocular matching) and the printing process through targeted adjustment, the participants (20) were tasked with “matching” values based on the scale of evaluation relationships (Stevens) for each of the previously defined primary stimuli for both effects. This was done so that the stimuli, regardless of their background (RTV range from 0% to 100%), would be perceived as identical.

The ambient conditions for visual evaluation were aligned with the guidelines of the ISO 3664:2009 standard (0° viewing angle, 60 cm distance of the participant from the test sample, natural matte gray environment). The effect evaluation, or adjustment of test samples, was conducted with a sample of 20 participants with an average age of 38 years (all participants were previously subjected to the Ishihara test for detecting visual anomalies). The principle of visual evaluation was based on the technique of simultaneous binocular visual matching, where, within the experiment, participants tried to “match” the values on printed samples so that all the internal/comparative fields printed on the reference reproduction (CIP3) visually aligned.

The participants were tasked with “matching” (adjustment method) primary stimuli on the test reproduction with primary stimuli on the reference reproduction (CIP3) in such a way that the reference values of the basic fields (25%, 50%, and 75% RTV) and the values of the adjacent fields +/- 5% RTV were identical for each of the backgrounds. Then, the arithmetic mean of the Lab values of the primary stimuli (results obtained from 10 repetitions) was calculated on the printed (test) reproductions, and these values were considered in further measurements. The deviation of the measured values of the test fields (stimuli) concerning the CIP3 reference values was also measured (spectrophotometric analysis and conversion to CIE Lab values). For both experiments, each participant underwent testing 10 times.

Based on the results obtained from the conducted research, the corresponding physical color values were statistically processed and presented, showing the relationship between the intensity of sensations and the size of the corresponding stimulus depending on the manifestation of the crispening effects.

2.1. Reproduction of test samples

The test forms were printed on a calibrated sheet-fed printing press – Heidelberg Speedmaster SM 74-5-P using the perceptual ICC rendering method. The rendering was performed in Adobe Photoshop, where the color space transitioned from Lab to the color space of the printing profile for two different printing substrates. The Adobe (ACE) conversion option was selected, and the printing substrates used were coated ("Kunstdruck") and uncoated (uncoated offset) papers. For the uncoated printing substrate, uncoated offset paper with a grammage of 140 g/m² was used. The paper was conditioned in the pressroom for 48 hours under standard environmental conditions (temperature of 23°C and relative humidity of 55%) before printing. The offset plates used to create the test forms were manufactured by Kodak, and the plate type was Electra XD (thermal positive plate) with a spectral sensitivity of 800 – 850 nm. The plates were produced at a resolution of 175 lines and a raster value of 2400 dpi (AM raster), and the plate format was 745 x 605 cm. The device used for the offset plate production was the Kodak Magnus Q800 Platesetter. The field (stimulus) on prints was measured using an X-Rite i1 Pro spectrophotometer with a wavelength range of 380 to 730 nm, light source gas pressure of 2856 K, step size of 10 nm, and illumination geometry of 45°/0°. Each sample was measured 10 times for statistical accuracy, from which average values (arithmetic mean) were obtained.

Spectrophotometric measurements of reference primary stimuli and test primary stimuli obtained through the calibration method were used to determine the corresponding colorimetric values in CIE Lab values. Based on these values, colorimetric differences in lightness and color were calculated between the previously mentioned relations.

2.2. Instrumental analysis

The field (stimulus) on prints was measured using an X-Rite i1 Pro spectrophotometer with a wavelength range of 380 to 730 nm, light source gas pressure of 2856 K, step size of 10 nm, and illumination geometry of 45°/0°. Each sample was measured 10 times for statistical accuracy, from which average values (arithmetic mean) were obtained.

Spectrophotometric measurements of reference primary stimuli and test primary stimuli obtained through the calibration method were used to determine the corresponding colorimetric values in CIE Lab values. Based on these values, colorimetric differences in lightness and color were calculated between the previously mentioned relations.

2.3. Visual evaluation

All participants (20) were required to meet the criteria of the Ishihara test to check for potential vision defects before the actual testing. Only those who passed the Ishihara test were allowed to participate in the study. The visual evaluation of the psychophysical part of the experiment was conducted under real graphic production conditions (10° viewing angle, 60 cm distance from the test sample, natural matte gray surroundings, artificial lighting) and in controlled ambient conditions (ISO 3664:2009).

The test samples were evaluated under standard CIE lighting D50 (5000K). The task of the participants in the study was to try to match the fields (primary stimuli) on the test reproduction so that they were identical or similar to the primary stimuli on the reference reproduction (CIP3).

2.4. Statistical analysis

A statistical analysis was performed on all the data obtained from the psychophysical visual experiment by "matching" of the fields on the reproduction (adjustment method). Specifically, the deviation values in lightness between the perceived and physical lightness of the primary stimuli and color, as well as the variable values ΔL00, ΔE00, ΔC00, and ΔH00 for the reproductions, were analyzed. The analysis was conducted using the STATISTICA 12 program (StatSoft, Tulsa, USA). It involved the calculation of descriptive parameters for the differences in lightness and color that the participants perceived. In the descriptive statistics table for the crispening effect, the arithmetic means and standard deviations of the perceived values of stimuli assigned by the participants to the primary stimuli on the reproduction are presented. The medians, maximum and minimum deviations of the perceived value from the reference stimulus, and the variance indicating the precision of the obtained data are shown. The results of the Kolmogorov-Smirnov test, which indicates the data's conformity to the law of normal distribution, and the results of the repeated-measures ANOVA test, which determines whether statistically significant differences exist between the arithmetic means of the visual perception of the primary stimuli, are also presented. A post-hoc Fisher analysis was conducted to identify differences among the groups of arithmetic means that differ from each other ($p < 0.05$).

3. Results and discussion

The graph displays and analyzes the data of ΔE00 values of the primary stimuli at 50% RTV for the simultaneous contrast effect on the CIP3 relation and the assigned values from the color atlas. In the following step, the relationship between the analyzed ΔE00 values obtained on the CIP3 – reproduction relation, using the adjustment method, is presented. Using the measured ΔE00 values, the relationship and correlation between the desaturated stimuli are demonstrated.

During the printing of the reproduction according to CIP3 values (reference stimulus), very small differences were observed between the Lab values of the reference primary stimulus. These differences could not be avoided due to the technical characteristics of the printing device and the background surrounding the primary stimulus. Specifically, since the primary stimulus and the background are in the same coloring zone, increasing the ink coverage on the background automatically raises the ink coverage on the primary stimulus as well.

As a result, when measuring the Lab values of the reference primary stimulus for the simultaneous contrast effect, a tolerance of ≤ 4 was set for the measured values of the reference primary stimuli under the same effect.

3.1. Statistical analysis of the desaturated crispening effect on the CIP3 – reproduction relationship

Table 1. *Display of obtained colorimetric difference values between the reference primary stimuli and the reproduction obtained by the adjustment method for the desaturated crispening effect*

Back-ground (RTV)	Primary stimulus (RTV)	ΔE_{00}	ΔL_{00}	ΔC_{00}	ΔH_{00}
25%	45%	2.89	0.30	2.70	0.98
	50%	2.88	0.46	2.79	0.56
	55%	2.88	1.43	2.43	0.59
50%	45%	2.43	-0.70	2.19	0.77
	50%	2.39	-1.87	1.17	0.91
	55%	2.42	0.90	2.20	0.48
75%	45%	3.69	-1.48	3.30	0.71
	50%	3.63	-2.18	2.90	0.21
	55%	3.70	-2.61	2.56	0.53
100%	45%	4.40	-3.46	2.02	1.84
	50%	4.41	-3.37	1.84	2.18
	55%	4.50	-3.78	0.99	2.25

Table 1 shows the measured values of ΔE00, ΔL00, ΔC00, and ΔH00 between the reference primary stimuli and the arithmetic mean of the fields (primary stimuli) obtained using the adjustment method for the reproduction concerning the reference primary stimuli from the reproduction obtained according to the CIP3 values. The values of ΔL00 are presented as positive and negative depending on whether the printed (adjusted) field of the primary stimulus on the reproduction obtained using the adjustment method is darker or lighter than the reference primary stimulus, which is located on the reproduction obtained according to the CIP3 values. Positive values of ΔL00 indicate that the perceived primary stimulus on the test reproduction is lighter than the reference primary stimulus, while negative values of ΔL00 indicate that the perceived stimulus is darker than the reference.

3.2. Descriptive statistics of lightness difference

The descriptive statistical analysis of the lightness differences for each subject is presented in Tables 1, 2, and 3. The differences were calculated for three primary stimuli and four different variations of background lightness, with each subsequent background lightness increasing by 25% RTV.

Table 2. *Descriptive statistics of perceived lightness differences for the effect of desaturated crispening on uncoated substrate for the primary stimulus of 45% RTV, CIP3 – reproduction (Arithmetic Mean ± Standard Deviation (μ±σ), Median (Med), Minimum (Min), Maximum (Max), Variance (Var))*

Background Lightness (RTV)	Descriptive statistics of lightness differences for the primary stimulus of 45% RTV				
		Min	Med	Max	Var.
25%	0.302.48	0.35	-3.44	3.93	6.18
50%	-0.783.22	-0.70	-5.49	3.74	10.39
75%	-1.603.86	-1.50	-8.59	4.87	14.91
100%	-3.634.69	-3.47	-10.84	3.13	22.07

Table 3. *Descriptive statistics of perceived lightness differences for the effect of desaturated crispening on an uncoated substrate for the primary stimulus of 50% RTV, CIP3 - reproduction (mean ± standard deviation (μ ± σ), median (Med), minimum (Min), maximum (Max), variance (Var))*

Background Lightness (RTV)	Descriptive statistics of lightness differences for the primary stimulus of 45% RTV				
		Min	Med	Max	Var.
25%	0.453.25	0.52	-4.09	4.82	10.57
50%	-1.912.73	-1.86	-6.14	2.14	7.45
75%	-2.293.51	-2.21	-7.94	3.05	12.37
100%	-3.473.69	-3.37	-9.90	2.54	13.66

Table 4. *Descriptive statistics of perceived lightness differences for the effect of desaturated crispening on an uncoated substrate for the primary stimulus of 55% RTV, CIP3 – reproduction (mean ± standard deviation (μ ± σ), median (Med), minimum (Min), maximum (Max), variance (Var))*

Background Lightness (RTV)	Descriptive statistics of lightness differences for the primary stimulus of 45% RTV				
		Min	Med	Max	Var.
25%	1.421.92	1.45	-1.48	.,26	3.71
50%	0.872.90	0.93	-3.53	5.11	8.42
75%	-2.713.77	-2.61	-8.27	2.59	14.24
100%	-3.823.27	-3.75	-10.17	2.08	10.70

Tables 1, 2, and 3 indicate that the values of standard deviations and variances are large for all samples (which is expected given the methodology used in the experiment). The largest difference is observed for the primary stimulus of 45% RTV on a 100% RTV background, while the smallest difference occurs for the primary stimulus of 55% RTV on a 25% RTV background. Additionally, all ranges between the minimum and maximum values are large. The mean values and medians are similar for all samples at all observed background lightness levels.

3.3. ANOVA Analysis for Repeated Measurements

Table 5. *Results of the Kolmogorov-Smirnov Test for lightness difference for the effect of desaturated crispening on an uncoated substrate for a primary stimulus of 45% RTV on the CIP3-reproduction relation (Max D Statistic, Empirical p-value)*

Background lightness (RTV)	Max D	K-S p
25%	0.10	p > 0.20
50%	0.13	p > 0.20
75%	0.10	p > 0.20
100%	0.11	p > 0.20

Table 6. *Results of the Kolmogorov-Smirnov Test for lightness difference for the effect of desaturated crispening on an uncoated substrate for a primary stimulus of 50% RTV on the CIP3-reproduction relation (Max D Statistic, Empirical p-value)*

Background lightness (RTV)	Max D	K-S p
25%	0.14	p > 0.20
50%	0.10	p > 0.20
75%	0.11	p > 0.20
100%	0.07	p > 0.20

Table 7. *Results of the Kolmogorov-Smirnov Test for lightness difference for the effect of desaturated crispening on an uncoated substrate for a primary stimulus of 55% RTV on the CIP3-reproduction relation (Max D Statistic, Empirical p-value)*

Background lightness (RTV)	Max D	K-S p
25%	0.12	p > 0.20
50%	0.10	p > 0.20
75%	0.10	p > 0.20
100%	0.11	p > 0.20

The results of the Kolmogorov-Smirnov test show that all variables for all three lightness levels of the primary stimuli are consistent with the normal distribution (Tables 5, 6, and 7). This confirms that the assumptions for performing ANOVA analysis with repeated measurements are met. ANOVA was used to analyze the differences between the pairs of arithmetic means of the lightness differences between the perceived and physical values of the stimuli for three primary stimuli and four different background lightness variations. The statistical parameters of the ANOVA analysis are presented in Tables 8, 9, and 10.

Table 8. *Results of the ANOVA analysis for lightness difference due to the effect of desaturated crispening on an uncoated substrate for the primary stimulus of 45% RTV, CIP3 – reproduction (repeated measurement)*

Effect	SS	Degrees of freedom	MS	F	P
R1	83.23	3	27.74	3.14	0.04
Error	283.13	27	8.81		

The F-value of the test is $F = 3.14$ with a statistical significance of $p = 0.04 < 0.05$ (Table 8). This indicates that there are statistically significant differences among the analyzed mean values.

Table 9. *Results of the ANOVA analysis for lightness difference due to the effect of desaturated crispening on an uncoated substrate for the primary stimulus of 50% RTV, CIP3 – reproduction (repeated measurement)*

Effect	SS	Degrees of freedom	MS	F	P
R1	81,19	3	27,06	2,81	0,06
Error	259,66	27	9,61		

The F-value of the test is $F = 2.81$ with a statistical significance of $p = 0.06 > 0.05$ (Table 9). Therefore, it was concluded that there are no statistically significant differences between the analyzed arithmetic means.

Table 10. *Results of the ANOVA analysis for lightness difference due to the effect of desaturated crispening on an uncoated substrate for the primary stimulus of 55% RTV, CIP3 – reproduction (repeated measurement)*

Effect	SS	Degrees of freedom	MS	F	P
R1	203,36	3	67,78	8,24	0,00
Error	221,96	27	8,22		

The F-value of the test is $F = 8.24$, with a statistical significance of $p = 0.00 < 0.05$ (Table 10). This indicates that there are statistically significant differences between the analyzed arithmetic means.

Additionally, post-hoc analyses using Fisher's test were conducted (Tables 11 and 12) to identify groups whose arithmetic means of lightness differences significantly differ ($p < 0.05$). The analyses were performed for all three primary stimuli.

Table 11. *Results of Fisher's Post-Hoc analysis of lightness differences for the effect of desaturated crispening on uncoated substrate for primary stimulus of 45% RTV (CIP3 – reproduction)*

Background Liightness (RTV)	Probabilities of the post-hoc test		
	25%	50%	75%
25%	-	-	-
50%	0.420	-	-
75%	0.160	0.537	-
100%	0.006	0.040	0.139

The Fisher's post-hoc analysis shows that there are no statistically significant differences in the arithmetic means of the lightness differences (ΔL_{00}) for the pairs with background lightness levels of 25% and 50% RTV, 25% and 75% RTV, 50% and 75% RTV, as well as the pair with background lightness levels of 75% and 100% RTV (Table 11). All other pairs show statistically significant differences ($p < 0.05$).

Table 12. *Results of Fisher's Post-Hoc analysis of lightness differences for the effect of desaturated crispening on uncoated substrate for primary stimulus of 50% RTV (CIP3 – reproduction)*

Background Liightness (RTV)	Probabilities of the post-hoc test		
	25%	50%	75%
25%	-	-	-
50%	0.671	-	-
75%	0.003	0.009	-
100%	0.000	0.001	0.392

Post-hoc analysis by Fisher indicates that there are no statistically significant differences in the mean values of lightness differences (ΔL00) for the pair with background lightness values of 25% and 50% RTV and the pair with background lightness values of 75% and 100% RTV (Table 12). All other pairs show statistically significant differences ($p < 0.05$).

For the primary stimulus with 45% RTV, at a background lightness of 25% RTV, the crispening effect is reflected through a shift in perceived lightness, with a mean value of $\mu\_25 = 0.30$ and a median value of Med_25 = 0.35 (Table 2). In this case, due to the crispening effect, the primary stimulus is perceived as darker than its physical value. For background lightness values of 50%, 75%, and 100% RTV, due to the same effect, the primary stimulus is perceived as lighter than its physical value. The corresponding mean values and medians are $\mu\_50 = -0.78$, Med_50 = -0.70, $\mu\_75 = -1.60$, Med_75 = -1.50. The crispening effect is most strongly manifested at a background lightness of 100% RTV, where the mean value is $\mu\_100 = -3.63$ with a corresponding median of Med_100 = -3.47.

In the case of the primary stimulus with 50% RTV, it is perceived as darker at a background lightness of 25% RTV (Table 3). At this background, the mean shift in lightness is $\mu\_25 = 0.45$, with a median value of Med_25 = 0.52. Due to the crispening effect, the primary stimulus is perceived as lighter at background lightness values of 50%, 75%, and 100% RTV. At background lightness values of 50% and 75% RTV, the mean lightness shifts are $\mu\_50 = -1.91$ and $\mu\_75 = -2.29$, with medians of Med_50 = -1.86 and Med_75 = -2.21. The crispening effect is most pronounced at a background lightness of 100% RTV, where the mean value is $\mu\_100 = -3.47$, with a median value of Med_100 = -3.37.

For the third primary stimulus with 55% RTV, it is perceived as darker at background lightness values of 25% and 50% RTV, while it is perceived as lighter at background lightness values of 75% and 100% RTV (Table 4). At a background lightness of 25% RTV, the crispening effect is manifested as a shift in perceived lightness, with a mean value of $\mu\_25 = 1.42$ and a median of Med_25 =

1.45. Additionally, at background lightness values of 50%, 75%, and 100% RTV, the crispening effect manifests as mean shifts in lightness of $\mu\_50 = 0.87$, $\mu\_75 = -2.71$, and $\mu\_100 = -3.82$, with corresponding medians of Med_50 = 0.93, Med_75 = -2.61, and Med_100 = -3.75.

3.4. Descriptive statistics of color difference

The descriptive statistical analysis of the color differences is presented in Tables 13, 14, and 15. The differences were calculated for three primary stimuli and four different background variations, with each successive background variation increasing by 25% RTV.

Table 13. *Descriptive statistics of the perceived color difference for the desaturation crispening effect on an uncoated substrate for a primary stimulus of 45% RTV, CIP3 – reproduction (mean ± standard deviation (μ±σ), median (Med), minimum (Min), maximum (Max), variance (Var)).*

Back-ground (RTV)	Descriptive statistics for color differences for the primary stimulus 45% RTV				
		Med	Min	Max	Var
25%	3.670.76	3.54	2.86	5.00	0.58
50%	3.791.14	3.60	2.32	5.86	1.30
75%	4.961.80	4.30	3.38	9.10	3.25
100%	5.832.73	4.74	3.22	11.03	7.46

Table 14. *Descriptive statistics of the perceived color difference for the desaturation crispening effect on an uncoated substrate for a primary stimulus of 50% RTV, CIP3 – reproduction (mean ± standard deviation (μ±σ), median (Med), minimum (Min), maximum (Max), variance (Var)).*

Back-ground (RTV)	Descriptive statistics for color differences for the primary stimulus 45% RTV				
		Med	Min	Max	Var
25%	3.670.76	3.54	2.86	5.00	0.58
50%	3.791.14	3.60	2.32	5.86	1.30
75%	4.961.80	4.30	3.38	9.10	3.25
100%	5.832.73	4.74	3.22	11.03	7.46

Table 15. *Descriptive statistics of the perceived color difference for the desaturation crispening effect on an uncoated substrate for a primary stimulus of 55% RTV, CIP3 – reproduction (mean ± standard deviation (μ±σ), median (Med), minimum (Min), maximum (Max), variance (Var)).*

Back-ground (RTV)	Descriptive statistics for color differences for the primary stimulus 45% RTV				
		Med	Min	Max	Var
25%	3.300.95	2.96	2.42	5.13	0.90
50%	3.511.18	3.30	2.18	5.74	1.40
75%	4.842.05	4.08	2.81	8.58	4.22
100%	5.142.13	4.49	3.10	10.31	4.56

Tables 13, 14, and 15 indicate that the values of standard deviations and variances for individual samples are very high, with the greatest difference being observed for the primary stimulus of 45% RTV on a 100% RTV background, and the smallest difference for the same primary stimulus on a 25% RTV background. The ranges between the minimum and maximum values show large deviations. The arithmetic means and medians are similar for all samples across all observed backgrounds.

3.5. ANOVA Analysis for Repeated Measurements

Furthermore, the compliance of all obtained data with the normal distribution law was checked. For this purpose, the Kolmogorov-Smirnov test was applied, and the results are presented in Tables 16, 17, and 18.

Table 16. *Results of the Kolmogorov-Smirnov Test for color differences for the effect of desaturated crispening on an uncoated substrate for the primary timulus 45% RTV on the relation CIP3- reproduction (Max D statistic, empirical p-value).*

Background lightness (RTV)	Max D	K-S p
25%	0.19	p > 0.20
50%	0.14	p > 0.20
75%	0.23	p > 0.20
100%	0.27	p > 0.20

Table 17. *Results of the Kolmogorov-Smirnov Test for color differences for the effect of desaturated crispening on an uncoated substrate for the primary stimulus 50% RTV on the relation CIP3-reproduction (Max D statistic, empirical p-value).*

Background lightness (RTV)	Max D	K-S p
25%	0.15	p > 0.20
50%	0.22	p > 0.20
75%	0.18	p > 0.20
100%	0.19	p > 0.20

Table 18. *Results of the Kolmogorov-Smirnov Test for color differences for the effect of desaturated crispening on an uncoated substrate for the primary stimulus 55% RTV on the relation CIP3-reproduction (Max D statistic, empirical p-value).*

Background lightness (RTV)	Max D	K-S p
25%	0.23	p > 0.20
50%	0.14	p > 0.20
75%	0.24	p > 0.20
100%	0.17	p > 0.20

The Kolmogorov-Smirnov test confirmed the conformity of all samples for all three primary stimulus colorings with a normal distribution, which is a prerequisite for performing the ANOVA analysis.

Since all variables were in accordance with the normal distribution law, repeated measures ANOVA analyses were conducted (Tables 19, 20, and 21). ANOVA was used to statistically test the differences between the mean values of the visual perception of deviations in color between the perceived and physical color values of the primary stimuli for all three primary stimulus values. This allowed for the identification of differences in the intensity of the wrinkling effect depending on the different background colorings.

Table 19. *Results of the ANOVA analysis on color difference for the desaturated crispening effect on an uncoated substrate for the primary stimulus of 45% RTV, CIP3 – reproduction (repeated measures).*

Effect	SS	Degrees of freedom	MS	F	P
R1	31.72	3	10.57	3.47	0.03
Error	82.23	27	3.04		

The F-value of the test is $F = 3.47$ with a statistical significance of $p = 0.03 < 0.05$ (Table 19). This indicates that there are statistically significant differences between the analyzed arithmetic means.

Table 20. *Results of the ANOVA analysis on color difference for the desaturated crispening effect on an uncoated substrate for the primary stimulus of 50% RTV, CIP3 – reproduction (repeated measures).*

Effect	SS	Degrees of freedom	MS	F	P
R1	24.45	3	8.15	2.62	0.07
Error	83.87	27	3.10		

The F-value of the test is $F = 2.62$ with a statistical significance of $p = 0.07 > 0.05$ (Table 20). This indicates that there are no statistically significant differences between the analyzed arithmetic means.

Table 21. *Results of the ANOVA analysis on color difference for the desaturated crispening effect on an uncoated substrate for the primary stimulus of 55% RTV, CIP3 – reproduction (repeated measures).*

Effect	SS	Degrees of freedom	MS	F	P
R1	25.81	3	8.60	3.24	0.03
Error	71.63	27	2.65		

The F-value of the test is $F = 3.24$ with a statistical significance of $p = 0.03 < 0.05$ (Table 21). This indicates that there are statistically significant differences among the analyzed arithmetic means.

Furthermore, post-hoc Fisher analyses were conducted (Tables 22 and 23) to identify groups whose arithmetic means of the color differences differ statistically significantly ($p < 0.05$).

Table 22. *Results of the Fisher's post hoc analysis for color difference due to the effect of desaturated crispening on an uncoated substrate for the primary stimulus of 45% RTV (CIP3 - reproduction).*

Background Liightness (RTV)	Probabilities of the post-hoc test		
	25%	50%	75%
25%	-		
50%	0.880	-	
75%	0.108	0.143	-
100%	0.009	0.014	0.275

Fisher's post-hoc analysis shows that there are no statistically significant differences in the mean color differences (ΔE00) between the pairs with 25% and 50% RTV backgrounds, 25% and 75% RTV, 50% and 75% RTV, and the pair with 75% and 100% RTV backgrounds (Table 22). All other pairs show statistically significant differences ($p < 0.05$).

Table 23. *Results of the Fisher's post hoc analysis for color difference due to the effect of desaturated crispening on an uncoated substrate for the primary stimulus of 55% RTV (CIP3 - reproduction).*

Background Liightness (RTV)	Probabilities of the post-hoc test		
	25%	50%	75%
25%	-		
50%	0.780	-	
75%	0.043	0.078	-
100%	0.017	0.033	0.684

Fisher's post-hoc analysis shows that there are no statistically significant differences in the mean color differences (ΔE00) between the pairs with 25% and 50% RTV backgrounds, 50% and 75% RTV, and the pair with 75% and 100% RTV backgrounds. All other pairs show statistically significant differences ($p < 0.05$).

For the primary stimulus of 45% RTV with a 25% RTV background, the color shift effect is evident through a change in color appearance, with a mean value of $\mu\_25=3.67$ and a median value of $Med\_25=3.54$. The corresponding mean values for 50% and 75% RTV backgrounds, with their respective medians, are $\mu\_50=3.79$, $Med\_50=3.60$ and $\mu\_75=4.96$, $Med\_75=4.30$. The color shift effect has the largest deviation at a 100% RTV background, with a mean value of $\mu\_100=5.83$ and a corresponding median value of $Med\_100=4.74$.

For the primary stimulus of 50% RTV, on 25% and 50% RTV backgrounds, the mean color shift values are $\mu\_25=4.12$ and $\mu\_50=3.22$, with medians of $Med\_25=4.10$ and $Med\_50=2.69$. On a 75% RTV background, the mean color shift is $\mu\_75=4.76$, with a median of $Med\_75=4.34$. The largest color deviation occurs on the 100% RTV background, where the mean value is $\mu\_100=5.32$, with a median of $Med\_100=4.59$.

For the third primary stimulus of 55% RTV, on 25% and 50% RTV backgrounds, the color shift effect is evident with mean values of $\mu\_25=3.30$ and $\mu\_50=3.50$, and medians of $Med\_25=2.96$ and $Med\_50=3.30$. The previous two mean values do not differ statistically significantly. Furthermore, on the 75% and 100% RTV backgrounds, the color shift effect manifests as mean color shifts of $\mu\_75=4.84$ and $\mu\_100=5.14$, with corresponding medians of $Med\_75=4.08$ and $Med\_100=4.49$.

4. Conclusion

Statistical analysis showed significant differences in brightness and color perception for different primary stimuli and backgrounds. Using the tuning method, statistically significant differences in brightness deviations were found for most primary stimuli, except for the 50% RTV stimulus on an uncoated substrate. Similar results were obtained for color deviations, where significant differences were found for primary stimuli of 45% and 55% RTV.

The intensity of the wrinkling effect varies depending on the brightness of the background, with the most pronounced deviation on the sample with 100% RTV background for all primary stimuli. This indicates a complex interaction between the primary stimulus and the background in the perception of color and brightness.

The high degree of correlation of the obtained results opens the possibility of developing a mathematical model for the standardization of the printing process. Such a model could predict quantitative and qualitative deviations of reproduction from the given parameters, which would be of great use in the graphic industry.

This research provides valuable insight into the complexity of visual color perception in printing, especially in the context of the wrinkling effect on desaturated samples. The results can have significant implications for the optimization of printing processes and the improvement of the quality of color reproduction on different printing substrates. Understanding and applying this knowledge in practice can help graphic designers create more accurate and visually attractive products, while minimizing potential problems caused by the wrinkling effect.

The limitations of this study relate to the specificity of the materials used, as different substrates, coatings, and colors may produce different results. Additionally, the perception of color and brightness varies among individuals, making it difficult to generalize the conclusions. In the next steps of future research, it is necessary to take into account other values of primary stimuli in order to cover both research areas in lower and higher RTV of primary stimuli, and the color characteristics of the researched samples will also be taken into account.

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