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Quality of Color Lightness Reproductions

Maja Brozovic, Jesenka Pibernik and Dubravko Banic
Faculty of Graphic Arts, University of Zagreb, Getaldiceva 2, Zagreb, Croatia
E-mail: maja.brozovic@grf.hr

Abstract. *The purpose of this study is to determine whether there is any correlation between subjective and objective artwork reproduction assessment when using different printing technologies. The investigations are based on reproductions of works of art, which belong to the traditional tonal system of visual representation, characterized by the brightness range of the dominant hue from a certain part of the spectrum. This system appeared in the period of the late Renaissance. Today it is often used for expressing volume in graphic media. As a method for assessing the quality of the reproductions, instrumental measurement and visual evaluation were used. The visual study included formal/methodological characteristics of the artwork. Based on the results, a correlation between objective and subjective approaches has been shown. The results demonstrate that the best quality of color lightness is produced with conventional offset printing and an amplitude modulation screen. These results can be applied in the reproduction of images employing this tonal system of visual representation. © 2008 Society for Imaging Science and Technology.*
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INTRODUCTION

In a work of art, not only is the clear reproduction of color important, but also the visual message which makes that piece a work of art. In that aspect this study is based on the analyses of artwork reproductions employing the tonal system of visual representation. The reproduction of artwork is one of the most challenging tasks in the graphic profession. This is especially important in lightness reproduction.

The attributes of brightness and lightness are very often substituted for each other, despite the fact that they have very different definitions. **Brightness:** The attribute of a visual sensation according to which an area appears to emit more or less light. **Lightness:** The brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting. Brightness refers to the absolute perception of the amount of light of a stimulus, while lightness can be thought of as the relative brightness. The human visual system generally behaves as a lightness detector.[1–4]

A system of visual representation is the combination of the optical structural elements in groups of recognizable wholes that can be interpreted by the human eye, more or less objectively. Structural elements are point, line, plane, volume, and color. In two-dimensional media the volume is represented by continuous tonality. Based on the structural elements, systems of visual representation can be classified as linear, one-dimensional, tonal, and colorist.

The tonal system of representation is established primarily as a dominant hue from a specific color of the spectrum. It is characterized by nuancing the specific color in gradual light-dark shades, by which the shades represent the third dimension or depth. The textural increments need to be in a continuous relationship, i.e., separated below the perceptive ability of the human eye. From the aesthetic point of view, brightness is one of the structural elements of visual form. Brightness is the basic element of a tonal system of visual representation.[5] This system of visual representation first appeared in the period of the Renaissance. In graphic design, brightness is often utilized for presenting volume in two-dimensional media. Modeling is used where the harmony and immobility of form need to be achieved.

The interdisciplinary approach to brightness/lightness is the key element for a successful color reproduction. This statement confirms the commonplace color experience in which the human eye is more sensitive to the change of brightness, as compared to other color attributes (hue and saturation).[6,7] Color involves both the physical facts of light and reflecting surfaces and a very complex perceptual response to those facts.[8] These are the reasons why color lightness reproduction process is demanding. Within the reproduction process, lightness is controlled by the halftone wedge, which also serves for contrast control. Control is monitored by employing the mathematical expressions of color-difference formulae, such as CIED94 (Ref. 9) and CIEE2000.[10] Some colors have a wider range of lightness values compared to others. Yellow, as the brightest color, has a very narrow lightness value. Violet, the darkest color, has a much wider range of lightness values compared to yellow. Therefore, graphic designers use quantity contrast for balancing these values.[11]

The reproduction process is primarily a technological process used for transferring the designer's ideas into graphic media. Color is often used for visual information presentation in graphic media.[12] Different equipment, materials, systems, and processes are applied in reproduction processes to obtain quality graphic media, i.e., graphic products.[13–17]

Each of the mentioned parameters has a determining influence on the quality of the final product. The printing process, one of the dominant segments of graphic industry,

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Figure 1. Mato Jurkovic: Winter in Posavina, 2002, oil on canvas, 25×19 cm, private collection Miniatures.

Figure 2. Mato Jurkovic: Split's Harbour-Detail, 2002, oil on canvas, 25×19 cm, private collection Miniatures.

Figure 3. Mato Jurkovic: The Ruins of Diocletian's Palace, 2002, oil on canvas, 25×19 cm, private collection Miniatures.

Table I. Systematization of reproduction in accordance with the printing techniques.

Reproduction	Printing technique
1.a	Digital offset printing AM screen
1.b	Conventional offset printing AM screen
1.c	Conventional offset printing FM screen
2.a	Digital offset printing AM screen
2.b	Conventional offset printing AM screen
2.c	Conventional offset printing FM screen
3.a	Digital offset printing AM screen
3.b	Conventional offset printing AM screen
3.c	Conventional offset printing FM screen

Table II. Values of the coefficient R^2 for linear regression equations of the reproductions.

	Printing techniques		
Color	Digital offset printing AM screen	Conventional offset printing AM screen	Conventional offset printing FM screen
Cyan	$R^2=0.9827$	$R^2=0.9794$	$R^2=0.9722$
Magenta	$R^2=0.9838$	$R^2=0.9791$	$R^2=0.9781$
Yellow	$R^2=0.9924$	$R^2=0.9920$	$R^2=0.9911$
Black	$R^2=0.9850$	$R^2=0.9838$	$R^2=0.9835$

is monitored for evidence of a successful reproduction process material index. However, the final evaluation is done by consumers of graphic media by the subjective experience of visualization.

The graphic designer has to be aware of the limitations of the reproduction process. Therefore, it is possible to adapt the original idea to the capabilities of the reproduction process, in order to simplify the whole process from aesthetical, technological, and economical standpoints. If the original idea is based on the tonal system of visual representation, the knowledge of possibilities of reproducing color lightness is required.

The purpose of this research is to determine whether there is any correlation between subjective and objective artwork reproduction assessment when using different printing technologies. If this correlation exists, it is possible to evaluate the quality of color lightness reproduction by visual evaluation or instrumental spectrophotometer measurements.

EXPERIMENTAL

In order to examine the quality of color lightness of the artwork reproduction from the standpoint of printing techniques and type of screening, three oil paintings on canvas (25×19 cm) done by academy-trained painter Mato Jurkovic in 2002 were used. The paintings belong to the author's private collection named "Miniatures" and embody

Table III. Evaluations of the visual judgments of observers of reproductions given by digital offset print with the AM screen.

Mark	1a (blue)	2a (red)	3a (yellow)
Acceptable	12 (26.7%)	4 (8.9%)	11 (24.4%)
Very good	31 (68.9%)	31 (68.9%)	31 (68.9%)
Excellent	2 (4.4%)	10 (22.2%)	3 (6.7%)

Table IV. Evaluations of the visual judgments of observers of reproductions given by conventional offset print with the AM screen.

Mark	1b (blue)	2b (red)	3b (yellow)
Acceptable	1 (2.2%)	—	1 (2.2%)
Very good	22 (48.9%)	10 (22.2%)	17 (37.8%)
Excellent	22 (48.9%)	35 (77.8%)	27 (60.0%)

Table V. Evaluations of the visual judgments of observers of reproductions given by conventional offset print with the FM screen.

Mark	1c (blue)	2c (red)	3c (yellow)
Acceptable	4 (8.9%)	1 (2.2%)	3 (6.7%)
Very good	33 (73.3%)	23 (51.1%)	34 (75.6%)
Excellent	8 (17.8%)	21 (46.7%)	8 (17.8%)

the tonal system of visual representation, characterized by the brightness range of the dominant hue of a specific part of the spectrum. The paintings are characterized by dominant hues: blue (Figure 1), red (Figure 2), and yellow (Figure 3). They were selected in order to cover greater color areas with their different brightness spans.

In the technological process of painting reproduction, two printing techniques are used: conventional and digital offset print. For color separation in conventional printing, amplitude modulation (AM) and frequency modulation (FM) types of screens were utilized.[18]

The reproduction process begins with photographing the paintings and halftone wedge. A Canon EOS 10D digital camera was used. Image capture was performed during daylight, i.e., noon sunlight on a clear day with CCT 5600K. The acquired digital data were the same size as the paintings (1:1). It was processed in Adobe Photoshop CS3 with usual corrective methods (determination of white and black range). From the digital data, color separation films were made using (1) an AM screen with a screen ruling 80 lines/cm and (2) a FM screen with a dot size of 20 μm. The reproductions were printed on a four-color conventional offset Heidelberg Speedmaster 102 press. For digital offset an Indigo PRO+ machine with AM screen printing was used. The white gloss paper Euro Art Gloss (M-Real Corporation, Germany, 11.5 g/m^2) was used for conventional offset printing. Sappy (Buttenpapierfabrik Gmund, Gmund am Tegernsee, Germany, 250 g/m^2) white gloss paper was used for digital offset printing. This process produced nine reproductions, three for each artwork done with different techniques, as summarized in Table I.

Method

The investigation of color brightness reproduction was performed by the visual evaluation by observers. The instrumental spectrophotometer measurements utilized patches of the halftone wedge for examining quality of color lightness reproduction.

The original paintings were used for visual assessment. The three reproductions produced in this process were evaluated with respect to their originals. Forty-five observers, 25 female and 20 male, aged from 25 to 40, participated in the estimation. The observers were persons with a history of art and graphic design backgrounds. This choice was made in order to obtain the evaluation from a purely aesthetic point of view. All the observers passed the Ishihara color vision test.

The visual evaluation was performed according to the conditions set by ISO 3664 standard.[19] Visual evaluation was carried out in an experimental booth. The inside of the experimental booth was illuminated by a broadband F7, CCT 6500K Ra 90 fluorescent lamp. The luminance level was 360 cd/m^2. The artwork and the reproduction were placed on the floor of the booth side by side. The floor of the booth was a matte of middle lightness. The booth's interior walls were matte and neutral. The illumination was centered perpendicular to the plane of the artwork and reproduction. The observer was standing approximately 30 cm from the opening of the booth. The observation angle is 45° from the normal to the artwork and reproduction. The same distance from the specimens was maintained during visual evaluation. The overhead light was turned off. Prior to the visual assessment, the observers were asked to adapt to the test illumination for 60 s.

The judgments of visual evaluation are given on the basis of the following criteria:

- Excellent: the range of brightness on the painting is identical to the reproduction; the light and dark parts of the reproduction are excellent.
- Very good: the range of brightness on the reproduction is insignificantly smaller/bigger to the painting; the light and dark parts of the reproduction are very good.
- Acceptable: the range of brightness on the reproduction is noticeably smaller/bigger to the painting; the light and dark parts of the reproduction are acceptable.
- Still acceptable: the range of brightness on the reproduction is significantly smaller/bigger to the painting; the light and dark parts of the reproduction are still acceptable.
- Unacceptable: the range of brightness on the reproduction is significantly smaller/bigger to the painting; the range of brightness within the light and dark parts of the reproduction is unacceptable.

Patches of the halftone wedge were made to check the quality of the printing process. Instrumental measurements

Table VI. ANOVA statistical data for reproductions obtained by digital printing with the AM screen.

ANOVA: Single factor

Summary

Groups	Count	Sum	Average	Variance
Fig. 1(a)	45	170	3.777778	0.267677
Fig. 2(a)	45	186	4.133333	0.3
Fig. 3(a)	45	172	3.822222	0.285859

ANOVA

Source of variation	SS	*df*	MS	*F*	*P* value	F_{crit}
Between groups	3.377778	2	1.688889	5.936095	0.003399	3.064756
Within groups	37.55556	132	0.284512			
Total	40.93333	134				

Statistics

		Fig. 1(a)	Fig. 2(a)	Fig. 3(a)
N	Valid	45	45	45
	Missing	0	0	0
Mean		3.7778	4.1333	3.8222
Median		4.0000	4.0000	4.0000
Mode		4.00	4.00	4.00
Standard deviation		0.51737	0.54772	0.53466
Variance		0.268	0.300	0.286
Range		2.00	2.00	2.00
Minimum		3.00	3.00	3.00
Maximum		5.00	5.00	5.00
Sum		170.00	186.00	172.00

were performed on an X-RiteColor Digital Swatchbook spectrophotometer. On every patch of the halftone wedge, the reflection factor was measured. The measuring geometry was 45/0. Each patch was measured on three spots, and the result was their average value.

RESULTS

The investigation results of the quality of the printing process are presented by color lightness reproduction curves obtained by measuring the patches of the halftone wedge. The degree of correlation of the color reproduction curves was based on linear regression.

Evaluations of the visual judgments of observers are given in the Tables III–V, systematized with the printing techniques and type of screen. One-way ANOVA was used for statistic analysis of the results obtained.

Based on the color reproduction curves a small deviation is visible for screen values of 20%–40% (light area on the reproduction). There are no differences for the screen value of 50% among the printing techniques and type of screen. The small deviations are again obtained in screen values of 60%–80%, while the greatest differences are shown in the dark area of the reproduction (90%–100% screen value).

The linearity of the reproductions was evaluated on the basis of the coefficient of variation, R^2. The regression equations for different printing process and screen are shown in Table II. The coefficient of variations R^2 (Table II) almost showed a linear reproduction for all colors ($R^2 \sim 1$). This indicated high correlation and confirmed the quality of the colors' lightness reproduction independent of the technological process. As well, regression equations are statistically significant. Therefore, the regression equations can be utilized for the prediction of the printing quality process.

Evaluations of the visual judgments of observers of single reproductions are given in Tables III–V. Based on the visual evaluations of observers, the most satisfactory reproduction was obtained by conventional offset printing using the AM screen. Less satisfactory evaluations were associated with the reproductions obtained by conventional offset printing using the FM screen and by digital offset printing and the AM screen. ANOVA statistical data for these evaluations are given in Tables VI–VIII.

One-way ANOVA has statistically shown significant differences between the evaluations of observers regarding the printing techniques and type of screen:

Table VII. ANOVA statistical data for reproductions obtained by conventional printing with the AM screen.

ANOVA: Single factor

Summary

Groups	Count	Sum	Average	Variance
Fig. 1(b)	45	201	4.466667	0.3
Fig. 2(b)	45	215	4.777778	0.176768
Fig. 3(b)	45	206	4.577778	0.294949

ANOVA

Source of variation	SS	*df*	MS	*F*	*P* value	F_{crit}
Between groups	2.237037	2	1.118519	4.348168	0.014833	3.064756
Within groups	33.95556	132	0.257239			
Total	36.19259	134				

Statistics

		Fig. 1(b)	Fig. 2(b)	Fig. 3(b)
N	Valid	45	45	45
	Missing	0	0	0
Mean		4.4667	4.7778	4.5778
Median		4.0000	5.0000	5.0000
Mode		4.00[a]	5.00	5.00
Standard deviation		0.54772	0.42044	0.54309
Variance		0.300	0.177	0.295
Range		2.00	1.00	2.00
Minimum		3.00	4.00	3.00
Maximum		5.00	5.00	5.00
Sum		201.00	215.00	206.00

[a]Multiple modes exist. The smallest value is shown.

Digital offset printing, AM screen

$$F(2.132) = 5.9360,\ P < 0.004;$$

Conventional offset printing, AM screen

$$F(2.132) = 4.3481,\ P < 0.004;$$

Conventional offset printing, FM screen

$$F(2.132) = 6.6944,\ P < 0.004.$$

In comparison with the critical value $F_{crit}=3.0647$, ANOVA indicated statistically significant differences in the visual evaluations of observers. The greatest mean mark, regardless of the printing technique and type of screen, was given to Fig. 2, where the red hue is dominant (magenta+yellow). The greatest total mean mark was given to Fig. 2, reproduced by conventional offset printing with the AM screen. The lowest mean mark was given to Fig. 1, with the dominant blue hue (cyan+black) reproduced by digital offset printing with the AM screen. In total, the lowest mean mark was given to the reproductions obtained by digital printing with the AM screen.

DISCUSSION

This study analyzed the quality of color lightness reproduction from two different points of view. One was based on the results objectively obtained from the instrumental characterization of the reproduction process. The second was based on the observers' subjective evaluations of the reproductions. We wished to ascertain if there was a correlation between the results obtained based on the subjective and objective methods.

On the grounds of the instrumental measurement results, the linearity of color reproduction curves for the printing techniques used and screen types was confirmed by linear regression (Table II). The curves show small differences in the reproduction of lighter tones, and larger differences in the reproduction of the darker tones (Figure 4). Here we can see that the differences regarding different screen types are greater with digital printing than with conventional printing. Regarding colors, the greatest lightness range was achieved with yellow, followed by black and magenta, and finally cyan.

Regarding the observers' visual assessments, it is apparent that a correlation exists in connection with printing techniques and screen types. The evaluations show a corre-

Table VIII. ANOVA statistical data for reproductions obtained by conventional printing with the FM screen.

ANOVA: Single factor

Summary

Groups	Count	Sum	Average	Variance
Fig. 1(c)	45	184	4.088889	0.264646
Fig. 2(c)	45	200	4.444444	0.29798
Fig. 3(c)	45	185	4.111111	0.237374

ANOVA

Source of variation	SS	*df*	MS	*F*	*P* value	F_{crit}
Between groups	3.57037	2	1.785185	6.694444	0.001701	3.064756
Within groups	35.2	132	0.266667			
Total	38.77037	134				

Statistics

		Fig. 1(c)	Fig. 2(c)	Fig. 3(c)
N	Valid	45	45	45
	Missing	0	0	0
Mean		4.0889	4.4444	4.1111
Median		4.0000	4.0000	4.0000
Mode		4.00	4.00	4.00
Standard deviation		0.51444	0.54588	0.48721
Variance		0.265	0.298	0.237
Range		2.00	2.00	2.00
Minimum		3.00	3.00	3.00
Maximum		5.00	5.00	5.00
Sum		184.00	200.00	185.00

lation regarding the dominant hue, that is to say, regarding certain colors. The results show that the greatest percentage of observers gave an excellent mark to all image reproductions obtained by conventional offset printing with the AM screen. According to the given criteria, this result implies an almost identical image lightness range in the reproductions compared to the original work of art and very visible light and dark tones. The reproductions obtained by conventional offset printing with the FM screen and digital offset printing with the AM screen were given a "very good" mark by the greatest number of observers. That means that the reproduction's lightness is either greater or smaller than in the original, but that light and dark parts are very good.

If we compare the reproduction color curve (Fig. 4) obtained by conventional printing with the AM screen, which got the highest marks from the observers, with other curves which got lower marks, we can see that it is located in the middle. With the conventional FM screen technique the lighter tones are reproduced lighter and the darker tones even darker. That implies a contrast increase which results in an increased image contrast when visually assessing an image. With the digital printing technique with the AM screen, the lighter tones are reproduced darker and the darker tones lighter. In this case the contrast was lowered over the entire image. With the conventional AM screen technique, the light and dark tones were reproduced with approximately identical values, which means a nearly identical contrast when compared with the original.

Although statistically significant deviations are present among the observers' visual assessments (Tables III–V), they still correlate will with the instrumentally measured results (Fig. 4), shown by the analysis of color reproduction curves in comparison to the observers' visual assessments.

FUTURE RESEARCH

As previously mentioned, in the reproduction process, different processes, systems, and materials are utilized and may influence the quality of the color lightness reproductions. This study investigates a limited range of printing processes. However, different image capturing systems, substrates, and other parameters are also able to influence the color lightness reproductions.

This particularly pertains to reproductions of works of art where each parameter of the reproduction process has

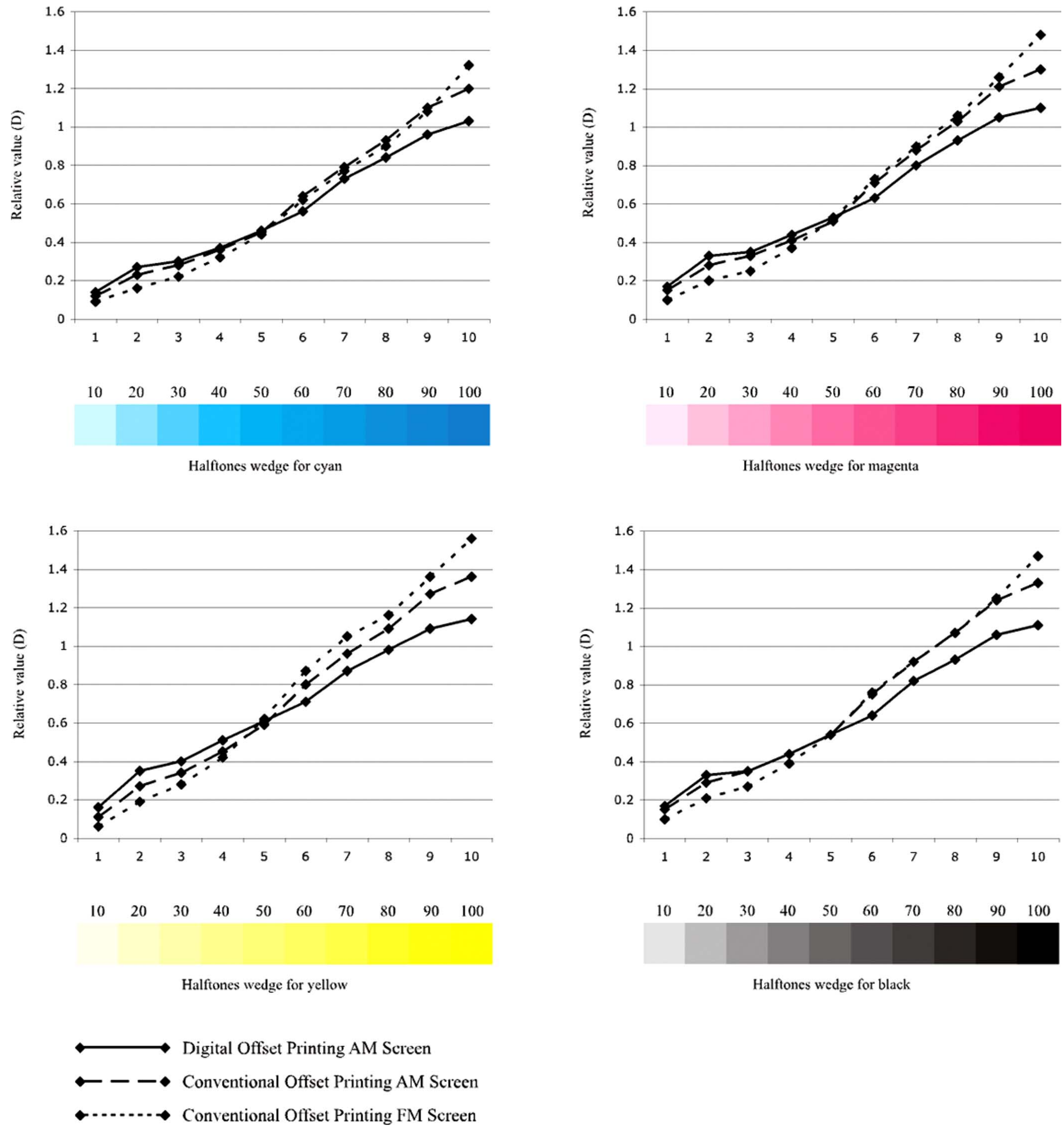

Figure 4. Color lightness reproduction curves produced by different printing techniques and type of screen.

great significance for the reproduction quality. These above mentioned parameters will be the subject of future research, with the aim of improving color reproduction quality and especially lightness as one of its characteristics.

CONCLUSION

The quality of color lightness reproduction was investigated from the point of view of different printing techniques and type of screen. For originals we used three paintings which belong to the tonal system of visual representation, characterized by the range of brightness of the dominant hue.

The dominant hues of the investigated images were blue, red, and yellow. The reproduction process quality was confirmed by the linear regression of the color curves. The reproduction assessment regarding printing techniques and screen types was performed by visual assessment on the part of observers. The results have shown a correlation between the results obtained by instrumental measurement and subjective perception of lightness. Based on the result obtained, the best results for lightness reproduction were achieved by conventional offset printing with an AM screen.

These research results can be applied to the reproduction of images utilizing the tonal system of visual presentation, where reproduction of lightness is most important.

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