The Effect of Black Printer Separation Algorithms on Perceived Spatial Image Quality

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Abstract

A visual experiment was performed to evaluate the effect of black separation on spatial image quality. Two types of black printer algorithms were evaluated. One closely simulated conventional printing with the exception of yielding colorimetric matching. The other employed a very simple algorithm based on minimum and maximum amounts of black and also employed a colorimetric paradigm. This second type is significantly easier to implement. Using pictorial and synthetically generated gradation images, two visual experiments were performed to understand the tradeoffs between processing complexity and spatial image quality. Two groups of observers from either academia or the printing industry evaluated six images. For pictorial images, the simple algorithm using the minimum amount of black resulted in the highest spatial image quality. However, this algorithm produced color contours, visible in the gradation images. Thus for general purposes, the conventional separation algorithm or the simple algorithm using nearly the minimum black amount is recommended.

Introduction

Four-color printing offers several advantages compared with three-color printing:[1] 1) extended gamut and dynamic range, 2) better shadow detail, 3) easier on-press gray balance and color control, and 4) economy (by replacing costly chromatic inks with inexpensive black ink). However, when employing a colorimetric paradigm for four-color printers, separation algorithms are under determined. There are three degrees of freedom in the input stage (colorimetric-based coordinates) and four degrees of freedom in the output stage (cyan, magenta, yellow, and black ink amounts).

A number of methods have been proposed to solve this under-determined problem.[2-8] However, many of these methods result in black ink characteristics quite different from conventional separation algorithms. Conversely, the method described by the present authors[2] results in similar black ink characteristics to that achieved in conventional color separation systems. This is important because prepress operators find unconventional systems objectionable due to their unfamiliar properties and difficulties in retouching. Of course, these limitations can be readily overcome through experience. If these unconventional methods have the additional advantage of improved spatial image quality, it may be worthwhile to implement these novel algorithms and retrain printing personnel. Thus it was of interest to evaluate the effect of black printer separation algorithms on spatial image quality.

Using a halftone proofing system set up to simulate the most common offset printing characteristics, two psychophysical experiments were performed. Both academic staff and students and printing professionals judged the spatial image quality of images printed using two types of black printer algorithms. One was a very simple model, due to Hung,[5] designed for digitally-controlled devices. The second closely approximated conventional separation practices.[2] Both types were constrained to produce colorimetric matching.

Black Printer Models

Conventional Color-Separation Black Printer Model

The first model results in very similar black ink characteristics to conventional color separation algorithms. Essentially, densitometric data are used to define the black ink amount, as is customary. Then, a spectral printing model is used to define the amounts of cyan, magenta, and yellow that yield a colorimetric match. The method is, by definition, iterative and employs a simplex search algorithm. At each iteration, the amount of black is redefined based on the chromatic ink amounts. Details are contained in reference 2. Figure 1 shows the relationship between dot areas obtained by using the model and a real prepress scanner. This model was used as a substitute of conventional color separation algorithms since prepress scanners do not guarantee colorimetric matching. This method is referred to as BP-I.

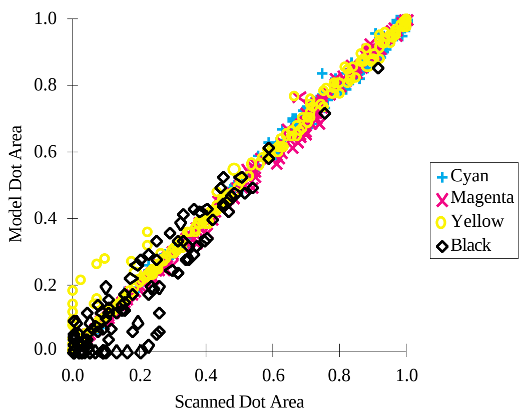


Figure 1. Relationship between dot areas of IT8.7/2 reproductions made using BP-I and a common prepress scanner

A Simple, Nonconventional Black Printer Model

Hung developed a very simple black printer algorithm for use with electronic printers.[5] In this algorithm, the minimum and the maximum black amounts are searched across the color gamut of a device in order to provide the desired colorimetric values at the first step. (In the present research, the total amount of the four inks was not constrained.) Next, the black amount was determined somewhere between the minimum and the maximum black amounts. One of the simplest methods was defined as a linear function of these black amount limits. This function is expressed as:

$$k = k_{min} + \alpha (k_{max} - k_{min}), \quad 0 \le \alpha \le 1 \tag{1}$$

where α is a coefficient which determines the amount of black, k_{min} is the minimum black, k_{max} is the maximum black, and k is the calculated black amount. The calculation was performed in the dot area space directory.

This black printer algorithm is referred to as BP-II. In this experiment, three α values (0.0, 0.5, 1.0) were selected as experimental conditions. Obviously, BP-II with α=0.0 is the same as the minimum black printer, and BP-II with α=1.0 the maximum. Therefore, four different black conditions were evaluated for each test image.

Experimental

Preparation of Test Images

Original Images: Six images were selected for study: three natural full color images, one black-and-white natural image, and two synthetically generated gradation images, shown in Figure 2. The pictorial images are ISO/JIS-SCID (Standard Color Image Data):[9] N3A, N4A, N6A, and N7A. They are named Fruit, Wine, Orchid, and Musicians, respectively. These are defined by their dot area ratios for four-color process printing. Using Adobe Photoshop, *CMYK* image data were converted into *RGB* 3-channel data for Fruit, Orchid, and Musicians. For image Wine, the "grayscale mode" was employed intermediately in order to produce a monochrome image. The others were synthetically generated gradation images in 8-bit-depth *RGB*. One had seven single color gradations (*C*, *M*, *Y*, *R*, *G*, *B*, *K*), Gradation-1. The other had three opponent color shadings (*R-C*, *G-M*, *B-Y*) in the *RGB* space and a gray (*W-K*) gradation in a diagonal direction, Gradation-2. Gradation-2 was used by Hung[5] to exaggerate potential color contouring.

Figure 2. Test images

Photographic-quality reflection prints were produced using a Fujix Pictrography 3000 at 400-dpi spatial resolution. Default color management was used and resulted in images with reasonable tone reproduction and color balance. These Pictrography images defined the "original" images. (Although transparencies are more common in graphic arts, they were not used in this experiment to avoid appearance matching confounds.) The printed image size of Gradation-2 was approximately 6.6"×6.6". The others were approximately 4"×5".

Image Reproduction: Using a Howtek Scanmaster D4000 drum scanner, the original images were scanned at 307-dpi spatial resolution (avoiding spatial interpolation), "gamma" of 1.8, and no sharpness enhancement. Reproduced images were made using the 3M Matchprint III color-proofing system. Common screen conditions were selected consisting of an AM screening, squared and hard dot screen, 175 line-per-inch resolution, and a set of normal screen angles.

A spectral reconstruction model for the scanner was developed which estimated spectral reflectance factor from digital data. This transformed the scanner into an approximate imaging spectrophotometer. From spectral data, colorimetric coordinates were directly calculated. Also, a spectral analytical model for the color proofing system was developed which predicted spectral reflectance factor from dot area ratios, based on the Yule-Nielsen-Neugebauer equations with an additional "optical trapping" ink interaction model. Employing the scanner model, two black printer algorithms, and the forward printer model, *CMYK* dot areas were calculated from scanner data. Linear optimization using the simplex algorithm was used to invert the printer model. Minimum ΔE^*_{ab} clipping was adopted as a gamut mapping technique for colors outside of the proofing color gamut. Since the goal was colorimetric color reproduction, the Pictrography paper white was not remapped to the Matchprint white. The colorimetric coordinates for both media were calculated for the 2° observer and the actual spectral radiance distribution of the light booth used in the visual experiments. This was done in order to minimize illuminant metamerism caused by differences in spectral power distributions between CIE illuminant D_{50} and the actual light source. Fluorescent lamps with high color rendering and chromaticities near D_{50} were used to illuminate the reflection prints. The illuminance was approximately 1000 lx. Because originals and reproductions were viewed under identical conditions, it was not necessary to use a color appearance model. Details on both BP-I and the various device models are also described in reference 2.

Four color-management modules, based on concatenating device profiles, corresponding to each black printer condition were made, which were 8-bit depth multi-dimensional (3-channel input and 4-channel output) CLUTs for 33×33×33 factorial digital design input sampling. Actual image data conversions were made from scanned *RGB* data to *CMYK* dot area data directory using RITRC 3DLUT[10] plug-in software for Adobe Photoshop based on cubical interpolation. A reproduced IT8.7/2 target using the Pictrography 3000 (generated by scanning an actual IT8.7/2 target and simply printing the digital file with default color management) was used as a test target to evaluate accuracy of these color-management modules. Colorimetric performance is listed in Table. I. Table I was constrained to include only common-gamut colors. Isolated black ink images of the IT8.7/2 obtained by the four black printer conditions are shown in Figure 3 as an illustrative example of the differences in black ink characteristics between the four black printer conditions.

Table I. Colorimetric accuracy of each method

	BP-I	BP-II (α=0)	BP-II (α=0.5)	BP-II (α=1.0)
Ave. ΔE^*_{ab}	2.3	2.5	2.6	2.9
Max. ΔE^*_{ab}	6.2	6.5	7.0	6.6

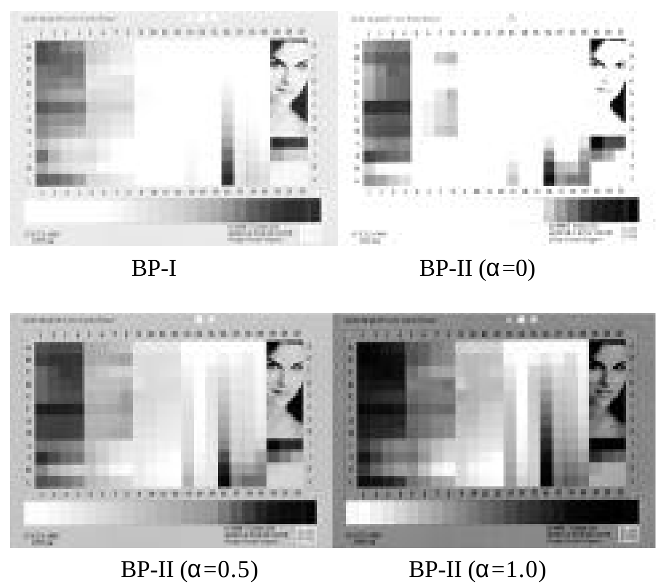


Figure 3. Isolated images of black ink obtained by four different black printer conditions

Four reproductions were made for each original. These original and reproductions were attached on 18% gray boards for psychophysical evaluation.

Psychophysical Experiment One: Paired-Comparison

A paired-comparison experiment was performed to determine whether the four reproductions were different from one another in spatial image quality. Stimuli were prepared where three images were mounted horizontally. The center image was an original. The left and the right images were reproductions of the original. Six stimuli were prepared such that each reproduction was compared pairwise. Observers were instructed to select the reproduction closest to the original in spatial image quality. The order of the stimuli was randomized for each of the observers. Stimuli were illuminated by fluorescent lamps simulating D_{50}.

For this experiment, two observer groups participated. One group consisted of 20 faculty, staff, and students of Rochester Institute of Technology. The observers belonging to this group were first trained to recognize spatial artifacts such as rosettes and pseudo-contours. The other group consisted of 13 professional printing employees who work on prepress, press, and print-quality evaluations. No training was given to this professional observer group. For both observer groups, the viewing distance was not constrained.

Psychophysical Experiment Two: Categorical Scaling

The interval scales obtained by the paired-comparison experiment indicate statistical differences and rank order. However, as a relative scale, it cannot reveal reproduction quality on an absolute basis. Therefore, a category-scaling experiment was performed to define absolute quality levels among the four reproductions.

In the categorical scaling experiment, observers saw two images at a time, the original and one reproduction. Observers judged spatial image quality using six categories: 1) art books, 2) catalogues, 3) magazines, 4) weekly magazines, 5) newspapers, or 6) unacceptable for any purpose. The same six original images were used. For this experiment, only the professional group participated because they are familiar with these print-quality categories. The number of observers was 12. The same viewing conditions were used as the paired-comparison experiment.

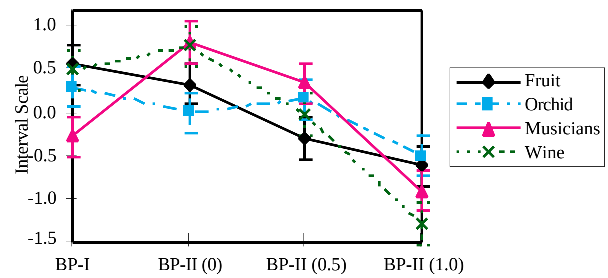
Results and Discussion

Results of Paired-Comparison Experiment

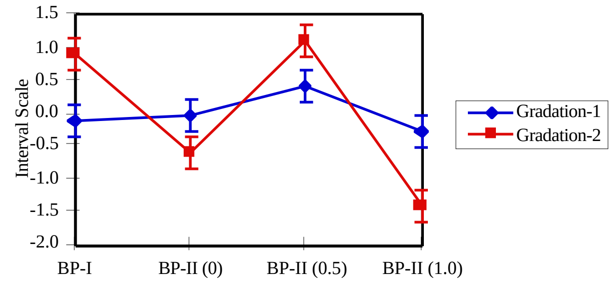
Using Thurstone's law of comparative judgments,[11] interval scales were derived from the results of the paired-comparison experiment. These interval scales indicate the psychophysical distances along the dimension of spatial image quality under the experimental conditions. The 95% confidence intervals on the scale values were calculated in terms of the scale units. These confidence intervals were used to determine whether two reproductions were statistically different from one another, facilitating ranking.

The two observer groups had similar systematic trends in visual evaluations. In fact, there was no significant difference between groups, even though one was professional and the other was not. This was an interesting result and suggests that these types of experiments can be performed in an academic environment and the results applied to industry. Because of the statistical similarity, the responses from the two observer groups were merged, and each interval scale was recalculated.

The results of the four natural images and the two gradation images are shown in Figure 4 (A) and (B), respectively. In addition, the average results for each image type are shown in Figure 5 (A) and (B), respectively.



(A)



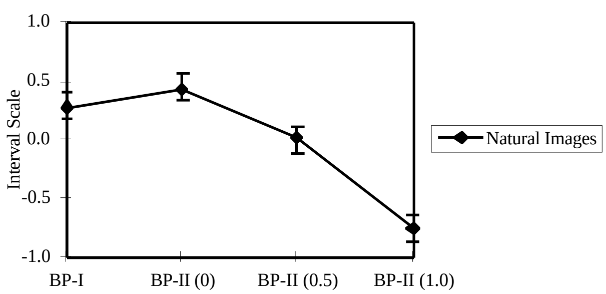
(B)

Figure 4. Interval scales of reproductions made with using four black conditions, (A): natural images, (B): gradation images

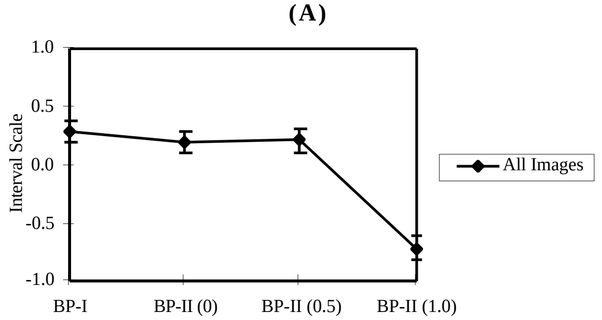
Based on evaluating the natural images, shown in Figure 4 (A), there are some small image dependencies denoted by the different rank orders of the four images. For example, the BP-I Musicians image was ranked third where for the other three images, BP-I ranked first or second. On average, as shown in Figure 5 (A), there are clear systematic trends. Smaller α values in BP-II resulted in closer spatial image quality to the original images. BP-II with α=1.0 always gave the worst results. This result is reasonable because three colored dots are replaced with one achromatic dot as α value increases. Apparently, the halftoning was more visible for the black ink than the chromatic inks, even when overprinted to produce a black. This resulted in a reduction in spatial image quality. The optical and mechanical dot gain for the chromatic inks are larger than for the black ink. Therefore, the image sharpness and contrast is reduced for the chromatic inks in comparison to the black ink. Even at 175 lines per inch, these differences were above the human visual system's contrast sensitivity threshold. The reproductions made with BP-I resulted in spatial image quality between α=0 and α=0.5 using BP-II, ranking second for the natural images. For the natural images, the rank order of each method was: 1) BP-II with α=0, 2) BP-I, 3) BP-II with α =0.5, and 4) BP-II with α=1.0.

Based on evaluating the gradation images, shown in Figure 4 (B), there was a very different data trend compared with the natural images, particularly for Gradation-2. This was due to visible pseudo-contours in the Gradation-2 image. These occurred at the two extrema, α=0 and α=1.0 in BP-II. This might be due to a nonsmooth connection of color gamut compositions separated by black ink amounts. This was pointed out by Hung.[5] This artifact was deemed more important than the appearance of the halftoning structure of the black ink.

The rank orders, based on Figure 5 (A) and (B), are summarized in Table II. Clearly, an α of 1.0 results in significantly lower spatial image quality. There were no significant differences among three of the four black conditions for all the images, even though there were significant differences for the natural images. It might be caused by the following reasons. First, BP-II with α=0, ranking first in evaluation of the natural images, had pseudo-contours in the reproduction of Gradation-2. Second, BP-II with α=0.5, ranking third in evaluation of the natural images, had no pseudo-contour in the reproduction of Gradation-2, and resulted a very good reproduction for it. Third, BP-I, ranking second in evaluation of natural images, had good reproductions of both types of natural and gradation images.



(A)



(B)

Figure 5. Averaged interval scales from the natural images (A) and all the images (B)

The best α value of BP-II for both natural and gradation images might exist somewhere between 0 and 0.5. This would provide a reasonable tradeoff between black ink visibility and pseudo-contours. BP-I would also result in reasonable spatial image quality. Through experience, the printing industry has developed a black printer algorithm which results in spatial image quality with a few visual artifacts.

To evaluate goodness of fit of the statistical analysis model to the data, a Chi-square test[12] was performed. All images were passed at a 95% confidence level.

Table II. Rank order of each black printer condition

	BP-I	BP-II (α=0)	BP-II (α=0.5)	BP-II (α=1.0)
Natural images	2	1	3	4
All the six images	1	1	1	4

Results of Categorical Judgments

The categorized quality was averaged for each reproduction. These category scaling results are given in Table III. Quality ranged between “magazines” and “weekly magazines.” All of the differences in image quality between the best and worst reproductions of each original were within one image quality unit. This means that all of the reproductions for each original might be classified in the same category. However, the reproductions of the maximum black printer (BP-II with α=1.0) were evaluated as the worst for all the images.

The reproductions of Wine, the one black-and-white image, resulted in lower quality than the other natural images. It seemed that the existence of rosettes occurred easily in the reproductions of Wine because dot areas of chromatic inks were nearly the same since only achromatic color were reproduced.

Table III. Average category

Image	BP-I	BP-II (α=0)	BP-II (α=0.5)	BP-II (α=1.0)
Fruit	3.2	3.3	3.3	3.6
Orchid	3.4	3.2	3.4	4.1
Musicians	3.6	3.0	3.4	3.5
Wine (B/W)	4.1	4.0	4.2	4.2
Gradation-1	4.2	4.4	3.8	4.3
Gradation-2	4.3	4.5	4.4	4.6
Ave. natural images	3.6	3.4	3.6	3.8
Ave. all images	3.8	3.7	3.7	4.0

There were two main reasons for the low category ranking of all of the images. None of the images were spatially enhanced (e.g. unsharp masking); the expert observers noted a lack of image sharpness. Second, the images were not reproduced using principles of preferred color reproduction resulting in "flat" images compared with typical reproduced images.

Although the paired-comparison experiment resulted in four different ranks, the category experiment resulted in only two different ranks. Thus, the four methods, while different in perceptibility, were not different in acceptability.

Conclusions

Based on the paired-comparison experiment, there was no significant difference between observer groups. Results from the "amateur" group were the same as those of the professional group. This confirms the suitability of using an academic environment for testing spatial image quality.

According to the interval scales obtained by the paired-comparison experiment in evaluation of natural images, reproductions made with the four different black conditions were significantly different. Smaller α values in BP-II resulted in closer spatial image quality to the original images. Amounts of black ink should be reduced if closer spatial image quality to photography is desired under the experimental screening conditions. These spatial quality differences were noticeable and perceptible for the observers tested.

Pseudo-contours, observable in the Gradation-2 image, resulted for both the minimum and maximum black conditions. This is a result of a lack of smoothness in ink amounts through the CLUT. This visual artifact had a greater impact on spatial image quality than black ink amount. This artifact can be readily eliminated by constraining α: $0<\alpha<1.0$.

Finally, the simple black printer algorithm with α somewhere between 0 and 0.5 worked as well as conventional separation techniques, simulated by BP-I. This algorithm may be very appropriate for four-color desktop devices printing natural and synthetic images. There is also an implication that 100% GCR techniques, common to these devices, will result in lower spatial image quality than the methods described in this research. For offset printing, either BP-I or BP-II with $0<\alpha<0.5$ should be used. However, to insure ease of on-press adjustments, BP-I seems the safer choice. Clearly, there is a need to evaluate spatial properties in addition to the usual colorimetric properties.

Acknowledgments

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Appendix

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Color Figures

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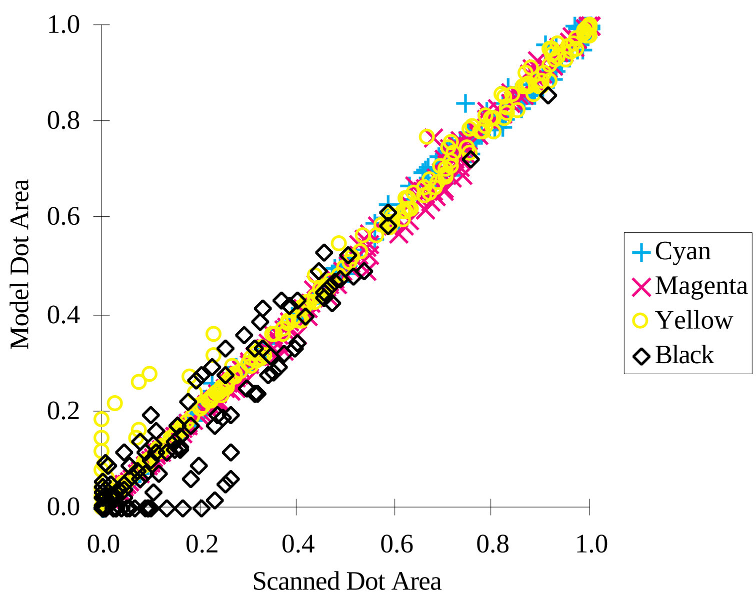
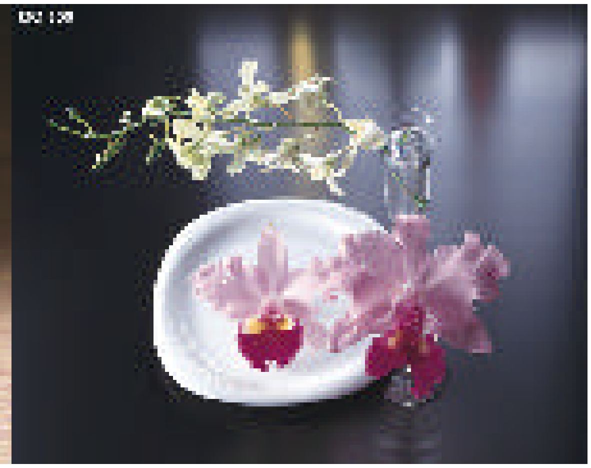


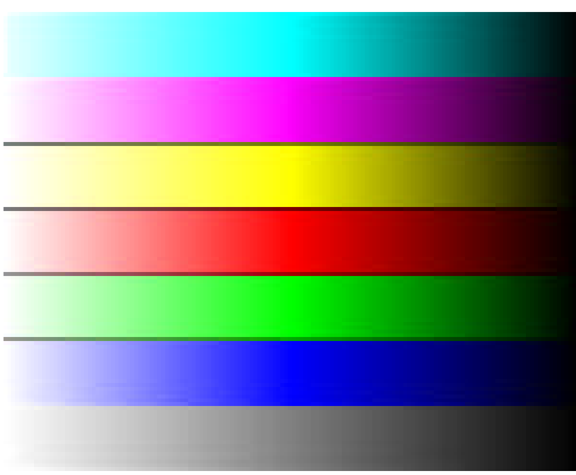
Figure 1. Relationship between dot areas of IT8.7/2 reproductions made using BP-I and a common prepress scanner


Fruit


Orchid


Musicians


Wine


Gradation-1

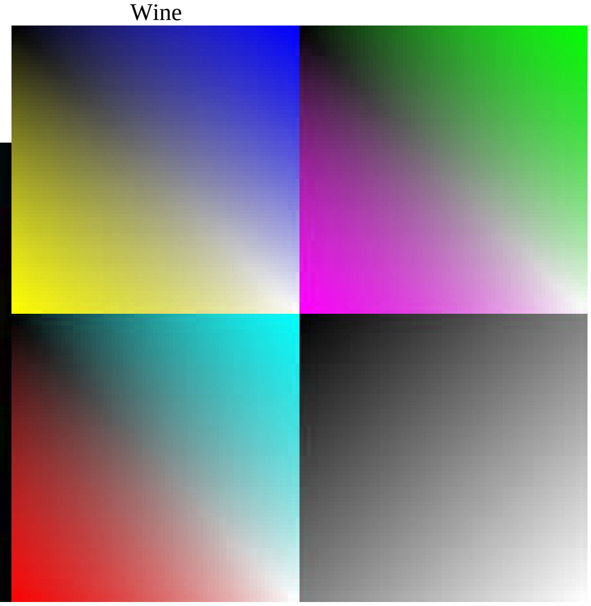
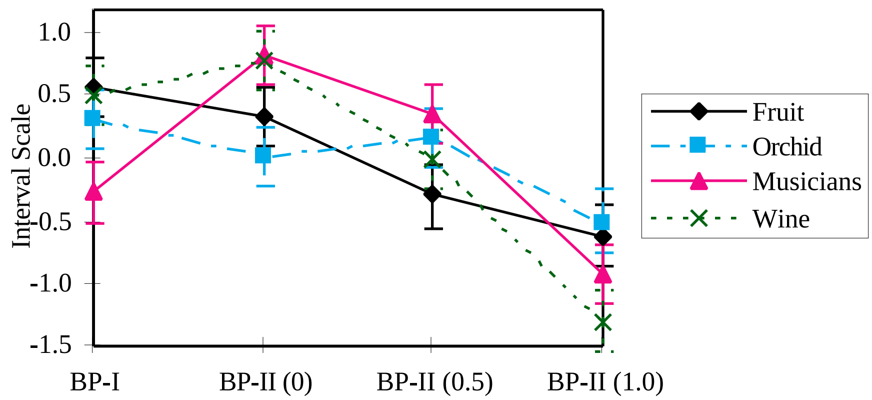
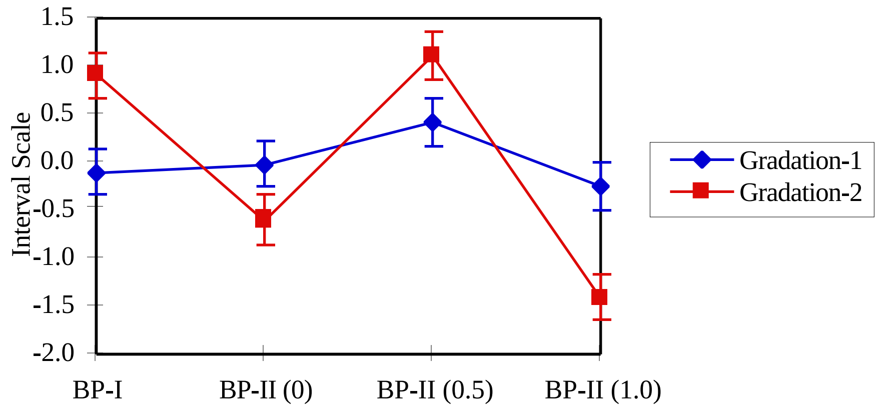

Gradation-2

Figure 2. Test images



(A)



(B)

Figure 4. Interval scales of reproductions made with using four black conditions, (A): natural images, (B): gradation images