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Psychophysical investigation of the effect of coring on perceived toner scatter

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Abstract. *The use of color electrophotographic (EP) laser printing systems is growing because of their declining cost. Thus, the print quality of color EP laser printers has become increasingly important. Since text and lines are indispensable to print quality, many studies have proposed methods for measuring these print quality attributes. Toner scatter caused by toner overdevelopment in color EP laser printers can significantly impact print quality. A conventional approach to reduce toner overdevelopment is to restrict the color gamut of printers. However, this can result in undesired color shifts and the introduction of halftone texture. Coring, defined as a process where the colorant level is reduced in the interior of text or characters, is a remedy for these shortcomings. The desired amount of reduction for coring depends on line width and overall nominal colorant level. In previous work, these amounts were chosen on the basis of data on the perception of edge blur obtained from softcopy simulation of the blurring. We describe psychophysical studies to directly establish optimal coring values as a function of line width and nominal colorant level. For each line width and nominal colorant level, this is done by asking human subjects to choose the minimum amount of coring that is necessary to eliminate the perception of toner scatter. We conduct four separate psychophysical studies to address different aspects of this question.* © 2010 SPIE and IS&T. [DOI: 10.1117/1.3267102]

1 Introduction

As color electrophotographic (EP) laser printing systems are being increasingly used because of their declining cost, the quality of print for color EP laser printers is more important than ever before. Defining print quality is, however, not an easy task, since it has to deal with both psychophysical and physical factors simultaneously and can deliver different meanings to different people. Yet there are standardized characteristics of printed characters to be assessed as the measured or perceived quality of print. These characteristics, termed as print quality attributes, include sharpness, contrast, graininess, tone scale, color rendition, quality of dots and lines, and so on. Thus, these attributes have been investigated for print quality assessment.[1–3] Sharpness describes the clarity of detail and edge transition of an image,[4] and contrast can be defined as a measure of the luminance variation relative to the average luminance in surrounding regions.[5] Graininess is represented as granularity that is a measure of visible fluctuation in reflectance. Tone scale refers to changes in lightness; and color rendition includes subattributes such as color quantization, color scale, and color fidelity.[6] Guidelines on hardcopy print quality assessment[3,7] and standards for the evaluation of image quality of printers based on appearance[8,9] have been proposed and established using these print quality attributes. As text and lines are part of most printed pages, it is hard to imagine defining print quality without considering them. Standards for the perceptual evaluation of text and line quality have been defined in detail,[10] and many studies have proposed methods for measuring these print quality attributes by both/either physical assessment and/or psychophysical assessment.

Grice and Allebach described the ISO/IEC metrics for hardcopy print quality and specified calculation techniques for the metrics.[3] Crawford, Elzinga, and Yudico investigated the measurement of print quality for tangential-edge roughness, modulation, and image grayscale fidelity.[11] These studies propounded the measurement of print quality by physical assessment, since the physical evaluation of print quality offers greater repeatability and the capability of automation that psychophysical assessment lacks. Nonetheless, a human viewer is the final arbiter of print quality, and the direct judgement of print quality by the viewer is key to the success of imaging products.[12] For this reason, Wolin, Johnson, and Kipman not only described the importance of physical analysis, but also emphasized a correlation between physical and psychophysical assessment to provide the physical measurement with meaning.[13] Burningham, Allebach, and Pizlo also discussed psychophysical approaches based on characterization of physical and per-

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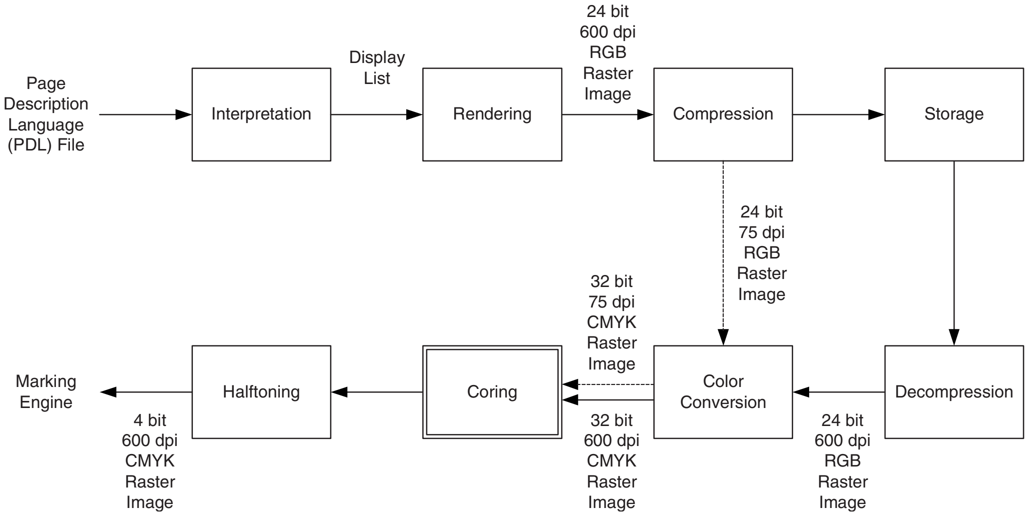


Fig. 1 Imaging pipeline for color printer containing an internal formatter/controller processor.

ceptual aspects of image quality.[2] Zhang, Allebach, and Pizlo presented print quality metrics for sharpness and performed psychophysical experiments to verify a correlation between these sharpness metrics and perceived sharpness.[14] Wu and Dalal provided a method for the assessment of perceived overall line quality that takes into account the relative perceptual weighting and preference weighting of raggedness, waviness, and lumpiness.[15] Hamerly and Dvorak studied the threshold for detection and discrimination of blur in edges and lines,[16] and determined the magnitude of change that is necessary for a noticeable change in a text image[17] by conducting psychophysical assessment.

Among the common features of text and line quality, toner scatter caused by toner overdevelopment in color EP laser printers can significantly impact print quality. A conventional approach to reduce toner overdevelopment is to restrict the color gamut of printers. However, this can result in undesired color shifts and the introduction of halftone texture. Coring, defined as a process where the continuous-tone colorant value of the pixels is reduced in the interior of text or characters, is a remedy for these shortcomings.[18] The desired amount of reduction for coring depends on line width and overall nominal colorant level. In previous work,[18] these amounts were chosen on the basis of previously published data on the perception of edge blur,[16] rather than perception of the toner scatter itself.

In the present work, we describe psychophysical studies to directly establish optimal coring values as a function of line width and nominal colorant level. For each line width and nominal colorant level, this is done by asking human subjects to choose the minimum amount of coring that is necessary to eliminate the perception of toner scatter. The resulting threshold is referred to as the *optimal coring value* throughout this work. Four separate psychophysical experiments are conducted on the perceived toner scatter. The first two experiments are designed to determine these optimal coring values by two different methods. The third experiment is to show how the direction of the edge affects the amount of toner scatter. The last experiment is to determine whether optimally cored prints are preferred to prints without coring. Of these four experiments, the results from the first experiment, performed using the symmetric coring approach, were previously reported.[19] The results for the remaining three experiments are reported in this work for the first time.

The remainder of the work is organized as follows. We first discuss preliminaries for understanding a color printer and our coring algorithm. We then describe the design of the test pages and psychophysical experiments and present results for optimal coring. We examine how the amount of toner scatter varies depending on the direction of an edge. With the results of these psychophysical experiments, we evaluate the improvement yielded by optimal coring. Finally, we draw conclusions.

2 Preliminaries

In this section, we briefly review a typical formatter/controller-based printer imaging pipeline, the marking technology for color EP laser printers, and our coring algorithm. Understanding these preliminaries is crucial to this work because the coring algorithm must function within the context of the imaging pipeline, and toner scatter is a direct result of the EP marking process.

2.1 *Imaging Pipeline, Marking Process, and Toner Scatter*

A typical imaging pipeline for color printers that have an internal formatter/controller processor is illustrated in Fig. 1. The host processor transmits a file written in a page description language (PDL) to the color printer. The PDL file describes text and graphics on a page as geometrical objects. After the PDL file is received by the controller processor, it is converted into a display list of objects to be rendered. The display list is then rasterized to a bitmap. The raster image is compressed to reduce the required storage, and then stored in memory. Before it is sent to the marking engine, the compressed data are decompressed, converted from RGB to CMYK, and halftoned. Our proposed coring algorithm is applied to the 32-bit CMYK data just prior to halftoning. In addition to the 32-bit 600-dpi CMYK data,

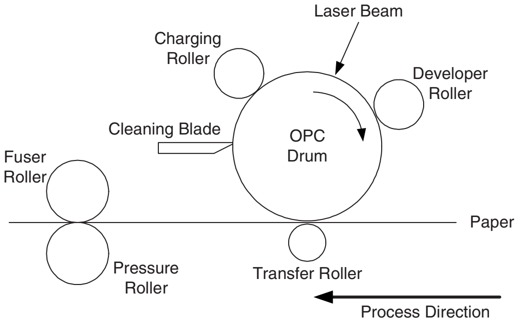


Fig. 2 Electrophotographic process.

the coring algorithm takes as input the 75 dpi low resolution image data that are available as block-averaged information from the compression process.

As illustrated in Fig. 2, the EP process consists of six steps:[20] charging, exposure, development, transfer, fusing, and cleaning. The charging roller charges the surface of the organic photoconductor (OPC) drum uniformly in the charging step. In the exposure step, the laser beam selectively discharges the OPC drum to create a latent image. In the development step, the development roller enables toner particles to move onto the exposed areas on the OPC drum. In the transfer step, toner particles are transferred to the paper, which is oppositely charged to the toner particles. In the fusing step, the toner particles are bound to the paper by the heated fuser roller and the pressure roller. In the cleaning step, the cleaning blade removes residual toner particles.

A major effect of toner scatter is to make the printed page appear blurred to the human viewer. The amount of toner scatter depends on the line width and colorant level. Figures 3(a) and 3(b) show the scanned images of a quarter section of a 10-pixel-wide annulus rendered with colorant levels cyan (C)=magenta (M)=100%, yellow (Y)=black (K)=0%, and colorant levels C=M=80%, Y=K=0%, re-

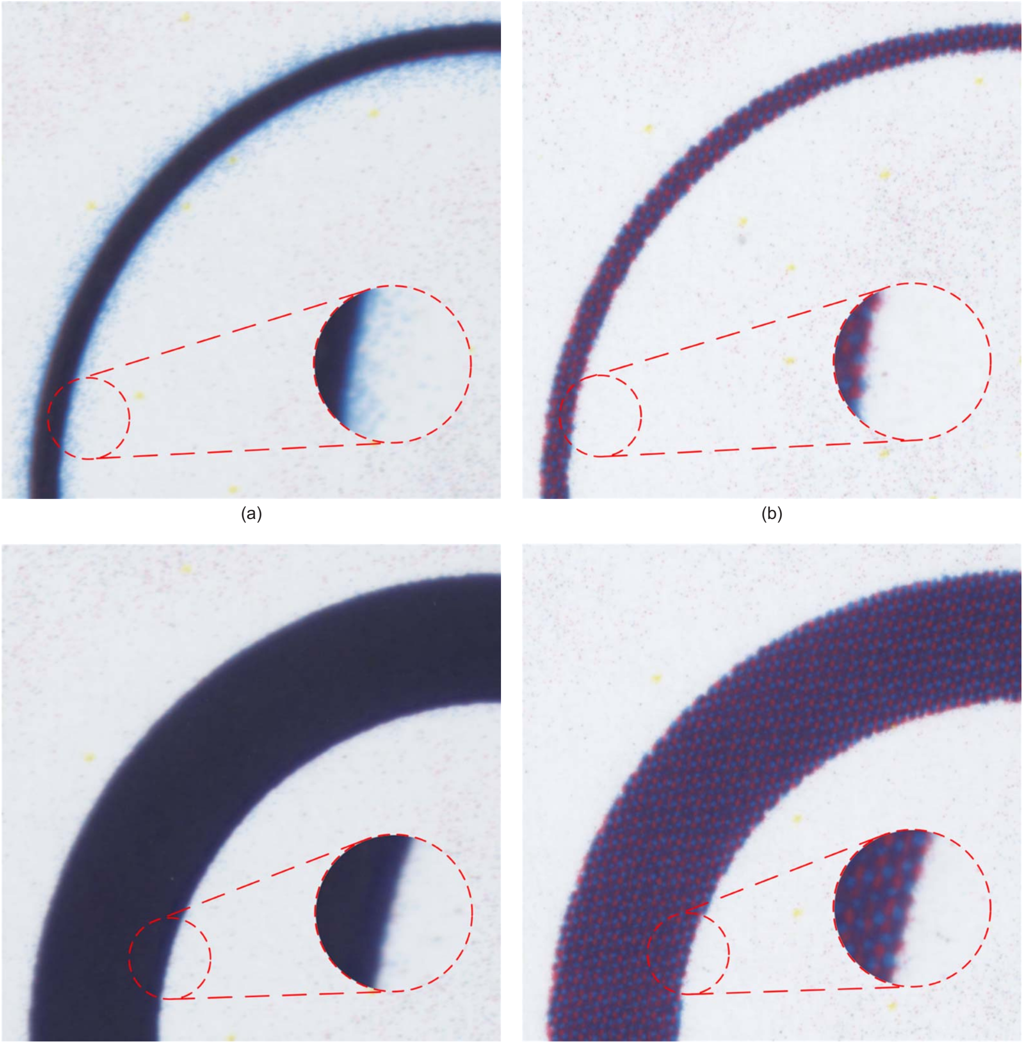
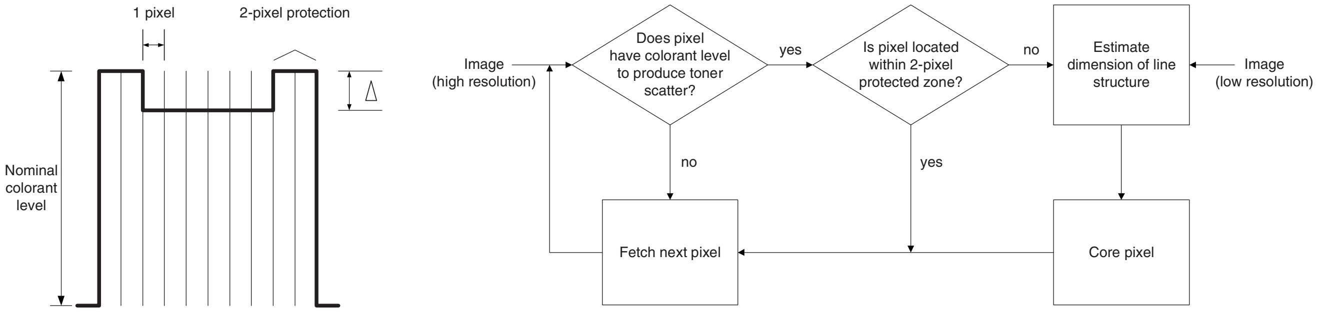

(a)
(b)
(c)
(d)

Fig. 3 Toner scatter around edges: (a) C=M=100%, Y=K=0% with 10-pixel line width. (b) C=M=80%, Y=K=0% with 10-pixel line width. (c) C=M=100%, Y=K=0% with 50-pixel line width. (d) C=M=80%, Y=K=0% with 50-pixel line width. Printed at 600 dpi, scanned at 2400 dpi, and reproduced at 240 dpi. So the, overall magnification of the images is 10×. Inserts are magnified by 20×.



(a) (b)

Fig. 4 Coring algorithm: (a) profile of cored line, and (b) overview of coring algorithm.

spectively. Note that a large amount of toner scatter appears near the edges of the annulus in Fig. 3(a). The scattered colorant is primarily *C*, which, for the particular printer used to generate these samples, is printed on top of the M colorant. This makes the C colorant much more susceptible to scatter than the M colorant, which is printed first. A comparison between Figs. 3(a) and 3(b) shows that lowering the colorant level reduces toner scatter. Similarly, the scanned images of a quarter section of a 50-pixel-wide annulus shown in Figs. 3(c) and 3(d) have colorant levels C =M=100%, Y=K=0%, and colorant levels C=M=80%, Y=K=0%, respectively. Lowering the colorant level with the wider lines also reduces toner scatter as shown by comparing Figs. 3(c) and 3(d). However, the effect is not as dramatic as in the case of the narrower lines. Comparing Figs. 3(a) and 3(c), we see that increasing the line width at full colorant level also significantly reduces toner scatter.

Toner repulsion by toner overdevelopment during the development step and air breakdown with unfused toner on the paper during the transfer step mostly account for such toner scatter.[21] Between these two sources of toner scatter, the goal of coring is to reduce toner scatter caused by toner overdevelopment during the development step while preserving the color and overall appearance of the printed page.

2.2 *Coring Algorithm*

Coring is a process that decreases the continuous-tone colorant value of the pixels in the interior of text or characters to diminish the effect of toner scatter.[18] Our goal is to accomplish this task with minimal changes to color and spatial appearance of the printed page. Coring offers the potential to achieve a better match to the colors intended by the designer for use in the document, since the amount of colorant reduction for coring varies depending on the line width and colorant level. This is in contrast to the conventional method that reduces the amount of colorant uniformly over the whole page.

Figure 4(a) shows how coring is implemented. It shows the cross section of a 10-pixel-wide line. Inside a two-pixel-wide zone on either edge of the line, the colorant amounts are decreased by a percentage Δ of the nominal colorant level. The two-pixel-wide protected regions are not modified. The optimal coring value is defined as the minimum amount of coring that will eliminate the perception of toner scatter at the edges of lines.

Figure 4(b) shows the steps that are part of the coring algorithm. The first step is to check the colorant level of a pixel to determine whether or not that pixel is a candidate for coring. The second step is to examine the location of the pixel. Pixels located within a two-pixel boundary of the edge will not be cored. The third step is to estimate the dimension of the surrounding line structure containing the candidate pixel by utilizing both the high and low resolution image data. Finally, the pixel is cored by the optimal coring value, determined as a function of the pixel colorant level and the estimated dimensions of line structure containing that pixel. Further details on the coring algorithm itself can be found in Ref. 18.

3 Determination of Optimal Coring Value

Although the coring values deployed by Bernal, Allebach, and Trask[18] provide a decrease in toner scatter with less color shift, these values were chosen on the basis of data from monochrome softcopy experiments using blur in edges and lines. To base the determination of optimal coring values directly on assessment of cored images, we conducted two psychophysical experiments to directly measure the perception of toner scatter. In this section, we describe the design of the test pages, the procedure of these psychophysical experiments, and the results we obtained.

3.1 *Overview*

The objective of these experiments was to determine the optimal amount by which the colorant level should be reduced in the interior of text or characters. To do this, subjects examined a series of character glyphs. Each series had a fixed line width and nominal colorant level. Within each series, only the coring amount varied. For each fixed line width and nominal colorant level, the subjects chose the character glyph with the minimum amount of coring that did not show toner scatter. Our psychophysical experiments were conducted with only the colorants C and M. However, we did examine test patterns printed with other combinations of colorants, as discussed later in the conclusions. To determine the optimal coring levels, we conducted two different psychophysical experiments. The first was a symmetric coring experiment in which a single optimal coring value was determined for each combination of line width and nominal colorant level by reducing the C and M colorants by the same amount in the interior of the character glyphs. The second was an asymmetric coring experiment

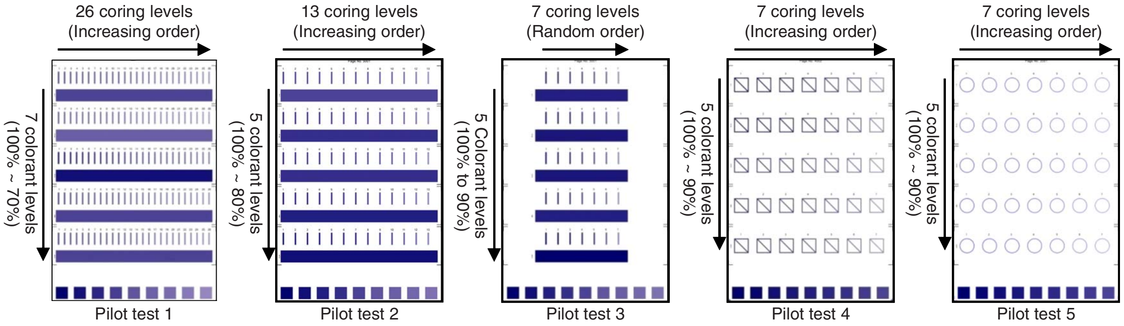


Fig. 5 Test pages for pilot psychophysical experiments conducted to determine best overall test page design.

in which a pair of optimal coring values was determined for each combination of line width and nominal colorant level by reducing the C and M colorants by possibly different amounts in the interior of the character glyphs.

Several pilot psychophysical experiments were conducted to choose the shape of the test stimulus, to determine the range of the nominal colorant levels and line widths of the test stimulus, and to arrange the order of the coring amounts. Figure 5 shows some of test pages that we used for the pilot experiments. Results from these experiments showed that the overall shape of the test stimulus and the order of the coring amounts had no significant influence on the results of the experiment. However, the subjects found that the experiment was more difficult when the coring amounts were not arranged in sequential order; and the step size of the coring amounts was too small. The results also indicated that the test stimuli with a nominal colorant level below 90% or a line width over 50 pixels did not contribute to perceivable toner scatter for most human subjects.

3.2 *Symmetric Coring*

The objective of the symmetric coring experiment was to determine the single optimal coring value at a specific line width and nominal colorant level. To do this, the same amount of coring was applied to both colorant C and colorant M in the experiment.

3.3 *Experimental Design*

We selected a glyph for the test stimulus in the shape of an annulus with diameter 360/600 in. to correspond to the form of the thin lines and text to which coring would be applied when implemented in a printer, and to average out any directional dependence of the optimal coring level. The annulus had a radius of 180/600 in. Only combinations of C and M colorants with the same amounts (e.g., C=M and Y=K=0%) were examined and five different nominal colorant levels of C and M were used, ranging between 90 and 100% in steps of 2.5%. For the line width of the annulus, six different line widths were used ranging from 5/600 in. to 50/600 in.

Each test pattern consisted of seven test stimuli, one without coring and six with different coring amounts that had identical line widths and fixed nominal colorant level, as shown in Fig. 6. Because the order of the coring amounts for these seven test stimuli did not significantly influence perception of toner scatter based on our observation from the pilot experiments, these test stimuli were arranged horizontally in increasing order of the coring amounts from left to right to show a clear transition of coring effect to the subjects. That is, the leftmost one had no coring and the rightmost one had the maximum coring amount. Note that the coring amount of colorant C was always equal to that of colorant M.

A test page comprised five test patterns. On each test page, these five test patterns had identical line width, but different nominal colorant levels. As there were five nominal colorant levels for each line width, one test page would be sufficient to accommodate all five nominal colorant levels at that fixed line width. However, a total of five test pages per line width were provided to the subjects to yield five repetitive trials. Contrary to the arrangement of the test stimuli with respect to the amount of coring for a fixed line width and nominal colorant level, the distribution of the test patterns with the same line width, but different nominal colorant levels, was randomized vertically throughout all five test pages to avoid response bias. Figure 7(a) shows a sample test page for the symmetric coring experiment.

Color plane misregistration causes images to appear out of focus.[22] At the same time, it reduces the amount of toner scatter near edges. To eliminate these confounding effects, it is desirable to choose test pages that exhibit minimal color plane misregistration. To facilitate this screening process, color plane registration (CPR) bars were inserted at the bottom of test pages. Calibration patches and skew marks that will be utilized for a follow-up research project were also placed on the test page. However, these three features were hidden from the subjects during the psychophysical experiment.

All test pages were printed at a resolution of 600 dpi, using an HP Color LaserJet 2605 printer (Hewlett-Packard, Palo Alto, California), which has a jump-gap developer system that prints the colorant planes in the order M, C, Y, K.

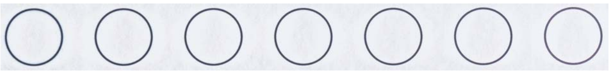


Fig. 6 Test pattern consisting of seven test stimuli with 10-pixel line width and nominal colorant level C=M=100%, Y=K=0%. The leftmost test stimulus has no coring, but the rest of them have increasing amounts of coring from left to right. Printed at 600 dpi, scanned at 1200 dpi, and reproduced at 1200 dpi. So the overall magnification of the image is 1×.

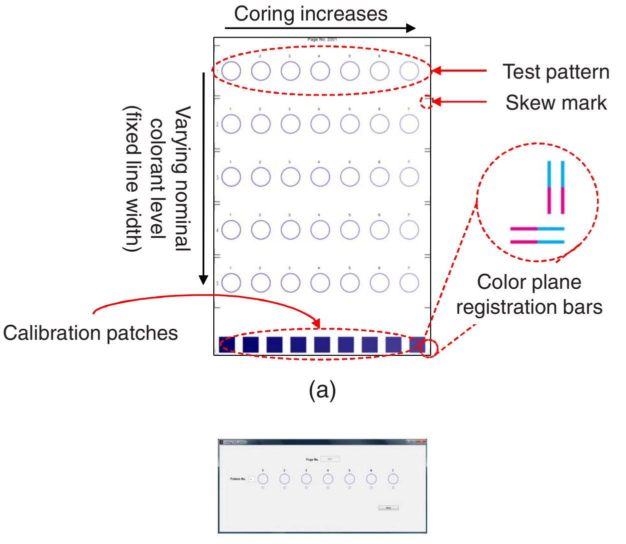


Fig. 7 Test page and graphical user interface (GUI) for collecting psychophysical data in the symmetric coring experiment (a) Test page consisting of five test patterns with a fixed line width and randomly selected nominal colorant levels. (b) The GUI shows a replica of the printed test pattern that subjects observed.

For our media, we used HP Color Laser Glossy Photo Paper 220 g/m^2. Glossy photopaper was selected because its relatively smooth, nonporous surface results in a larger amount of toner scatter. One would expect to observe less toner scatter with an EP printer that utilizes a contact development system and when printing on media with a rougher, uncoated surface. However, the methodology that we use here to investigate toner scatter should be generally applicable to other EP printing systems and media types. One would also expect the general characteristics of the results obtained with other EP printing systems and media types to be similar to those observed with our printer and media.

The psychophysical experiment was conducted in a controlled laboratory under normal ambient lighting conditions at Purdue University. All subjects were asked to take two prescreening tests, a visual acuity test for normal vision and the Ishihara test for color blindness, and one postscreening test, the 100-hue test for color discrimination. Only subjects who passed both prescreening tests could participate in the experiment, and only the responses of subjects without a significant color vision deficiency as assessed by the postscreening test were included in the data analysis.

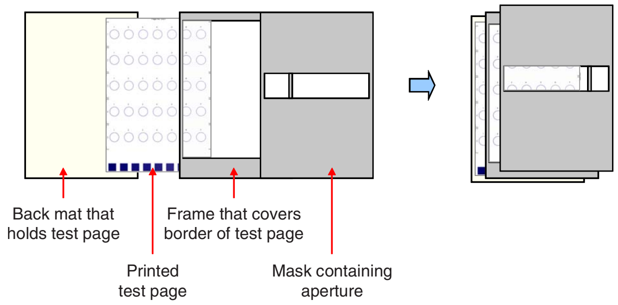


Fig. 8 Apparatus for viewing test pages in the symmetric coring experiment.

Subjects viewed the test pages in groups, each containing five pages with identical line width. Since there were six different line widths, a total of 30 test pages were examined by each subject. During the experiment, the subjects were encouraged to look at the test pages at a normal viewing distance of 10 to 15 in. For viewing, the test page was placed in the apparatus shown in Fig. 8 (MatShop/Island Art Publishers, Blaine, Washington). This apparatus consisted of a back mat, a frame, and a mask. These components served to protect the test page; to hide the skew marks, CPR bars, and calibration patches; and to facilitate the examination of one test pattern at a time. To view the next test pattern in the sequence, the subjects slid the mask down the test page. The subjects were instructed to ignore three undesired factors: background noise, jaggedness, and color plane misregistration, as shown in Fig. 9, since these factors could undesirably affect the subjects's choices. Even with the prescreening process based on the CPR bars shown in Fig. 7(a), it was very difficult to completely eliminate color plane misregistration in the printed test pages. The average misregistration plus or minus the standard deviation was $0.56/600 \pm 0.42/600$ in. for the horizontal direction and $0.67/600 \pm 0.45/600$ in. for the vertical direction, respectively.

Within each single test pattern, the subjects were asked to choose the leftmost test stimulus that did not show toner scatter near the edges. The subjects recorded their re-

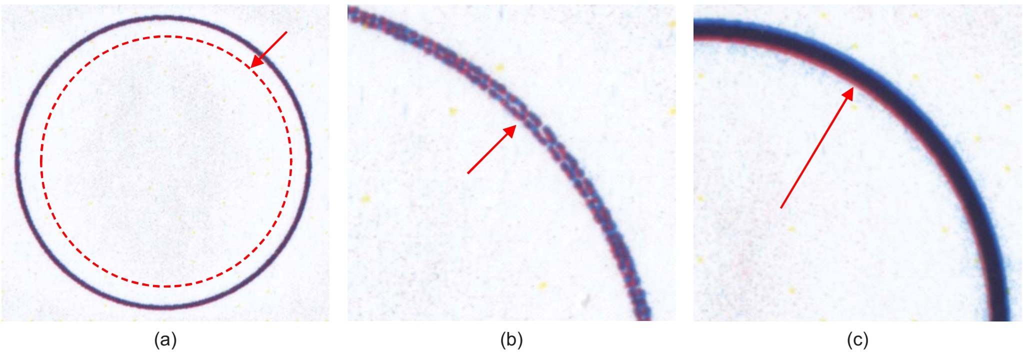
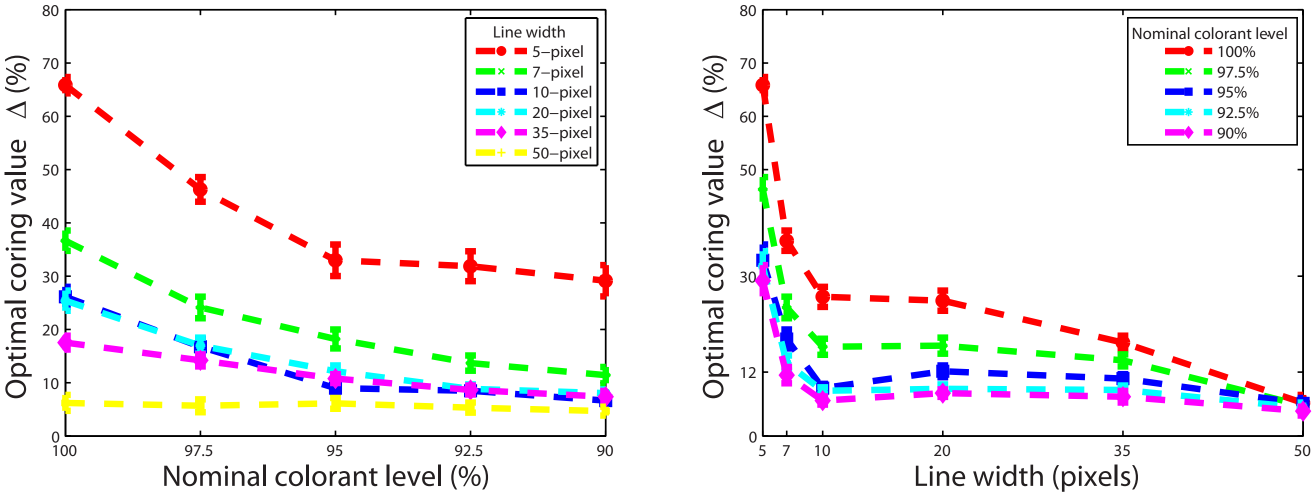

(a) (b) (c)

Fig. 9 Undesired factors that subjects were instructed to ignore: (a) background noise (inside dotted circle), (b) jaggedness, and (c) color plane misregistration.



(a) (b)

Fig. 10 Measured optimal coring values for symmetric coring averaged over the responses of 25 subjects. The C and M colorants were cored by the same amount, and the character shape was an annulus. Error bars for 95% confidence interval are also shown. The same dataset is plotted in two different ways: (a) optimal coring value versus nominal colorant level, and (b) optimal coring value versus line width. Refer to Fig. 4(a) for illustration of how coring is done.

sponses on a laptop computer by selecting the appropriate radio button in the graphical user interface (GUI) shown in Fig. 7(b), and were free to take as much time as needed. On average, each subject spent around two hours on the experiment.

3.4 *Experimental Results*

A total of 25 subjects participated in the symmetric coring experiment. They were mostly students and postdoctoral researchers at Purdue University. Results showing the optimal coring value as a function of line width and nominal colorant level from this experiment are contained in Fig. 10. Figure 10(a) shows that for fixed line width, the optimal coring value decreases with decreasing nominal colorant level. Figure 10(b) shows that for fixed nominal colorant level, the optimal coring value generally decreases with increasing the line width. Figure 11 shows our experimental data again. However, they are plotted separately for each line width to facilitate comparison with the predictions of Bernal, Allebach, and Trask's model, which are also shown in this figure. At very thin line widths or low colorant levels, Bernal, Allebach, and Trask's model underpredicts the optimal coring values. At very thick line widths, their model overpredicts the optimal coring values. This may be because the coring values adopted by Bernal, Allebach, and Trask's model were chosen based on data from monochrome softcopy display of blurred lines, as mentioned earlier, while this work provides those values directly from an experiment based on viewing color hardcopy prints with actual toner scatter.

3.5 *Asymmetric Coring*

In the process of conducting the symmetric coring experiment, we observed that for some combinations of line width and nominal colorant level, coring C and M by the optimal amount resulted in a visible shift in perceived hue toward M, even though both colors had been cored equally. We hypothesized that for these combinations of line width and nominal colorant level, it might be possible to achieve the desired reduction in toner scatter, yet stay closer to the desired hue by allowing C and M to be cored by different amounts. Specifically, we expected that observers would generally choose to core M more than C. This led to the design of an asymmetric coring experiment in which we determine separate optimal coring values for C and M, respectively, for each fixed line width and nominal colorant level.

3.6 *Experimental Design*

Since the overall goal of the asymmetric coring experiment was the same as that of the symmetric coring experiment,

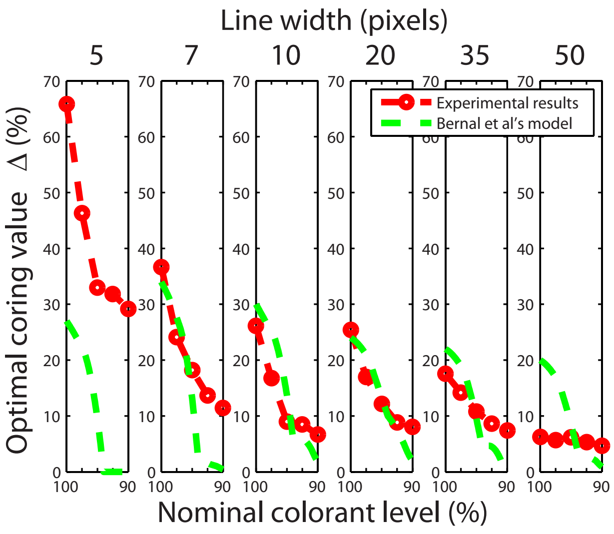
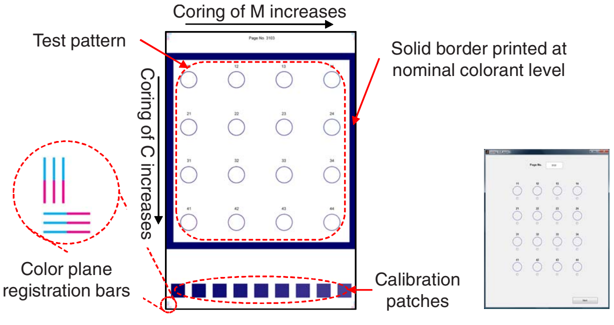


Fig. 11 Comparison between coring values based on Bernal, Allebach, and Trask's model and coring values obtained from our psychophysical experiment with symmetric coring applied to annuli.



(a) (b)

Fig. 12 Test page and graphical user interface (GUI) for collecting psychophysical data in the asymmetric coring experiment. (a) Test page consisting of one test pattern with a fixed line width and fixed nominal colorant level. (b) The GUI shows a replica of the printed test pattern that subjects observed.

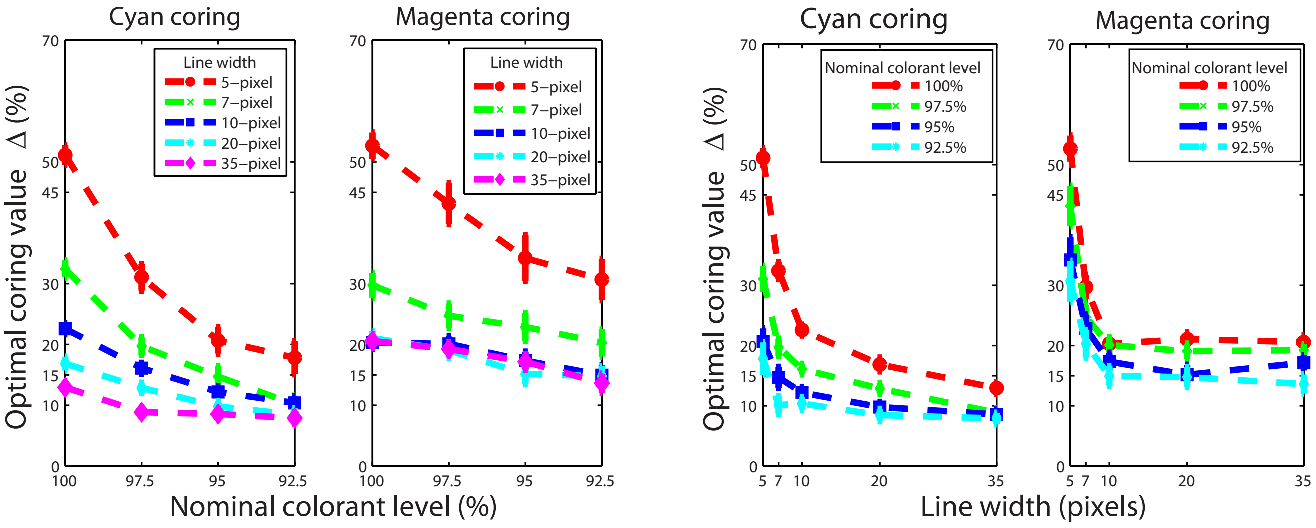
the basic features of the asymmetric coring experiment were inherited from those of the symmetric coring experiment. Therefore, the design of the symmetric and asymmetric coring experiments shared the same formalities such as the random distribution of test patterns with the same line width throughout all test pages, CPR bars and calibration patches at the bottom of the test page, screening tests for the subjects, and the use of the apparatus. However, the details of the test page and procedure of the asymmetric coring experiment were different because we added color matching as an additional factor in this experiment. We used four different nominal colorant levels of C and M ranging between 92.5 and 100% in steps of 2.5%, and five different line widths ranging from 5/600 in. to 35/600 in..

Each test pattern for the asymmetric coring experiment was composed of 16 test stimuli with identical line width and fixed nominal colorant level distributed in the form of a 4×4 array. A test stimulus without coring was located at the first row and column of the 4×4 array. Within each row, the coring of C was fixed and the coring of M increased from left to right. Within each column, the coring of M was fixed and the coring of C increased from top to bottom. Note that the coring amount of colorant C was equal to that of colorant M for the test stimuli on the diagonal, as in the case of the symmetric coring experiment.

In contrast to the symmetric coring experiment, a test page for the asymmetric coring experiment included only one test pattern, as shown in Fig. 12(a). For each line width, a total of 20 test pages with four different nominal colorant levels and five repetitive trials were shown to the subjects. Thus, while there were a total of 30 test pages in the symmetric coring experiment, the asymmetric coring experiment was run with the total number of 100 test pages, because there were five different line widths. In this experiment, the subjects were asked to choose the test stimulus that had no toner scatter near the edges and that most closely matched the color of the thick border of solid colorant that was printed at the nominal colorant level. On the average, each subject spent 100 min on the experiment.

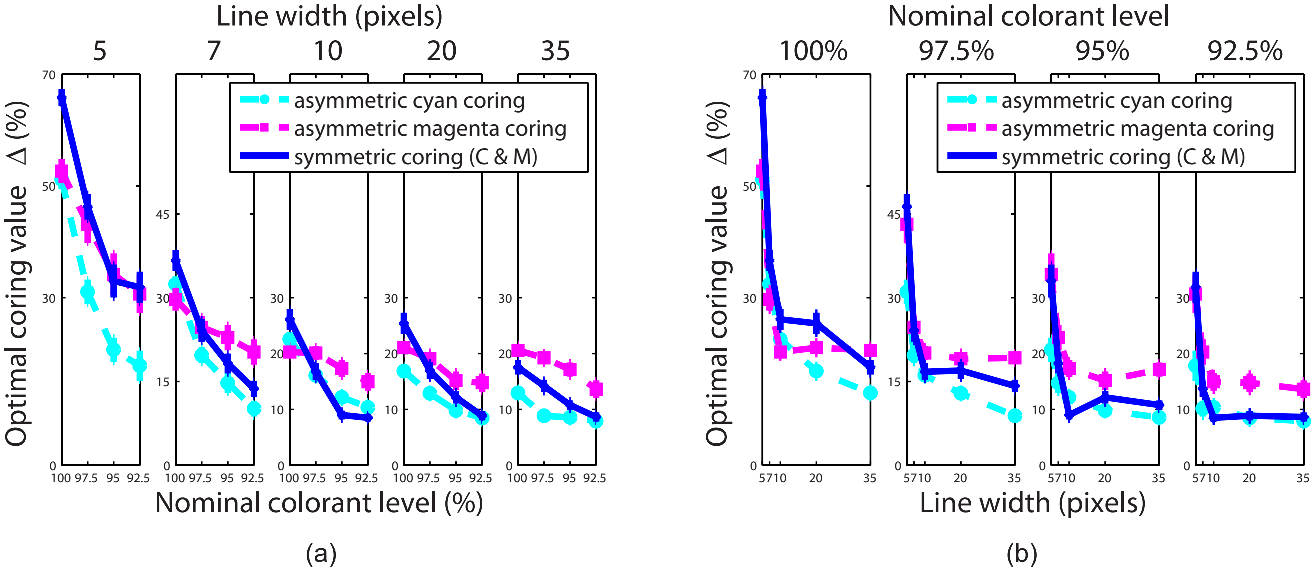
3.7 *Experimental Results*

A total of 21 subjects participated in the asymmetric coring experiment. They were also mostly students at Purdue University. Some of them had already participated in the previous symmetric coring experiment. Figure 13 shows the optimal coring value as a function of line width and nominal colorant level. As observed from the symmetric coring experiment, for both colorants, the optimal coring values also decrease as the nominal colorant level decreases for fixed line width, as shown in Fig. 13(a). For both colorants, the optimal coring values also generally decrease as the line width increases for fixed nominal colorant level, as shown in Fig. 13(b).



(a) (b)

Fig. 13 Measured optimal coring values averaged over the responses of 21 subjects in the asymmetric coring experiment. The character shape was an annulus. Subjects could choose different levels of coring for C and M. Error bars for 95% confidence interval are also shown. The same dataset is plotted in two different ways: (a) optimal coring value versus nominal colorant level, and (b) optimal coring value versus line width. Refer to Fig. 4(a) for illustration of how coring is done.



(a) (b)

Fig. 14 Comparison between the symmetric and asymmetric coring experiments. Error bars for 95% confidence interval are also shown. The same dataset is plotted in two different ways: (a) optimal coring value versus nominal colorant level, and (b) optimal coring value versus line width.

While symmetric coring requires a single optimal coring value, asymmetric coring requires a pair of optimal coring values because the individual levels of optimal coring, depending on colorant, can be different. To compare results from the two coring experiments and to observe optimal asymmetric coring values of both C and M colorants in the same figure, the data of the two experiments are plotted again, but separately for each line width and nominal colorant level, as shown in Figs. 14(a) and 14(b), respectively. The preferred level of optimal coring of colorant C is smaller than that of colorant M. Optimal symmetric coring values are generally located between optimal asymmetric coring values of colorant C and colorant M, except for the nominal colorant level 100% or the 5-pixel line width. If eliminating the perception of toner scatter were the only criterion used by the subjects, as it was in the symmetric coring experiment, one might expect for each fixed line width and nominal colorant level that the optimal symmetric coring value would lie between the optimal asymmetric coring values for C and M. However, for the asymmetric coring experiment, subjects were asked to consider both toner scatter and fidelity of the color of the character glyphs to the solid color border that surrounded the test pattern. We believe that this difference in criteria is responsible for the small discrepancy between the results of the two experiments.

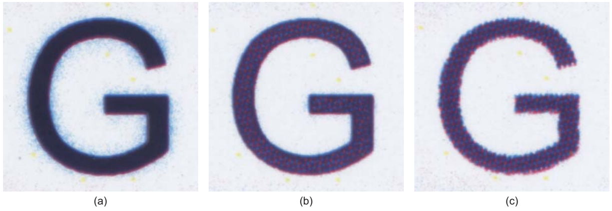
Figure 15 compares the results of optimal asymmetric coring and the conventional method of color clipping. With optimal asymmetric coring, we reduce toner scatter near the edges of text and lines while yielding the appearance of a sharper edge transition and offering a better match to the intended colors than color clipping.

4 Effect of Edge Direction on Preferred Coring Level

During our investigations of toner scatter and the effect of coring on toner scatter, we observed informally by visual inspection that the toner scatter from edges appeared to be dependent on edge orientation. This motivated us to design an experiment to determine the amount of coring preferred by subjects as a function of edge orientation. In the remainder of this section, we describe this experiment and discuss the experimental results that we obtained.

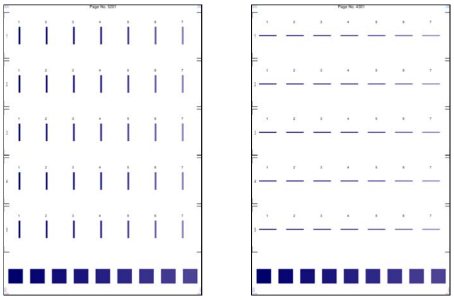
4.1 *Experimental Design*

The design of the test page for this experiment followed the same format as the test page for the symmetric coring experiment except for the shape of the test stimulus. Instead of using an annulus, vertical bars and horizontal bars were used in the experiment to clearly show the directional influence on the preferred coring level. The length of the vertical or horizontal bar was the same as the diameter of the annulus (360/600 in.). Therefore, the bar character shape fitted perfectly into the test page format used in the symmetric coring experiment. As shown in Figs. 16(a) and 16(b), each test page included a single character shape: either vertical bars or horizontal bars. Accordingly, subjects viewed the test pages in groups, each containing the same character shape. To expedite the experiment, only three different nominal colorant levels for C and M ranging be-



(a) (b) (c)

Fig. 15 Comparison between optimal asymmetric coring and color clipping. (a) Print without coring. (b) Optimally cored print. (c) Color clipped print. Printed at 600 dpi, scanned at 1200 dpi, and reproduced at 140 dpi. The overall magnification of these images is 8.5×.



(a) (b)

Fig. 16 Test page for assessing the dependence of optimal coring values on edge direction. All features of the test page were the same as for the symmetric coring experiment except for the character shape, which was either a vertical or horizontal bar with a length of 360/600 in. The colorant level on each page was fixed, and the line width varied randomly from test pattern to test pattern. (a) Test page containing vertical bars. (b) Test page containing horizontal bars.

tween 95 and 100% in steps of 2.5%, and four different line widths ranging from 7/600 in. to 35/600 in. were used. In addition, we considered only symmetric coring. For each bar character shape, there were a total of 12 test pages with four different line widths, three different nominal colorant levels, and five repetitive trials. Thus, the subjects viewed a total of 24 test pages because of the two bar character shapes. The instructions and framework of the experiment were the same as for the symmetric coring experiment. The average time spent on the experiment by each subject was approximately 40 min.

4.2 *Experimental Results*

A total of ten subjects, who had previously performed the symmetric coring experiment and/or the asymmetric coring experiment, participated in this experiment. Figures 17(a) and 17(b) show the experimental data of optimal coring as a function of line orientation for each line width and nominal colorant level, respectively. The overall results for the vertical bars follow the same pattern as in the two previous coring experiments. For a fixed line width, the optimal coring value decreases as the nominal colorant level decreases. For a fixed nominal colorant level, the optimal coring value generally decreases as the line width increases. For horizontal bars, the optimal coring value also decreases as a function of nominal colorant level with the line width fixed. However, the optimal coring value is approximately constant as a function of line width, and does not consistently vary as a function of line width for a fixed colorant level. Comparing the optimal coring amounts between the vertical and horizontal bars for each fixed colorant level and line width, the level of optimal coring for the vertical bar is always larger than that of the horizontal bar.

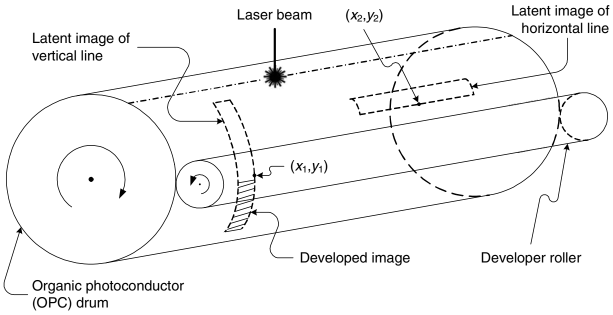
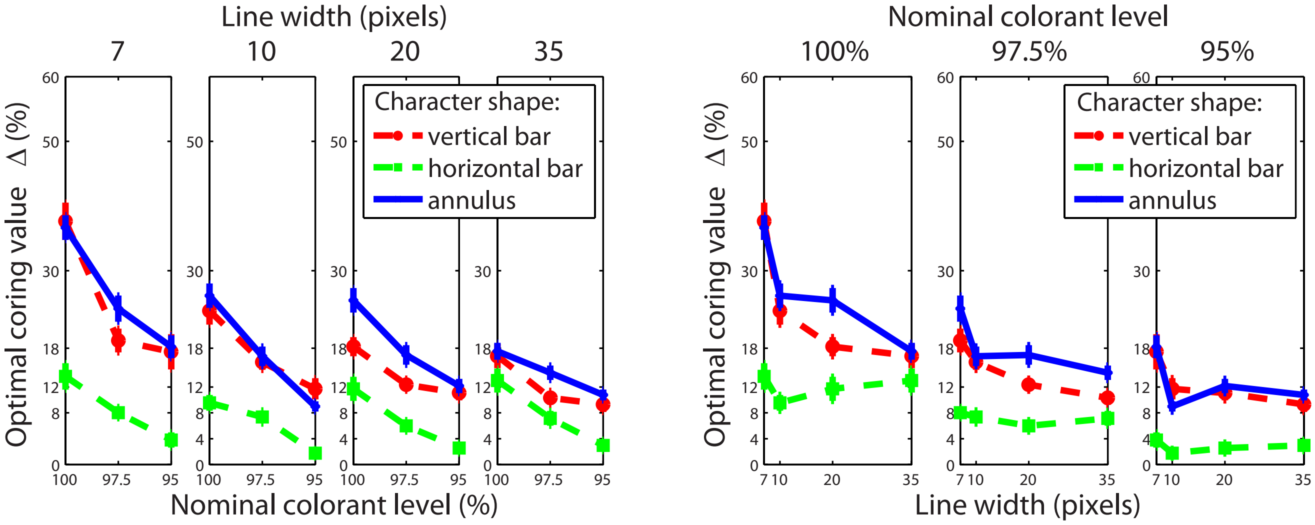


Fig. 18 Dependence of toner stealing on line orientation.

This is consistent with our earlier observation that toner scatter is greater along vertical edges than along horizontal edges. We hypothesize that this phenomenon is caused by "toner stealing," as illustrated in Fig. 18. With the target



(a) (b)

Fig. 17 Comparison between optimal coring values for horizontal and vertical bars with symmetric coring. For comparison, we also show the optimal coring values for the annulus character shape, which is a subset of the data shown in Figs. 10 and 11. Error bars for 95% confidence interval are also shown. The same dataset is plotted in two different ways: (a) optimal coring value versus nominal colorant level, and (b) optimal coring value versus line width.

printer, vertical lines are oriented in the process direction, and horizontal lines are oriented in the scan direction. Consider first the development of the particular position (x_1, y_1) shown in Fig. 18 on a vertical line that has been imaged onto the OPC drum. In a jump-gap development system, such as is deployed in the printer used in our experiments, this position eventually comes nearly into contact with the developer roller as the OPC drum rotates. This is the point in time at which development occurs at (x_1, y_1). However, at this point in time, the developer roller surface in the direction orthogonal to the line is parallel to the OPC drum surface. Thus, the size of the air gap between the OPC drum surface and the developer roller surface is constant in the direction orthogonal to the line, providing an opportunity for attraction to (x_1, y_1) of toner from the area on the developer roller that is horizontally adjacent to the edge of the line. This causes overdevelopment at (x_1, y_1), and consequently toner scatter.

Next, consider the development of the position (x_2, y_2) also shown in Fig. 18 on a horizontal line that has been imaged onto the OPC drum. At the point in time when development occurs at (x_2, y_2), the surface of the developer roller curves away from the surface of the OPC drum in both directions orthogonal to the line. This reduces the opportunity for attraction of toner from the area on the developer roller that is vertically adjacent to the edge of the line. The result is less development at (x_2, y_2), and consequently less toner scatter.

Finally, it is interesting to note in Fig. 17 that for each fixed nominal colorant level and fixed line width, the optimal coring amount selected by subjects for the annuli closely matches and even exceeds in some cases the optimal coring amount that subjects selected for the vertical lines. One might have expected instead that for each annulus, subjects would choose an optimal coring amount that lies between the optimal coring amounts for the vertical and horizontal lines, respectively. However, the result that we actually observed is consistent with the well-known “tent-pole” effect, where subject responses are driven by the worst image quality defect observed. In the situation at hand, one could argue that the subjects chose an overall coring level that eliminates the percept of toner scatter along the vertical portions of the annuli, where it was most noticeable.

The fact that the optimal coring amounts chosen for the annuli actually exceeds that chosen for the vertical lines at some combinations of nominal colorant level and line width may be due to the fact that the test pages for the line orientation experiment were printed several months later than the test pages for the symmetric coring experiment that used the annuli. Thus, the toner cartridges may have been at very different stages in their useful lifespan when the two sets of test pages were printed, resulting in somewhat different development characteristics.

5 Preference Test

Experiments to determine the optimal coring values were conducted using very specialized stimuli that the subjects were instructed to evaluate according to very specific and narrowly proscribed criteria that might not agree with their overall preference. To confirm the benefits of coring, we conducted a fourth experiment to gauge the preference of subjects for optimally cored printed pages with content similar to that which might be encountered in real-world applications.

5.1 *Experimental Design*

The objective of the experiment was to evaluate, with prints that contain real-world content, whether human subjects prefer optimally cored prints over prints without coring. In this preference experiment, the asymmetric coring scheme was used, since color matching was taken into account. Seven different page contents were chosen from various websites at Purdue University, as shown in Fig. 19. Two of them were in a landscape orientation, and five of them were in a portrait orientation. Those page contents were originally stored in PDF format. However, they were converted into TIFF format to implement the coring algorithm. For each page content, we generated pages printed with seven different levels of C and M colorants ranging from 100% down to 94% in steps of 1%. In each case, the nominal level of colorant C was equal to that of colorant M, and it remained constant throughout the page. This resulted in 49 unique pages. Each page was printed with optimal asymmetric coring and without coring. Thus a total of 49 pairs of pages were provided to the subjects. The pairs were arranged in two stacks that had been randomized in the following manner.

1. Content varied randomly from pair to pair as the subject went down through the stack.
2. Nominal colorant level varied randomly from pair to pair as the subject went down through the stack.
3. The relative position of the optimally cored versus noncored pages (i.e., whether a noncored page was on the left and an optimally cored page was on the right, or vice versa) varied randomly as the subject went down through the stack.

The experiment was conducted with 20 subjects in two separate groups: a non-naive group and a naive group. The non-naive group consisted of ten individuals who had participated in a previous experiment to identify optimal coring levels. The naive group was comprised of ten new subjects who had never participated in a coring experiment. For each pair of pages in the stack, the subjects were asked to choose which page they preferred in terms of color and blur. The reference color was printed as a solid colorant in the form of a thick border on the periphery of the page.

5.2 *Experimental Results*

The preference rate is shown in Table 1. The overall rate of preference for optimal coring over no coring was 98.57%. The preference rate of the non-naive group was 99.39%, and the preference rate of the naive group was 97.76%. Although the preference rate of the naive group is only slightly lower than that of the non-naive group, the two preference rates cannot be declared to be statistically the same without further investigation. Hence, we performed a Wilcoxon-Mann-Whitney test[23,24] at the significance level $\alpha=0.05$ to determine if the preference rates of the non-naive and naive groups have a statistically significant difference, and a Kruskal-Wallis test[24,25] at the significance

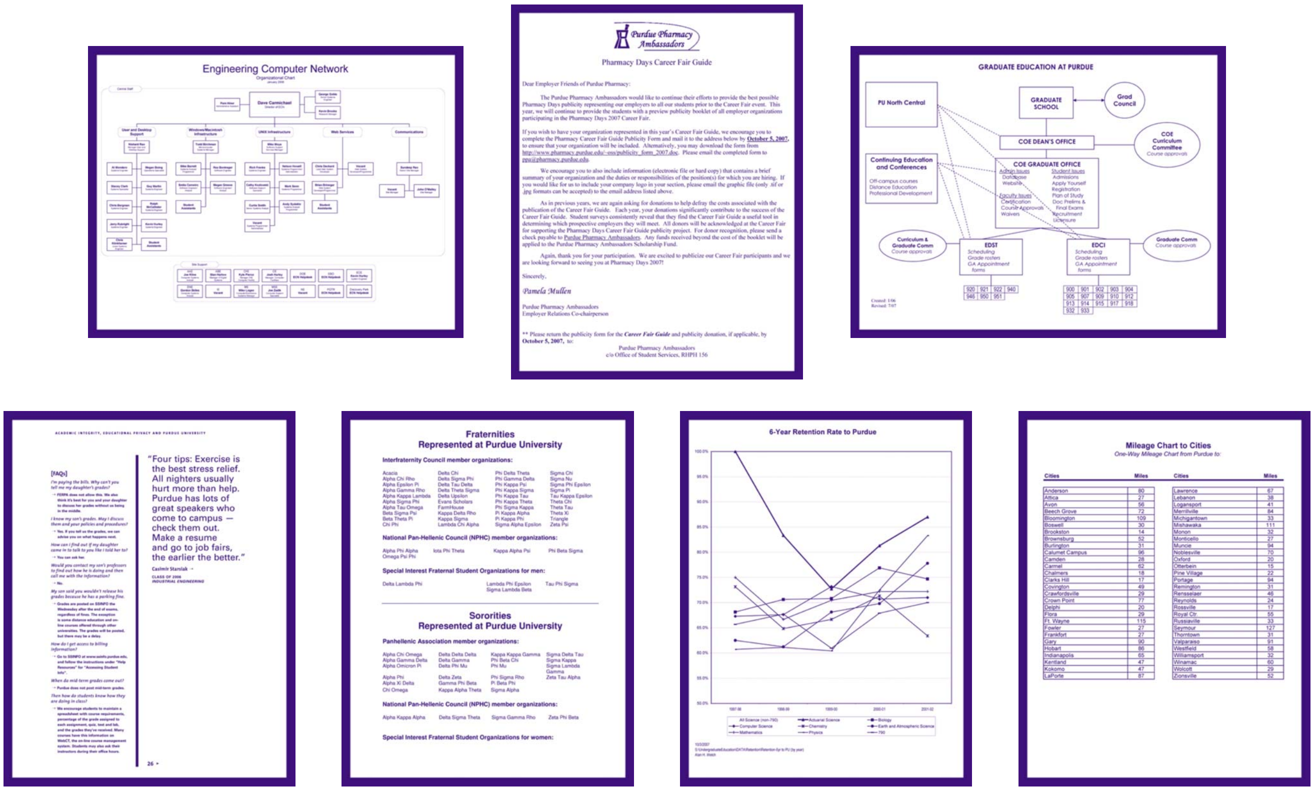


Fig. 19 Seven different page contents used in the preference experiment. Each page content was generated with seven different levels of colorant C and colorant M, ranging from 100 to 94% in steps of 1%. The nominal colorant level remained unchanged throughout the page.

level $\alpha=0.05$ to see the effect of the nominal colorant level. The reason why we used these two tests is that the collected data came from a binomial distribution and were highly skewed. The result from the Wilcoxon-Mann-Whitney test for the group showed that the two-sided p-value was 0.1052, which is greater than 0.05. Therefore, we conclude that the two preference rates are statistically the same, and there is no statistically significant difference between the two groups of subjects. However, the Kruskal-Wallis test for the nominal colorant level resulted in a p-value that was approximately 0.0001. Since this is less than 0.05, there is a statistically significant difference among the nominal colorant levels. Since the nominal colorant level at 94% had a somewhat different result from the other nominal colorant levels, we decided to run another Kruskal-Wallis test to see whether or not there is still a statistically significant difference when the nominal colorant level of 94% is excluded. The result from this additional test showed that the p-value was 0.7014, which is greater than 0.05. Thus, we assume that there is no statistically significant difference among the six nominal colorant levels from 100% down to 95%, but that the result for the 94% level is significantly different than the others. This may be explained by noting that the subjects preferred the optimally cored prints over the prints without coring at the higher colorant levels. However, their judgements were more heavily influenced by the closeness of the color match at the lowest colorant level, where there is less toner scatter and the effect of the coring is not as visually significant.

6 Conclusions

We conduct psychophysical experiments to determine the optimal level of coring that eliminates the perception of toner scatter near edges of text or thin lines for stimuli printed with nominally equal levels of colorants C and M. In general, we find that the subjects prefer a level of coring

Table 1 Rate of preference for optimal coring over no coring.

Colorant level (%)	Number of pages chosen		Preference rate (%)
	No coring	Optimal coring	
100	0	140	100
99	0	140	100
98	1	139	99.29
97	1	139	99.29
96	0	140	100
95	2	138	98.57
94	10	130	92.86
Total	14	966	98.57

that decreases as the colorant level decreases or as the line width increases, and that the subjects prefer to core colorant M more than colorant C. Compared to a previously used model,[18] subjects prefer less coring for wide lines and more coring for thin lines or low colorant levels. Finally, we demonstrate the improvement in print quality obtained by applying optimal asymmetric coring to printed pages containing real-world contents. The optimally cored prints are overwhelmingly preferred over the original noncored prints.

Although we do not conduct formal psychophysical experiments with other colorant combinations, we do print the test pattern with several different line widths and the colorant combinations CY, MY, YK, and CMY at equal nominal levels of 100%. We also print the test pattern with CMYK using several combinations of equal nominal levels for CMY and a different nominal level for K to explore the effect on the toner scatter of using a *rich black*. In all cases, we observe strong scattering of the colorant that is printed last. As mentioned earlier, our particular printer puts down the colorant planes in the order M, C, Y, K. So the combinations CY, MY, and CMY show yellow scatter, and the combinations KY and CMYK show black scatter. In addition, the coring of the character glyphs printed with these other colorant combinations has the same benefits in terms of reducing scatter as it does for CM. While the scattered Y toner is not as visible as is the scattered toner for the other colorants, it is still sufficiently visible to be objectionable.

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References

1. B. W. Keelan, *Handbook of Image Quality*, Marcel Dekker, New York (2002).
2. N. Burningham, J. P. Allebach, and Z. Pizlo, "Image quality metrics," in *Encyclopedia of Imaging Science and Technology*, J. P. Hornak, Ed., pp. 598–616, Wiley, New York (2002).
3. J. Grice and J. P. Allebach, "The print quality toolkit: an integrated print quality assessment tool," *J. Imaging Sci. Technol.* **43**, 187–199 (1999).
4. J. Caviedes and S. Gurbuz, "No-reference sharpness metric based on local edge kurtosis," in *Proc. IEEE ICIP* 3, 53–56 (2002).
5. C. Taylor, "Image quality assessment based on a human visual system model," PhD Thesis, Purdue University, West Lafayette, IN (Dec 1998).
6. S. Farnand, K. Topfer, W. C. Kress, O. Martinez, A. L. McCarthy, H. H. Shin, E. K. Zeise, and D. Gusev, "Update on the INCITS W1.1 standard for evaluating the color rendition of printing systems," *Proc. SPIE* **5668**, 157–162 (2005).
7. "Document B123: NP 13660. Measurement of image quality attributes for hardcopy output," 7th Working Draft, ISO/IEC, Geneva, Switzerland (1995).
8. "W1.1/2000-002 future new work item proposal on image quality for printer systems," ISO/IEC, Geneva, Switzerland (1999).
9. "W1.1/2000-003 image quality of printers, guide for the development of standards," ISO/IEC, Geneva, Switzerland (2000).
10. E. Dalal, A. Haley, M. Robb, D. Mashtare, J. Briggs, P. Jeran, T. Bouk, and J. Deubert, "INCITS W1.1 standards for perceptual evaluation of text and line quality," *Proc. SPIE* **5294**, 34–38 (2003).
11. J. L. Crawford, C. D. Elzinga, and R. Yudico, "Print quality measurement for high-speed electrophotographic printers," *IBM J. Res. Develop.* **28**, 276–284 (May 1984).
12. J. E. Farrell, "Image quality evaluation," in *Colour Imaging: Vision and Technology*, L. Macdonald and M. R. Luo, Eds., pp. 285–313, Wiley, New York (1999).
13. D. Wolin, K. Johnson, and Y. Kipman, "The importance of objective analysis in image quality evaluation," in *IS&T's NIP 14 Intl. Conf. Digital Print. Technol.*, pp. 603–606 (1998).
14. B. Zhang, J. P. Allebach, and Z. Pizlo, "An investigation of perceived sharpness and sharpness metrics," *Proc. SPIE* **5668**, 98–110 (2005).
15. W. Wu and E. Dalal, "Perception-based line quality measurement," *Proc. SPIE* **5668**, 111–122 (2005).
16. J. Hamerly and C. Dvorak, "Detection and discrimination of blur in edges and lines," *J. Opt. Soc. Am.* **71**, 448–452 (1981).
17. C. Dvorak and J. Hamerly, "Just-noticeable differences for text quality components," *J. Appl. Photogr. Eng.* **9**, 97–100 (1983).
18. E. Bernal, J. P. Allebach, and J. Trask, "Model-based memory-efficient algorithm for compensation of toner overdevelopment in electrophographic printers," *J. Imaging Sci. Technol.* **52**, 1–15 (2008).
19. H. J. Park, Z. Pizlo, and J. P. Allebach, "Determination of optimal coring values from psychophysical experiments," *Proc. SPIE* **7242**, 72420K (2009).
20. L. Schein, *Electrophotography and Development Physics*, 2 ed., Laplacian Press, Morgan Hill, CA (1996).
21. L. Schein and G. Beardsley, "Offset quality electrophotography," *J. Imaging Sci. Technol.* **37**, 451–461 (1993).
22. W. Y. Jang, M. C. Chen, J. P. Allebach, and G. T. C. Chiu, "Print quality test page," *J. Imaging Sci. Technol.* **48**, 432–446 (2004).
23. B. A. Thyer, *The Handbook of Social Work Research Methods*, 1st ed., SAGE Publications, Thousand Oaks, CA (2000).
24. A. Narayanan and D. Watts, *Exact Methods in the NPAR1WAY Procedure*, SAS Institute Inc., Cary, NC (1996).
25. D. J. Sheskin, *Handbook of Parametric and Nonparametric Statistical Procedures*, 3rd ed., CRC Press, Boca Raton, FL (2003).

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