Journal of Imaging Science and Technology® 51(3): 271–281, 2007.

Softcopy Banding Visibility Assessment

Osman Arslan
School of Electrical and Computer Engineering, Purdue University, 465 Northwestern Ave., West Lafayette, Indiana 47906-2035
E-mail: arslan@ecn.purdue.edu

Zygmunt Pizlo
Department of Psychological Science, Purdue University, 703 Third Street, West Lafayette, Indiana 47907-2081

Jan P. Allebach
School of Electrical and Computer Engineering, Purdue University, 465 Northwestern Ave., West Lafayette, Indiana 47906-2035

Abstract. *Banding is a printer artifact perceived as one dimensional luminance variations across the print-out caused by different mechanical problems such as vibration of different printer components in laser electrophotographic (EP) printers or media advance errors in inkjet printers. In the printing industry, banding is considered to be one of the worst defects that dominates overall perceived image quality. Understanding the visibility of banding will help us in developing strategies to reduce the banding artifact. We developed a soft-copy environment to conduct various experiments for investigating the visibility of banding in laser EP printers. This environment includes the methodology to duplicate the print on the monitor, and a banding extraction technique. This technique enables us to freely adjust the magnitude of banding of any printer. We validated the accuracy of this methodology by conducting a banding matching experiment. We used this platform to conduct banding visibility assessment experiments. One of them was a banding discrimination experiment. The results showed that for the printers investigated, a reduction of 6.5% in the banding magnitude will be just noticeable by an average observer. We were also able to find the detection thresholds of banding in grayscale images for three laser electrophotographic printers. The detection threshold of the best printer was about 50% of its original banding. So there is still plenty of room to reduce the visibility of the banding artifact. We were also able to compare the banding visibility of different printers quantitatively by conducting a cross-platform experiment. This methodology can form the basis for a metric for visibility of banding in laser EP printers. With some modifications, these techniques could also be adapted to other printer technologies such as ink jet printers.* **© 2007 Society for Imaging Science and Technology.**
[DOI: 10.2352/J.ImagingSci.Technol.(2007)51:3(271)]

INTRODUCTION

Fine-pitch banding is a printer artifact perceived as one-dimensional luminance variations across the print-out that are caused by the vibrations of different printer components. This artifact was categorized under the macrouniformity image quality attribute in Dalal et al.'s paper, where he proposed a methodology to evaluate the overall image quality of hardcopy output.[1] In his paper, he also points out that the "tent-pole effect" plays an important role in deciding on the overall image quality, which is basically the idea that "worst defect dominates." We can arguably state that, in the printing industry, banding is considered as one of the most objectionable defects that dominates the overall perceived image quality. That is the reason why, in a later study, while defining the objectionability function of overall macrouniformity, the highest weight was given to banding by Rasmussen et al.[2] As this leads to the idea that "worst defect has to be removed first," the banding artifact has caught the attention of many researchers. Briggs et al. proposed a method to characterize banding of ink jet printers.[3] Cui et al. measured the visibility and objectionability threshold of ink jet banding.[4] Kane et al. presented metrics for quantification of banding.[5] And other researchers made use of these studies to develop methodologies to reduce banding.[6–8]

Our motivation for investigating banding is mostly related to the image quality assessment area. As Dalal et al. state in their paper, "There is a big need for a manageable method of evaluating the overall image quality of hardcopy output from printer systems so that the systems can be compared in a meaningful way."[1] This method should make use of the image quality metrics but at the same time take image preference into account. The "image quality attributes" that Dalal et al. introduced have this property. But the main issue here is that these kind of attributes have to be judged by human observers each time. To solve this issue, one has to develop correlations between the instrumentally measured image quality metrics and the image preference. Once this correlation is established, then one can directly quantify the image quality of the print-out. On the other hand, these correlations will include essential clues for the manufacturers in choosing their design parameters. In this study, our aim is to develop experimental techniques to measure visibility of banding by conducting softcopy psychophysical experiments and to investigate correlations between banding parameters and the visibility of banding. Bang et al. have developed an analytical tool for measuring banding and proposed a methodology for measuring the visibility of banding

Received Apr. 22, 2005; accepted for publication Jan. 29, 2007.
1062-3701/2007/51(3)/271/11/$20.00.

by conducting psychophysical experiments.[9,10] They used hardcopy images in their experiments. In this study, we will use a similar methodology and measurements, but will conduct the experiments in a softcopy environment. Two important advantages of the softcopy environment are the reduced time and the cost savings.[11] In the softcopy environment, it is easy to change the visibility of the artifacts by modifying the parameters. This gives us the ability to conduct psychophysical experiments more reliably. For our specific application, the softcopy environment will also give us the ability to simulate banding at lower amplitudes than the actual printer banding amplitude.

One of the challenges of this approach is simulating the actual printing artifact in a softcopy environment. For this simulation, we made use of scanned samples of actual printouts. A detailed explanation of the simulation process is given in the third section of this paper. The other question that comes to mind at this stage is how well a hardcopy can be simulated by making use of self-luminous displays. The two media have differences in their color gamuts, viewing conditions, nature of illumination (emissive versus reflective), and color reproduction methods (additive versus subtractive).[11] For example, the hardcopies are viewed in lighted environments whereas the softcopies can also be viewed in dim or dark environments. So one has to develop a softcopy environment based on an appearance match between softcopy and hardcopy to be able to simulate and conduct hardcopy quality assessment experiments in this environment. When viewing conditions and the state of adaptation are identical, a colorimetric match is also a color appearance match.[12] But when there are differences in viewing conditions or the state of adaptation, there is no longer a one-to-one correspondence between the colorimetric match and color appearance match because of certain color appearance phenomena such as chromatic adaptation, Stevens effect, and surround-contrast effects.[12] Many color appearance models have been proposed to extend colorimetric models to account for these color appearance phenomena. Among them are the RLAB model, Hunt's model, CIELAB, and the Von Kries model.[13,14] The performance of these models has been investigated in the literature given different viewing conditions.[15,16]

Our aim is to develop a softcopy environment which will give us the same image appearance as the hardcopy experimental environment utilized by Bang et al. In the next section, we present the hardcopy-softcopy matching experiments that we conducted for this purpose. In our banding experiments, the subject's task is to judge the banding defects of different images. As banding can be considered as a contrast modulation,[17] this will be a task related to detection or comparison of contrasts. Choi et al. investigated the color-difference (with ΔE_{ab} of around 5 to 10) perception in hardcopy versus softcopy display.[11] He found that there is no significant efficiency difference in color-difference perception between hardcopy and softcopy especially for experienced subjects. In the third section, we give a brief summary of our banding measurement and analysis methodology. In the fourth section, we first explain our experimental methodology. Then, we present our banding matching and banding visibility assessment experiments. Finally, in the last section, we present our conclusions with a brief discussion.

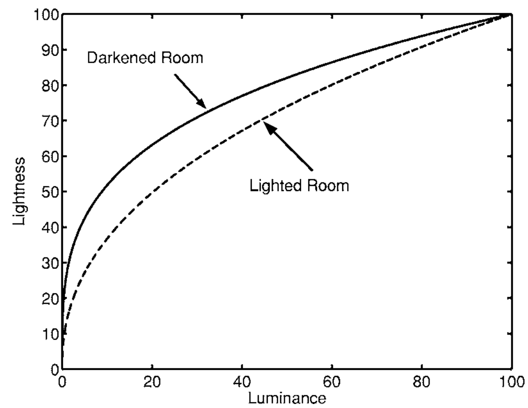

Figure 1. The relation between luminance and predicted lightness for different surroundings.

BUILDING THE SOFTCOPY ENVIRONMENT

In this section, we describe our softcopy environment for the banding visibility assessment experiments (and for any softcopy print quality assessment experiment in general). Our development is based on an appearance match between hardcopy and softcopy that takes all the differences into consideration. The effect of the room illumination on the appearance of images has been investigated in several papers.[18–20] In general, predicted lightness L as a function of luminance Y for different surroundings is given by the equation[20]

$$L = 100(Y/100.0)^{\sigma}, \tag{1}$$

where the σ values are $1/2.3$ and $1/3.5$ for average and dark room illuminations, respectively. The plots of these relationships can be seen in Figure 1. If we combine the equations for dark and average surroundings, we get a general relationship between the lightness viewed in a lighted room and the lightness viewed in a darkened room.

$$L^{\text{dark}} = 100(L^{\text{light}}/100)^{2.3/3.5}. \tag{2}$$

Several mapping techniques have also been proposed to match media with different luminance levels.[21,22] Viggiano et al. summarized the luminance/lightness mapping techniques that have been proposed in the literature.[21] These consist of Rhodes' uniform compression of L^*[23] and Maurer's mapping which is a refinement of Rhodes' mapping using Bartleson and Breneman's lightness scale.[24] Park et al. showed that linear lightness rescaling gives the best matches among other techniques when combined with black point adaptation.[22]

We conducted two experiments to investigate the effect of the differences in the viewing conditions on the appearance of the media. Table I summarizes the conditions of these experiments. In the first experiment, the maximum luminances are different, but the images are viewed in the

Table I. Viewing conditions of the two matching experiments.

	Softcopy		Hardcopy	
	Dynamic Range	Surrounding	Dynamic Range	Surrounding
Experiment 1	1.51–80 cd/m^2	Dark	29.52–298 cd/m^2	Dark
Experiment 2	1.20–80 cd/m^2	Dark	27.80–284 cd/m^2	Light

same room illumination. In the second experiment, both the room illuminations and the maximum luminances are different. In fact, in this case, the viewing condition for the softcopy matches with our softcopy banding assessment experimental conditions, and that of hardcopy matches with the viewing condition for Bang et al.'s experiments.

Experimental Procedure

The softcopy patches were viewed on a 21 in. Barco Monitor.[†] The resolution of the monitor was set to 1200 $\times$1600 pixels. This system has its own external colorimeter connected to the monitor, and there is a chip in the monitor to update the look-up tables for the color output. The monitor comes with its own software called "Reference Calibrator V." With this software, the monitor calibrates itself automatically at 25 different locations on the screen by making use of the colorimeter. The gamma value, the maximum luminance, and the white point of the monitor can be preset before calibration. In our experiments, the white point was set to $D65$. Based on our measurements using a PhotoResearch 750 spectroradiometer[§] as the reference, calibration of the monitor can be achieved with an average error of 1 ΔE_{ab} throughout the screen. The automatic calibration feature of the Barco monitor gave us the ability to calibrate the monitor each day we conducted the experimental sessions. The hardcopy patches were printed with an HP LJ 4050 printer.[‖] The measurements were taken with the PhotoResearch 750 spectroradiometer.

For the setup of the experiment, we followed the "CIE Guidelines for Coordinated Research on Evaluation of Colour Appearance Models for Reflection Print and Self-Luminous Display Image Comparisons."[25] In the experiments, we used the memory matching technique.[26] Basically, the subjects first memorized the lightness of the hardcopy patch and then adjusted the brightness of the patch on the monitor to yield an appearance match with the perceived reflectance of the hardcopy patch. The patches were uniform gray with a white background. The size of the patches was 1.75 square inches, and the background was 8$\times$8 inches The patches were mounted on a solid background; and they were surrounded by a 1in. wide gray frame. Patches with 8 different gray levels were shown in random order as the stimuli. Before observing each patch, the subjects adapted to an 18% gray background for one minute. Chromatic adaptation at constant luminance is 90% complete after approximately one minute.[27]

†Barco Company, Kortrijk, Belgium.
§Photo Research, Inc., 9731 Topanga Canyon Place, Chatsworth, CA 91311-4135.
‖Hewlett-Packard Company, 3000 Hanover Street, Palo Alto, CA 94304-1185.

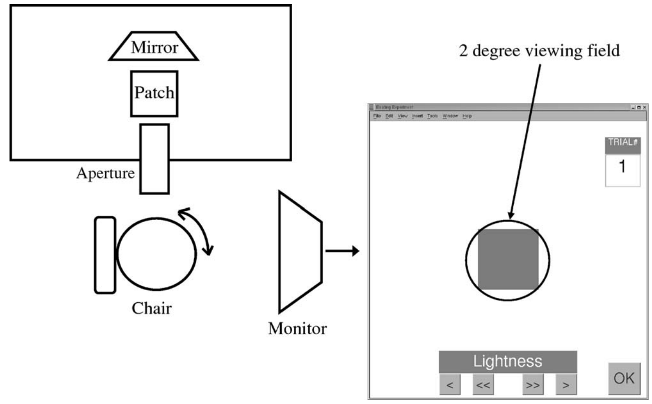

Figure 2. Setup for experiment 1.

Experiment 1

The setup of the experiment is shown in Figure 2. The printed patch was positioned flat on the floor of the viewing booth. As the light was coming from the top, this configuration gave good spatial uniformity of illumination. The white point of the illumination in the viewing booth was $D65$. The subject first observed the printed patch through the aperture via the mirror, and memorized its appearance. Then the subject turned to the monitor and adjusted the patch on the monitor with the buttons on the screen and clicked the "OK" button when an appearance match was achieved between the patch on the monitor and the patch in his/her memory. In our user interface, buttons instead of a slider were used to make sure that the subject did not memorize the location of the slider. Both the hardcopy and softcopy patches had a 2° viewing field. The room was darkened. The luminance range between the black and white points of the monitor and the viewing booth were 1.51–80 cd/m^2 and 29.56–298 cd/m^2, respectively. A total of 20 subjects participated in this experiment.

Results and discussion

The results of this experiment are shown in Figure 3(a). A straight line is fitted to the data. The viewers are assumed to have completely adapted to the white point of the reproduced image,[28] so the white of the softcopy image is assumed to perceptually match the white of the hardcopy image. For this reason, the fitted line is constrained to pass through the point with coordinates (100, 100) on the graph in both Figs. 3(a) and 3(b). It is interesting to note that despite the fact that the subjects performed a memory match, the variability of the settings as represented by the error bars in both Figs. 3(a) and 3(b) was small. The F-test we performed showed that a second order term is insignificant to characterize the data in Fig. 3(a). So in this case, the subjects match the luminance of the hardcopy to that of the softcopy by a linear mapping. But it is important to note that the intercept of this line with the x axis has a positive value.

Experiment 2

In this experiment, the subjects first memorized the appearance of the hardcopy patch in a lighted room. Then they

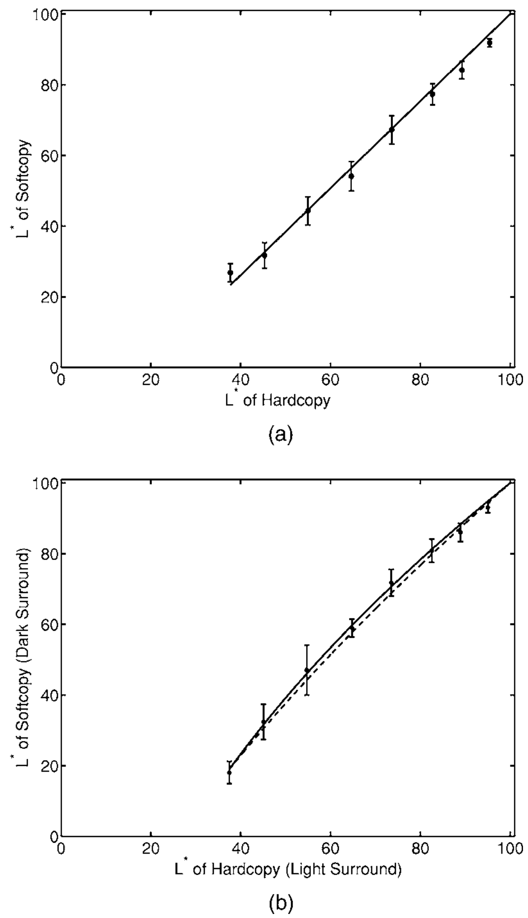

Figure 3. The results of (a) experiment 1, and (b) experiment 2. The solid line is the curve for the experimental data and the dashed line is from previous literature. (Ref. 19). The error bars represent 95% confidence intervals.

went to the next room which was darkened, and adjusted the brightness of the patch on the monitor to match it with the one in their memory. The luminance range between the black and white points of the monitor and the hardcopy were 1.20–80 cd/m^2, and 27.80–284 cd/m^2, respectively. A total of 14 subjects participated in this experiment. The viewing field of the monitor and the hardcopy were approximately 10°.

Results and discussion

The results of this experiment are shown in Fig. 3(b). The F-test showed that a second order term is significant to characterize this data. So we fitted a power function in this case. The solid line in the figure shows this function which is represented by the equation below:

$$L_{\text{softcopy}} = 225.8(L_{\text{hardcopy}}/100)^{0.45} - 125.8. \quad (3)$$

The viewer matches the lightness of the stimulus viewed in a darkened room to that viewed in a lighted room by a nonlinear mapping. Again the intercept of the mapping with the x axis is positive. The dashed curve in the figure shows the relation between lightness viewed in a dark surrounding and the lightness viewed in a light surrounding in general. This was derived in the previous section and is represented by Eq. (2). Here we modified this equation to have the same black point coordinates as Eq. (3), and we obtained

$$L^{\text{dark}} = 176.1(L^{\text{light}}/100)^{0.66} - 76.1. \quad (4)$$

If we compare the curve fitted to experimental data with the dashed curve obtained from Fairchild et al.'s equations,[20] we see that there is a very close match.

Table II. Black level match of the hardcopy and softcopy environments.

	Experiment 1		Experiment 2	
	Y	L^*	Y	L^*
Black of Hardcopy	29.56 cd/m^2	37.7	27.80 cd/m^2	37.46
Black of Monitor	1.51 cd/m^2	14.89	1.20 cd/m^2	12.61
Black of Softcopy	4.02 cd/m^2	26.80	2.73 cd/m^2	20.41

Analysis of Black Level Match

The black levels of the two media and the matched values are shown in Table II. The subject chooses a black level for the softcopy to match that of the hardcopy which is less than the black of the hardcopy. In fact, the results can best be described by Nakabayashi et al.'s conclusion: "Human visual system is adapted to the about middle point between input device black point and output device black point when comparing a softcopy image with other images under ambient illumination."[29]

SUMMARY OF BANDING MEASUREMENT AND ANALYSIS TECHNIQUES

Our final goal here is to simulate a print with banding on the monitor and to be able to adjust the level of banding on that simulated print. In the first stage of our approach, we extract the banding from the scanned printed patch. The patch sample size is 1.25×4.25 in. The patch is printed at a 50% gray level. A Heidelberg Linocolor Saphir Ultra2 Flatbed Scanner[¶] is used for scanning the patches. This scanner has 1200 dpi optical resolution. The patches are scanned at 600 dpi resolution. This resolution is sufficient to capture the banding frequencies that are of interest. The gamma of the scanner is 1.76. No sharpening effect is introduced. We first print several patches from a specific printer. We check the variation of banding magnitude from print to print. The variation is negligible for the printers that we considered. So we choose the print-out among these samples which has a banding magnitude of about the average of all the samples. Thus the banding signal extracted from this print-out can be considered as a typical banding signal for the printer in question. The extracted banding will be our "banding prototype;" and the patch after the banding is removed will be our "background." The block diagram of this process can be seen in Figure 4. First we calibrate the scanned patch by applying the scanner calibration curve. This curve is obtained by comparing scanner digital value and luminance Y

[¶]Kurfursten-Anlage 52-60, D-69115 Heidelberg, Germany.

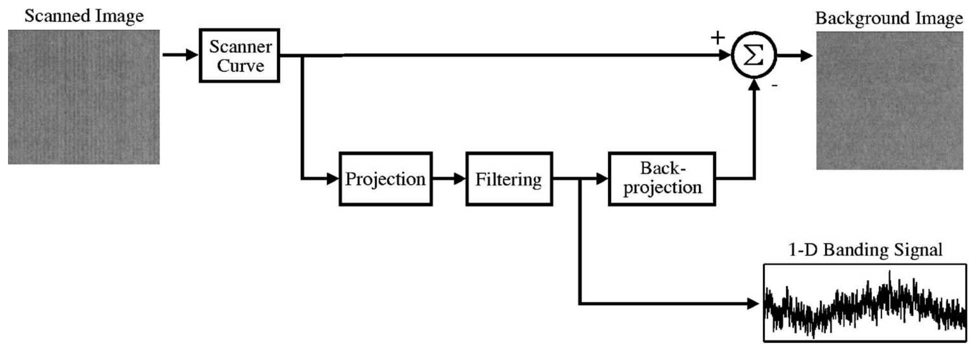

Figure 4. Block diagram for extraction of banding and the background image from the scanned patches.

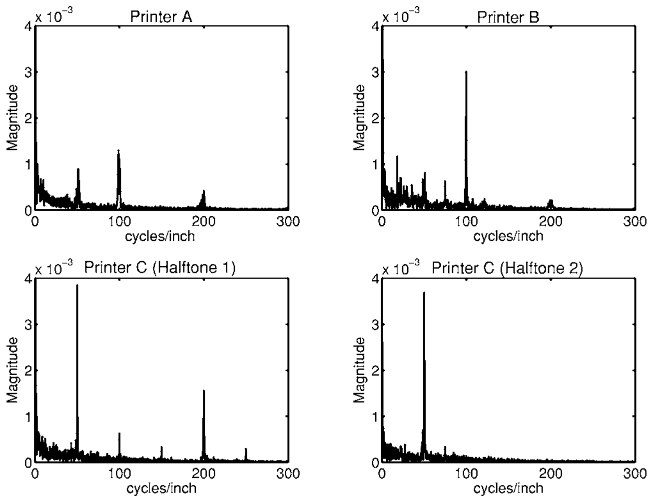

Figure 5. Spectral content of the 1D projection of patches printed with four different printer/halftone combinations.

measured with a Gretag SPM-50 spectroradiometer** for a series of constant patches with varying lightness. Thus it enables us to convert the scanner output to luminance values. Then we project the image in the direction perpendicular to the process direction to get a one-dimensional signal. The spectral distributions of the projected signals for four different printer/halftone combinations are shown in Figure 5. We used these four combinations for all of the experiments to be described in this paper. Printers A, B, and C are three different models of laser electrophotographic printers. We used two different halftone screens with Printer C. We filter this one dimensional signal to extract our prototype banding signal. Because we want to assess the visibility of fine-pitch banding associated with the printer mechanism, we use a Butterworth bandpass filter with cutoffs 5 cycles/in. and 80 cycles/in. These cutoffs are chosen to eliminate the near dc components in the low frequency range, and the halftoning frequencies in the high frequency range. For example, the peaks at 100 cycles/in. in the spectral plots observed for three of the printer/halftone combinations of the printers in Fig. 5 are caused by the halftoning patterns. We use the *filt filt* function in Matlab†† to design a precisely zero-phase filter. Then we back-project the prototype banding signal and subtract this from the scanned image to obtain the background. An example of the spectral contents of the background and the prototype banding signal for Printer A can be seen in Figure 6. Now that we have obtained our background and the prototype banding signal, we can add different amounts of banding to our image by simply multiplying the prototype banding signal by a scaling factor. We call this scaling factor β. The value $\beta=1.0$ corresponds to the amount of banding in the original image. After the banding is added, we use our results from the previous section to generate an appearance match between the hardcopy and the simulated print on the softcopy. The block diagram of this process can be seen in Figure 7. The "appearance match curve" shown in the block diagram is given by Eq. (3) from the previous section.

In the hardcopy case, Bang et al. added extra banding to the image and then printed it. As the printer already has its original banding, the print-out has the simulated banding added to the original banding. Since the phase of the original banding of the printer cannot be controlled, the original banding and the simulated banding may be out of phase. This phase difference may cause a cancellation effect, and also may change the spectral content of the banding. In fact, Bang et al. took this effect into account when they calibrated their results. But in the softcopy case, we do not have this problem at all. Another advantage of the softcopy environment is that we can simulate banding levels lower than the actual level of banding of the printer by simply choosing a value for β that is less than 1.0. In this way, banding detection or objectionability thresholds can also be investigated.

BANDING VISIBILITY ASSESSMENT EXPERIMENTS

To conduct the softcopy banding visibility assessment experiments, the 21 in. Barco Monitor was again used. The experiments were conducted in a completely darkened room. The experiment was self-paced. Matlab was used to generate the user interface for the experiments. There was one issue that had to be resolved for the softcopy experiments. The resolution of the printers was 600 dpi, whereas

**GretagMacbeth, 617 Little Britain Road, New Windsor, NY 12553-6148.

††The Mathworks Company, 3 Apple Hill Drive, Natick, MA 01760-2098.

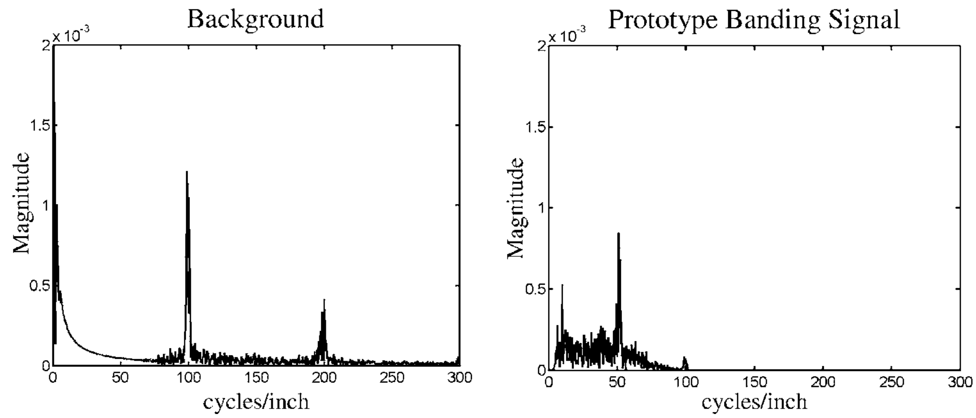

Figure 6. An example of the spectral contents of the background and the prototype banding signal for Printer A.

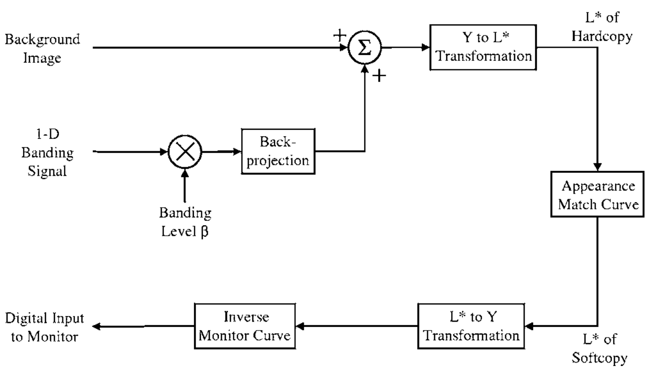

Figure 7. Generating the softcopy display.

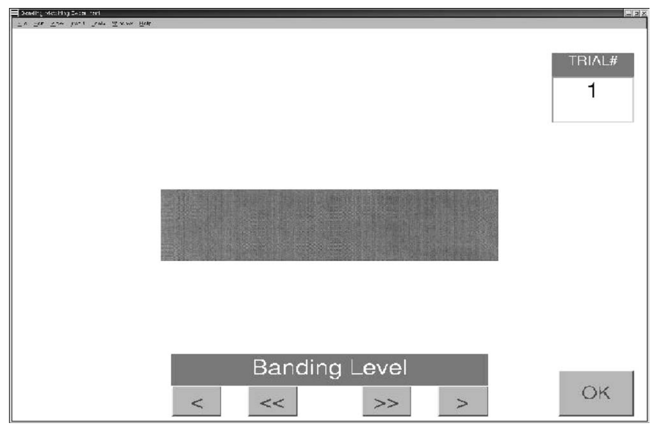

Figure 8. User interface for banding matching experiments.

the resolution of the monitor was only 100 pixels/in. This could be a potential problem if the banding that is to be displayed on the monitor has a sufficiently high spatial frequency. In fact that was the case for Printers A and B. Their principal banding frequency was around 50 cycles/in. A waveform with this frequency cannot be accurately rendered with a 100 pixels/in. display device. Our solution to this problem was to downsample the images by 3 instead of by 6 before displaying on the monitor. This increased the size of the images on the monitor by 2× with respect to the hardcopy. The subjects viewed the patches from about 24 in., which is twice the distance at which they normally viewed the hardcopy. In this way, we were able to generate essentially the same stimulus on the retina that the subjects would have seen when viewing the 600 dpi hardcopy at a distance of 12 in.

Banding was added to the images using the procedure described in the previous section. We did not remove the other artifacts such as graininess from the background of the printed patch. These other artifacts can affect visibility of banding. In this paper, we measured the visibility of banding of different printers including these effects in our experiments. The method of constant stimuli was used in the psychophysical experiments and "Probit Analysis" of the SAS software[‡‡] was used to analyze the data. This method fits a cumulative Gaussian function to the constant stimuli data, and estimates the mean and standard deviation of this function. The subjects were all Purdue University students. The banding of three laser electrophotographic printers Printer A, Printer B, and Printer C (with two different halftone patterns) was investigated.

Banding Matching Experiment

Method

The purpose of this experiment was to validate the accuracy of the softcopy banding simulation by matching the level of banding of the hardcopy and that of the softcopy. In this experiment, the memory matching technique was used. The viewing conditions of the softcopy and the hardcopy were exactly same as the hardcopy-softcopy matching Experiment 2 described in the section entitled Experiment 2. The subject first memorized the level of banding on the hardcopy in one room and then went to the next room and adjusted the level of banding of the softcopy to match it with the hardcopy. The user interface for this experiment is shown in Figure 8. The subject was able to vary the level of banding on the softcopy from $\beta=0.0$ to $\beta=2.0$. As usual, $\beta=1.0$ corresponds to the original amount of banding in the hardcopy.

Results and discussion

A total of 20 subjects completed the experiment. The results can be seen in Table III. The entries tell us the average value

[‡‡]SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414.

Table III. Results of the banding matching experiment.

	Printer A	Printer B	Printer C (Halftone 1)	Printer C (Halftone 2)
Average Match Level β and 95% Confidence Range	1.05 ± 0.08	0.98 ± 0.10	1.04 ± 0.08	1.06 ± 0.07

Table IV. Results of the banding discrimination and detection experiments.

	Printer A	Printer B	Printer C (Halftone 1)	Printer C (Halftone 2)
Average DL and 95% Confidence Range	0.064 ± 0.014	0.064 ± 0.011	0.066 ± 0.013	0.063 ± 0.014
Average AL and 95% Confidence Range	0.560 ± 0.049	0.500 ± 0.067	0.360 ± 0.039	0.354 ± 0.053

of β that is judged to yield a match. For example, for the first printer, the subjects matched 1.05 times the original banding displayed on the monitor with the original banding of the hardcopy, and so on. The error term corresponds to a 95% confidence interval. The match levels for all the printers are statistically same as 1.00, which shows that our softcopy banding simulation accurately duplicates the hardcopy banding.

Banding Discrimination Experiment

Method

In this experiment, our objective was to find the discrimination threshold (DL) of banding for different printers. The discrimination threshold is the smallest difference between two stimuli that a subject can reliably detect. The standard deviation of the cumulative Gaussian curve calculated by "Probit Analysis" was used to estimate DL. In each trial, two patches were presented to the subject. One was the reference patch, which was the patch with banding level equal to that of the printer ($\beta = 1.0$). The other patch was the "test patch" which had one of eight levels of banding ($\beta = 1.00, 1.05, 1.10, 1.15, 1.20, 1.25, 1.30, 1.35$), which includes banding equal to that of the reference patch. The subject's task was to tell if the test patch had "more banding" or the "same banding" compared to the reference patch. The interface that was used for this experiment can be seen in Figure 9. The subjects were instructed to be close to perfect on "catch trials," that is the trials where the test patch had the same level of banding as the reference patch. If the proportion of error in the catch trials is too high, then the psychometric function cannot be reliably estimated, because the subject's response will be biased toward saying that the test patch has more banding than the reference patch.

Results and discussion

The experiments were conducted with 16 subjects. The results for one subject were excluded from the data, because the proportion of error in that subject's catch trials was 80%. The same printer/halftone combinations as in the banding matching experiment were tested. The average DL's were obtained by first calculating the DL of each individual subject, and then taking the average. These are shown in the first row of Table IV. The error term is the 95% confidence interval of the variation of DL's among subjects. Figure 10 shows the pooled data from all 15 subjects for each printer. Superim-

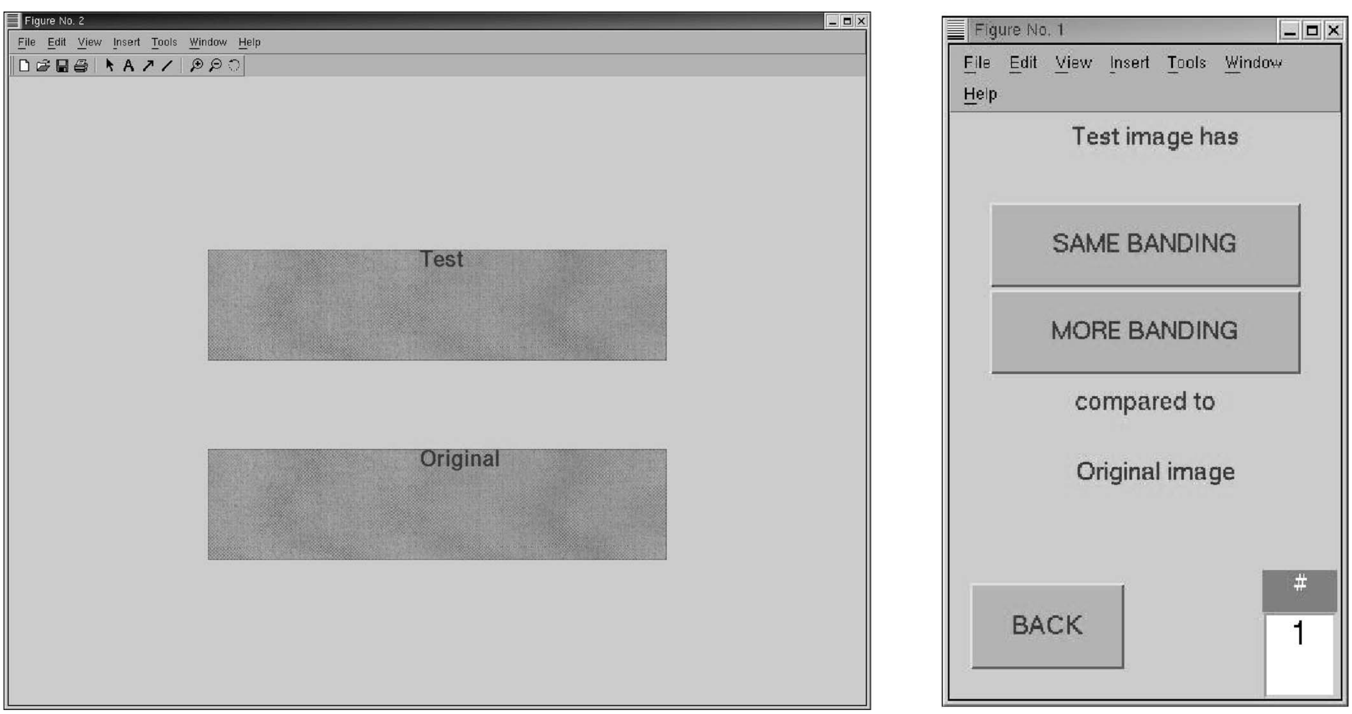

Figure 9. User interface for banding discrimination experiments.

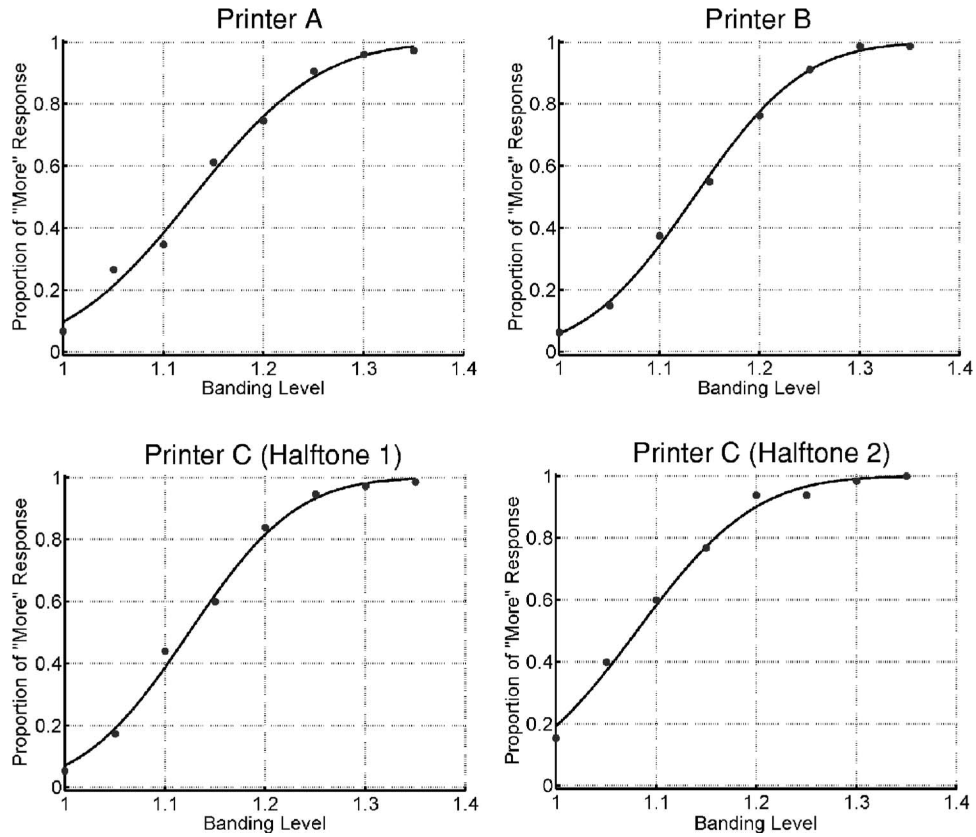

Figure 10. Psychometric functions for the pooled data of the banding discrimination experiment.

posed are the cumulative Gaussian functions that provide the best fit to the pooled data. The standard deviations (SD) of these Gaussian distributions are usually higher than the average of the SD's of the fits to individual subjects. The reason is that different subjects are likely to have different response biases related to the criterion for responding "more" banding. The DL's for all the printer/halftone combinations are statistically the same. This supports the idea that Weber's rule applies to banding discrimination. Namely, we need to reduce the banding magnitude by 6.5% to yield a statistically significant reduction in banding visibility; and this number is constant over the different printers.

Banding Detection Experiment

Method

The methodology for the banding detection experiment was very similar to that of the banding discrimination experiment. Again, the subjects compared the "test image" with the "reference image." But this time, the reference image had no banding at all. The banding in it had been removed by the banding extraction technique we described in the third section. The test images had banding levels distributed around the absolute threshold (AL) that had been roughly estimated by a few preliminary trials. The subject's task was to tell if there was any banding visible in the test image compared to the reference image.

Results and discussion

A total of 15 subjects participated in this experiment. The 50% mean of the Gaussian curve was used as an estimate for AL. Figure 11 shows the psychometric function of the pooled data for each printer. The average of AL across all subjects is given in the second row of Table IV. The entries show the fraction of original banding that is detectable. The higher the fraction, the less visible is the banding. The visibility of banding for the printers arranged from high to low is as follows: Printer C, Printer B, and Printer A. The ratio of AL for the printer for which banding was least visible (Printer A) to that for which the banding was most visible (Printer C) was 1.58. This suggests that the banding of Printer C is 1.58 times worse than that of Printer A. In general, these results show that there is still a lot of room to reduce the visibility of fine-pitch banding with these printers. We should note that the AL's may also be affected by the background noise of the printers. This consists of other artifacts such as noise due to scattered toner and the nonuniform paper reflectance, as well as the halftone pattern of the specific printer. We did not attempt to isolate various sources; but in this case, changing the halftone pattern did not appear to change the visibility of banding of Printer C significantly.

Cross-platform Experiment

Method

In our cross-platform experiment, an experimental procedure developed by Bang et al. was used to compare the level of banding for different printers. Two images having the banding of two different printers were displayed side by side and the subject was asked to make a comparison. The image

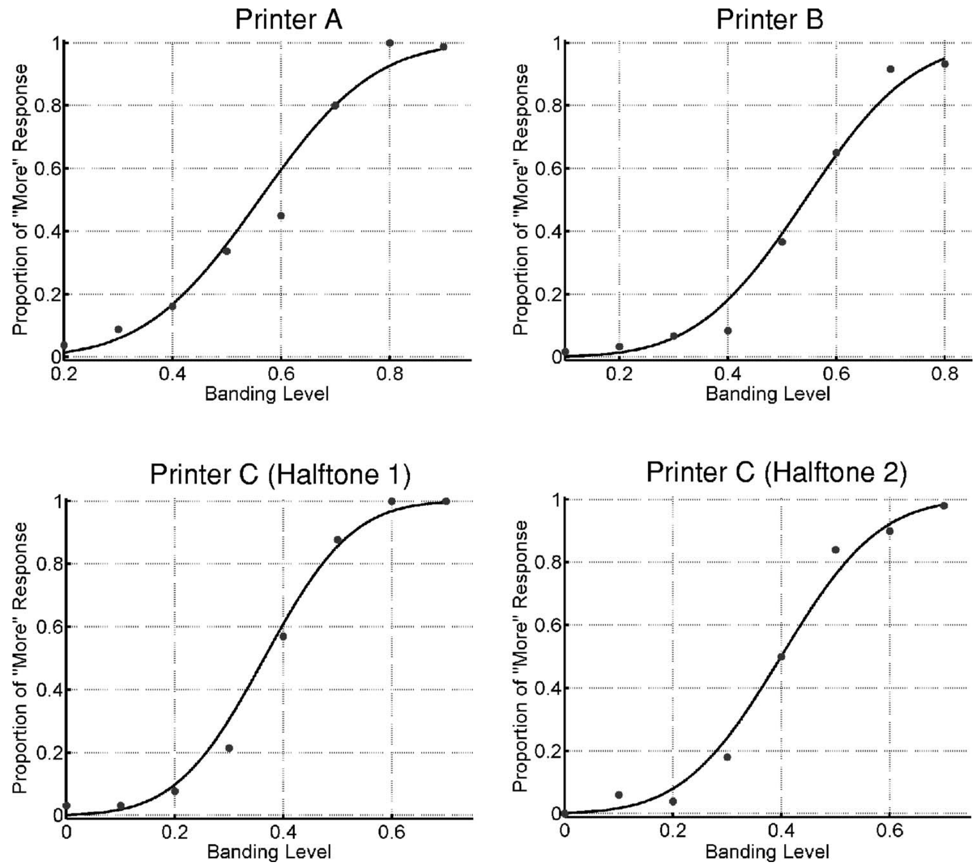

Figure 11. Psychometric functions for the pooled data of the banding detection experiment.

having stronger banding was fixed as the reference image. The other image with different levels of banding was compared with that of the reference image. The subject's task was to tell which image has more banding. For example, in one case, the reference image had the banding of Printer B with $\beta = 1.0$, and the test image had the banding of Printer A with $\beta = 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6$, since Printer A had the least visible banding. During the experiment, the order of the presentation of the images with different values of β was randomized. The value of β for the test printer where the subject gives the answer "more" 50% of the time is called the point of subjective equality (PSE). This point shows us the relative level of banding of the two printers. The first question that had to be addressed here was whether it was even at all possible for the subjects to reliably compare the banding of two different printers. This may be difficult, because the spectral content of the banding of different printers can be very different. For example, Printer A has its principal banding frequency at 50 cycles/in., whereas the principal banding frequency of Printer B is around 18 cycles/in. Again, the method of constant stimuli was used in this experiment.

Results and discussion

A total of 18 subjects participated in the experiment. Printers B and C were compared with Printer A. As a control case, the subjects also compared Printer A with itself. The psychometric function for the pooled data for each printer is shown in Figure 12. The x axis is the increasing banding level of Printer A, and the y axis shows the percent of the time that the subject says the test image has more banding. The point where the "more" answer is given 50% of the time is taken as the point of subjective equality (PSE) where the banding of the two printers is equally visible.

The average of the PSE's across subjects is given in the first row of Table V. The error term is the 95% confidence interval of the variation in PSE among subjects. The confidence intervals turned out to be reasonably small. This shows that the subjects were able to compare the visibility of banding of different printers in a consistent manner. For Printer A, the average PSE turned out to be exactly 1.00 as expected. In the second row of Table V, we show the standard deviations of the cumulative Gaussian curve fits. The error term is the 95% confidence interval of the variation in the fitted standard deviation among subjects. The standard deviation for the comparison of Printer A with itself is slightly lower than the other cases. This suggests that comparison of bandings with different spectral contents is more difficult than comparing bandings with the same spectral content. Using this methodology, we can give a grade to each printer for the visibility of banding. Again, the different halftone patterns for Printer C did not significantly affect the visibility of banding.

The ratio of the AL's of the printers acquired in the previous section is shown in the third row of Table V for a comparison with the PSE's shown in the first row that were obtained from the cross platform experiment. There is a good match between the PSE's and the ratio of the AL's of

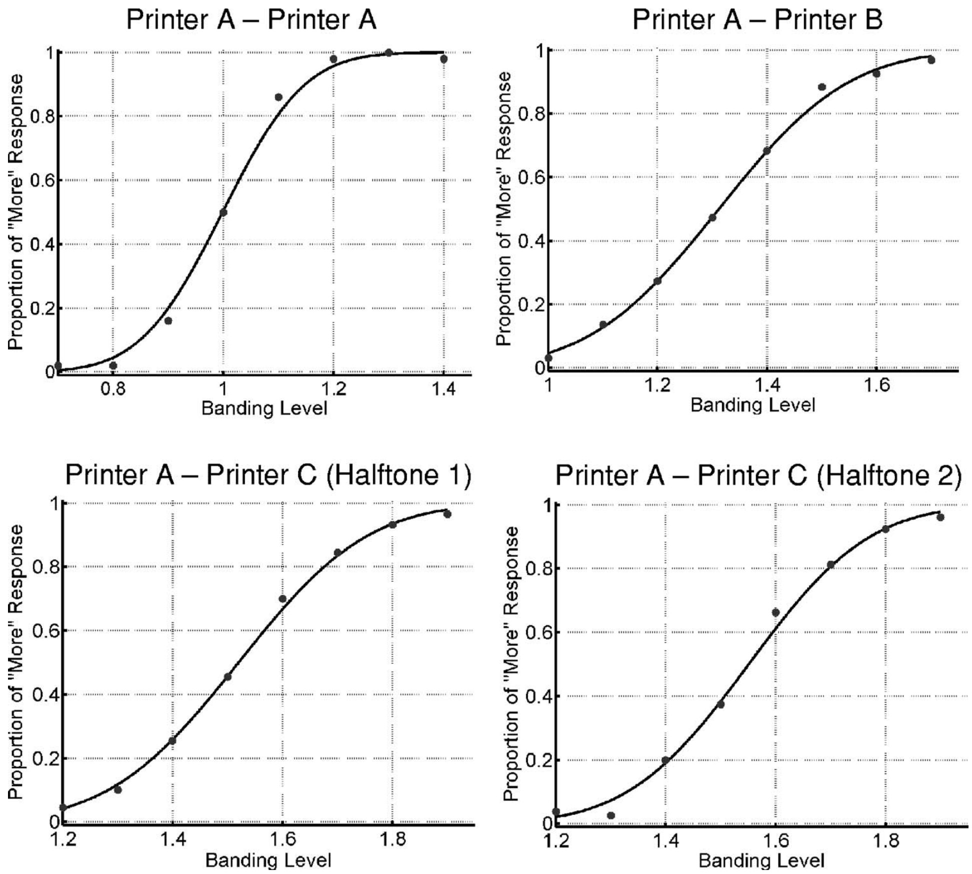

Figure 12. Psychometric functions for the pooled data of the cross platform experiments. The abscissa is the level of banding for Printer A.

Table V. Results of the cross platform experiment and the ratio of AL's acquired from the banding detection experiment.

	Printer A - Printer A	Printer A - Printer B	Printer A - Printer C (Halftone 1)	Printer A - Printer C (Halftone 2)
Reciprocal of Banding Level for the Test Printer $(1/\beta)$	1.00 ± 0.03	1.31 ± 0.07	1.48 ± 0.07	1.56 ± 0.07
Std. Dev. of Psychometric Function	0.071 ± 0.019	0.101 ± 0.030	0.095 ± 0.016	0.120 ± 0.031
Ratio of AL's	1.00	1.12	1.56	1.58

the corresponding two printers except between Printer A and Printer B. In this case, the ratio of their AL's is lower than the PSE. This could be due to the high background noise of Printer B, which might have caused its AL value to be larger. In general, the ranking of the printers generated with both methods match with each other.

In the cross platform experiment just discussed, the reference printer was Printer A in all cases. The question is whether using a different printer as the reference will affect the results. So we conducted a control experiment to compare the banding of Printer C with that of Printer B as the reference. Five subjects participated in this experiment. The PSE we found was 1.17 ± 0.13. If we take the ratio of the PSE's from the previous experiment:

$$\frac{1.48(\text{Printer } C \Leftrightarrow \text{Printer } A)}{1.31(\text{Printer } B \Leftrightarrow \text{Printer } A)} = 1.13 \approx 1.17 \pm 0.13(\text{Printer } C \Leftrightarrow \text{Printer } B). \quad (5)$$

This result shows that the grading of the printers by cross platform experiment does not depend on the choice of the reference printer.

CONCLUSION AND DISCUSSION

We developed a softcopy environment for conducting print quality assessment experiments. This environment includes the methodology to duplicate the print-out on the monitor, and a banding extraction technique. This technique enables us to freely adjust the magnitude of banding of any printer. We validated the accuracy of this methodology by conducting banding matching experiments.

We used this platform to conduct banding visibility assessment experiments. One of them was a banding discrimination experiment. The results showed that, for any printer, a reduction of 6.5% in the banding amplitude will be just noticeable by an average observer. We were also able to find the absolute threshold (AL) of banding visibility for the three printers. The AL of the best printer was about 50% of its original banding. So there is still plenty of room to reduce the visibility of banding. Finally, we were able to compare the banding visibility of printers quantitatively by conducting a cross-platform experiment. This methodology can be used to compare any two printers and could form the basis for developing a metric for banding visibility.

ACKNOWLEDGMENTS

We wish to thank N. Burningham for helpful comments that improved this paper. This research was supported by the Hewlett-Packard Company.

REFERENCES

[1] E. N. Dalal, D. R. Rasmussen, F. Nakaya, P. A. Crean, and M. Sato, "Evaluating the overall image quality of hardcopy output", *Proc. IS&T's 1998 PICS Conference* (IS&T, Springfield, VA, 1998) pp. 169–173.

[2] D. R. Rasmussen, E. N. Dalal, and K. M. Hoffman, "Measurement of macrouniformity: Streaks, bands, mottle, and chromatic variations", *Proc. IS&T's 2001 PICS Conference* (IS&T, Springfield, VA, 2001) pp. 90–95.

[3] J. C. Briggs, "Banding characterization for inkjet printing", *Proc. IS&T's 2000 PICS Conference* (IS&T, Springfield, VA, 2000) pp. 1–2.

[4] C. Cui, D. Cao, and S. Love, "Measuring visual threshold of inkjet banding", *Proc. IS&T's 2001 PICS Conference* (IS&T, Springfield, VA, 2000) pp. 87–89.

[5] P. J. Kane, T. F. Bouk, P. D. Burns, and A. D. Thompson, "Quantification of banding, streaking, and grain in flat field images", *Proc. IS&T's 2000 PICS Conference* (IS&T, Springfield, VA, 2000) pp. 1–2.

[6] G.-Y. Lin, J. M. Grice, J. P. Allebach, G. T.-C. Chiu, W. Bradburn, and J. Weaver, "Banding artifact reduction in electrophotographic printers by using pulse width modulation", J. Imaging Sci. Technol. **46**, 326–337 (2002).

[7] C. lun Chen, G. T.-C. Chiu, and J. P. Allebach, "Banding reduction in electrophotographic process using human contrast sensitivity function shaped photoreceptor velocity control", J. Imaging Sci. Technol. **47**, 209–223 (2003).

[8] M. T. S. Ewe, G. T.-C. Chiu, J. Grace, J. P. Allebach, C. S. Chan, and W. Foote, "Banding reduction in electrophotographic processes using a piezoelectric actuated lasr beam device", J. Imaging Sci. Technol. **46**, 433–442 (2002).

[9] Y. Bang, Z. Pizlo, N. Burningham, and J. P. Allebach, "Banding titration", *Proc. IS&T's NIP19: International Conference on Digital Printing Technologies* (IS&T, Springfield, VA, 2003) pp. 745–750.

[10] Y. Bang, Z. Pizlo, and J. Allebach, "Banding assessment with controlled halftoning: The ten printer experiment", J. Imaging Sci. Technol. **50**(6), 522–529 (2006).

[11] K. F. Choi, "Comparison of color difference perception on softdisplay versus hardcopy", *Proc. IS&T/SID 2nd Color Imaging Conference* (IS&T, Springfield, VA, 1994) pp. 18–21.

[12] M. D. Fairchild, "Using color-appearance models in device independent color imaging", *5th International Conference on High Technology* (Chiba, Japan, 1996) pp. 128–135.

[13] M. D. Fairchild, "Refinement of the *RLAB* color space", Color Res. Appl. **21**, 338–346 (1996).

[14] G. M. Johnson and M. D. Fairchild, "A top down description of *S—CIELAB* and *CIEDE* 2000", Color Res. Appl. **28**, 425–432 (2003).

[15] T.-C. Hseue, Y.-C. Shen, P.-C. Chen, W.-H. Hsu, and Y.-T. Liu, "Cross media performance evaluation of color models for unequal luminance levels and dim surround", Color Res. Appl. **23**, 169–177 (1998).

[16] M. D. Fairchild and L. Reniff, "A pictorial review of color appearance models", *Proc. IS&T/SID 4th Color Imaging Conference* (IS&T, Springfield, VA, 1997) pp. 97–100.

[17] D. D. Haas, "Contrast modulation in halftone images produced by variation in scanline spacing", J. Imaging Technol. **15**, 46–55 (1989).

[18] Y. Shiraiwa, Y. Hidaka, T. Mizuno, T. Sasaki, K. ichi Ohta, and A. Usami, "Matching of appearance of colors in hard-copy and softcopy images in different office environments", Proc. SPIE **3300**, 148–158 (1998).

[19] H. Komatsubara, S. Kobayashi, N. Nasuno, Y. Nakajima, and S. Kumada, "Visual color matching under various viewing conditions", Color Res. Appl. **27**, 399–420 (2002).

[20] M. D. Fairchild, "Considering the surround in device-independent color imaging", Color Res. Appl. **20**, 352–363 (1995).

[21] J. A. S. Viggiano and C. J. Wang, "A comparison of algorithms for mapping color between media of differing luminance ranges", Proc.-TAGA **2**, 959–974 (1992).

[22] S. J. Park and M. D. Fairchild, "Color reproduction using black point adaptation", *Proc. IS&T/SID 9th Color Imaging Conference* (IS&T, Springfield, VA, 2001) pp. 245–250.

[23] W. L. Rhodes, "Tone and color control in reproduction process," Proc. TAGA, pp. 48–61 (1954).

[24] R. E. Maurer, "The reproduction of over- and underexposed transparencies", Proc. TAGA, pp. 38–64 (1972).

[25] "CIE guidelines for coordinated research on evaluation of colour appearance models for reflection print and self-luminous display image comparisons", Color Res. Appl. **19**, 445–453 (1994).

[26] K. Braun and M. D. Fairchild, *Recent Progress in Color Science* (John Wiley and Sons, New York, 1997), Chap. 1.

[27] M. D. Fairchild and L. Reniff, "Time course of chromatic adaptation for color appearance judgments", J. Opt. Soc. Am. A **12**, 824–833 (1994).

[28] N. Katoh, K. Nakabayashi, and M. Ito, "Effect of ambient light on the color appearance of softcopy images: Mixed chromatic adaptation for self-luminous displays", J. Electron. Imaging **7**, 794–806 (1998).

[29] K. Nakabayashi and M. D. Fairchild, "Appearance match between softcopy and hardcopy using lightness rescaling with black point adaptation", Proc. SPIE **4663**, 217–228 (2002).