Does Error-Diffusion Halftone Texture Mask Banding?

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Abstract

One type of common printer banding artifact is a thin white horizontal line. This can result from a clogged ink jet nozzle, from paper-feed problems in electrophotographic printers, and from other causes. The halftone texture might be expected to mask the visibility of the line, so a line on a strong texture might be less visible than a line on a uniform field. To test this hypothesis, white lines were printed on fields with different texture contrasts, and we measured the threshold visibility for detecting the line.

The line was printed as a reflectance increment in one of the pixel-rows of an error-diffusion pattern. The error diffusion-pattern was produced by applying the Floyd and Steinberg algorithm to a gray square. Two experiments were conducted. In one experiment, only the contrast of the halftone pattern was varied, and the subject was required to detect the pattern. In the second experiment, both the contrast of the halftone pattern and the contrast of the line were varied, and the subject was required to detect the line. The threshold for detecting the line was then plotted as a function of the strength of the halftone.

It was found that the error-diffusion halftone pattern does not mask sensitivity to a line until the halftone pattern was many times above its own detection strength. Even when the halftone pattern was at the highest contrast that could be printed (about 20 times threshold contrast), the threshold amplitude for detecting the line was only doubled. Error diffusion is typically used because it reduces the visibility of the halftone texture. Since only very strong halftone textures provided any visual masking, the contrast of the error diffusion texture had to be very high to obtain any significant masking effect. This has the unfortunate implication that objectionable banding may only be hidden with even more objectionable halftone texture. Some of the implications for modeling band visibility will be discussed. It is important to note that there are previously described halftone patterns that can physically reduce the amplitude of the bands, and the present result does not run counter to these findings.

Introduction

One of the most objectionable image artifacts introduced by computer printing is banding. Printer bands are typically horizontal striate patterns introduced by defects in the procedure that scans the image onto the page, or as defects in the shape or location of a row of dots. Frequently the pattern is periodic, and it can consist of errors in color, brightness, gloss, and other factors. For the purpose of this study we only considered a single horizontal line of increased brightness. Many papers have addressed the visibility of line-like stimuli, but for the purposes of computer printing the banding is typically produced on an image that has been rendered by means of halftoning. The halftone pattern acts as a visual mask, and it reduces the visibility of the banding. The objective of this study is to measure the masking produced by halftone texture patterns in hardcopy.

In this study, we first measured the visibility of a white line that was superimposed on a halftone texture background. The contrast of the texture was varied, and the threshold visibility of the line was measured. In a second experiment, we varied the strength of the texture, and found the threshold contrast for detecting the texture. This allows us to plot line threshold contrast vs. texture strength in units of times-threshold.

Experiment 1. Detection of Banding

We used the method of constant stimuli to determine the contrast threshold for detecting a positive contrast horizontal line on a halftone texture mask.

Methods

We first generated a halftone texture by converting a gray square with an extent of 200 X 200 pixels into a bi-level error-diffusion pattern of white and black pixels by means of the error diffusion algorithm described by Floyd and Steinberg [ref]. We chose a gray level that had 62% white pixels by examining the Wiener power spectrum of several different gray levels until we found one that was reasonably isotropic. This was a somewhat arbitrary selection, but we wanted to avoid the gray levels at which the Floyd-Steinberg algorithm produces highly regular and anisotropic patterns (e.g. .5 reflectance). In typical imaging applications, highly regular patterns are not common because of irregularity in the image content. To avoid the periodic effect created by the error diffusion at the edges of the square, we extracted just the center 100 X 100 pixel region of the square. The final halftone noise pattern was a 1/2 inch square when printed at 200 dots per inch. The exact pattern that we used is illustrated in Figure 1.

We then converted this square to 4 different contrast levels by increasing the reflectance of the dark pixels and by decreasing the reflectance of the light pixels in such a way that the mean level was held constant. At the lowest contrast level, (contrast 0) the dark and light pixels had the same reflectance. At the highest level, the dark pixels were as dark and as light as the printer was able to produce.

For each level of halftone texture, we created a white band by reducing the reflectance of a single row of the dark pixels. Instead of attempting to calibrate the printer to produce bands at specific levels, we printed the bands at arbitrary levels and then measured their contrast, as is described in Appendix 1.

We only made the dark pixels lighter, as opposed to making both the dark and light pixels brighter, for three reasons. First, the highest contrast level of halftone texture already had light pixels that were as light as possible. Second, it is very difficult to calibrate a printer on a pixel-by-pixel basis, and if we did not make the light pixels the same amount brighter as we made the dark pixels brighter, the form of the stimulus would have changed. Third, banding defects in computer printers usually only effect areas that are printed with dark dots, so this type of line more closely resembles a printer banding artifact.

We surrounded the halftone texture with a neutral gray 1/2 " thick square boarder. Four black fiducial crosses were placed in the corners of the stimulus. These crosses were used mainly to facilitate scanning the cards (described in Appendix 1).

We printed the cards on a Fujix Pictrography 3000 printer[2] and cut them into 1.5" squares. We provided an indexing notch in the upper right corner of the card to facilitate orientation. Figure 1 shows an example of a card.

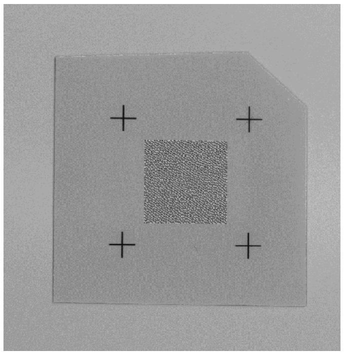

Figure 1. A scan of one of the cards used in the experiments.

In total, we used 16 types of cards: 4 levels of halftone pattern with 4 line strengths on each. We conducted four experiments with each subject, one for each level of halftone strength. The subject was required to sort the cards into 4 levels of line strength, as will be described.

We presented the cards to the subject one at a time on an easel that was 12" from the subject's eye and oriented at an angle that was normal to the subject's eye. The easel was the same neutral gray color as the surrounding region of the card. The subject was placed in a chin-rest to control viewing distance. We used a MacBeth viewing booth with a D50 light source to illuminate the cards and easel. We chose a random set of 100 cards from a deck of 150 cards, so the subject did not know how many cards there were from each category. We then presented the cards in a random order.

On the easel there were 4 example cards printed with the 4 strengths of bands. The subject's task was to examine each card, one at a time, and to place it into a bin that corresponded to the strength of the band. The subject was allowed any amount of time to make the observations, but typically required about 15 minutes to sort the deck of 100 cards. After this experiment, a new set of cards with a different halftone strength was used, and the experiment was repeated as before.

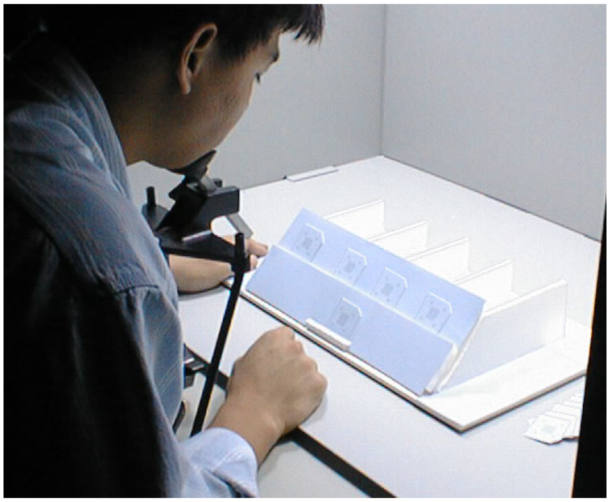

Figure 2. The experimental arrangement.

The subject viewed the stimulus card on the lower portion of the easel. The 4 samples in the upper portion of the easel are examples of the 4 possible stimulus strengths. The subject would judge the strength of the sample, and place it into the bin behind the example card that was most similar to it.

In each block of trials, the subject was required to sort the cards into 4 bins. After sorting, the contents of the bins were tallied to produce a 4 by 4 response matrix for each subject. For each response matrix, the d'=1 threshold for detecting the pattern was estimated with the Rocflex analysis program [Levi 1984]. A transducer exponent between contrast and d' was also calculated, and this was found to be approximately 1.5 in preliminary studies, so this value was used to estimate thresholds. 3 blocks of trials were conducted for each of the four halftone strengths. Each block of trials produced a separate estimate of line threshold, and these estimates were averaged together for each of the four conditions.

Experiment 2. Detection of Halftone Texture

We used the method of constant stimuli to determine the detectability of the lowest contrast halftone texture pattern. We were then able to specify the other halftone texture patterns in units of times-threshold contrast.

Methods

We used the same methods in experiment 2, but instead of 4 levels of line strength we used 4 levels of halftone texture strength.

Halftone Texture Contrast Units

We were primarily interested in specifying the noise strength in threshold units, as will be described in the discussion. We first scanned the cards using the methods described in Appendix 1, and then we computed statistics that measured the strength of the halftone texture patterns.

As an intermediate statistic of the noise strength, we used the root-mean-square (RMS) amplitude of the noise. Since the halftone texture pattern was spatially the same in all of our experiments and always had the same mean level, the RMS amplitude is proportional to the contrast of the pattern, where contrast is defined as the amplitude of the pattern divided by the mean of the pattern. Proportionality is preserved despite any linear operation on the pattern, so we do not need to be concerned about the exact pattern that reaches the subject's retina, as long as that pattern is formed by a reasonably linear process. We also do not need to measure the modulation transfer function (MTF) of our scanner, since this is itself a linear model of the scanner response.

After we had determined the RMS amplitudes of the 4 stimuli, we could estimate the RMS amplitude that was required for threshold detection. We could then analyze the patterns used in experiment 1 with the same RMS statistic to determine how many times they were above the threshold contrast level for detection.

Results and Discussion

In figure 3 we show the results of our two experiments plotted together. To interpret our results, we consider a two-source noise model. One source is internal to the visual system, and it limits the absolute threshold for seeing a line. Even if the line is presented on a noiseless background, it will still need to have a certain amount of contrast to be visible. The second source of noise is external to the visual system. It is the noise of the halftone pattern. Any mechanism that is used to detect the line may also be sensitive to the halftone noise texture pattern. The line will then be detected as an increment on top of the stimulation due to the halftone noise pattern. To detect the line, the subject would require sufficient percentage strength over the strength of the noise, that is, a sufficient Webber fraction.

When the internal noise is much stronger than the external noise, the subject should perform at a constant level regardless of the strength of the external noise. As figure 3 shows, we found that this was the case to at least 4 or 5 times threshold noise. After that, we expected the threshold line strength to vary in direct proportion to the external noise strength. When the noise was 20 times the subject's threshold, we found an increase of only a factor of 2 in the strength required for detection of the line. This indicates that halftone noise is only a weak mask of a line.

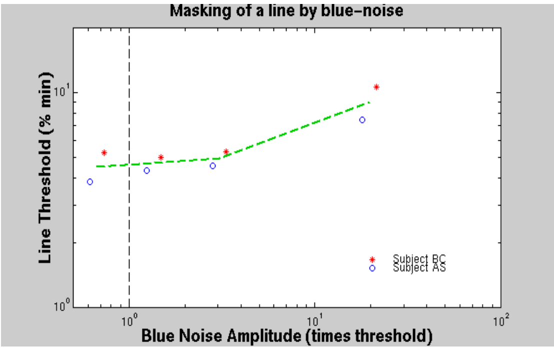

Figure 3. Detectability as a function of masking strength. The data points are from the two subjects. The dashed line is the linear interpolation between the averaged data from the two subjects. The vertical dashed line at 1 indicates the threshold for detecting the halftone noise as measured in experiment 2.

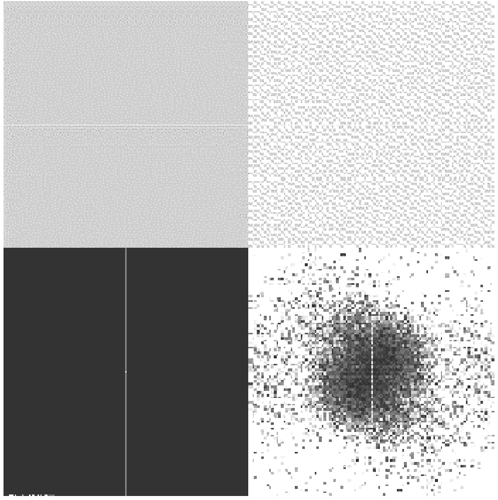

Figure 4. Power spectra

Upper left: A white line on a gray background.
Upper right: A white line on a halftone texture pattern.
Lower left: The power spectrum of the line on a gray background.
Lower right: The spectrum of the line/halftone texture pattern.

To see why, it is useful to look at the stimulus in the frequency domain. Figure 4 shows a white line in the upper left. In the upper right, it shows the line in a field of halftone noise. Below, it shows the Wiener power spectrum of the two figures above. As the figure shows, halftone texture has very little power at low spatial frequencies. The line can therefore be detected by the low-spatial frequency mechanisms of the visual system.

Appendix 1. Determining the Contrast Strength of Bands

Attempting to generate bands at specific strengths presents a very difficult calibration problem. The pixels on the page interact in complex ways that are difficult to predict, so it is difficult to produce a small feature (such as a thin line on a halftone noise texture) with a specific reflectance. Because of this, we chose to print lines at many different levels, and then we selected ones that were near the threshold for detection. We conducted our experiments with these near-threshold lines, and we found the detectability of the lines without knowing their exact description. By subsequently scanning the printed patterns with a calibrated scanner, we were able to obtain a description of the stimuli.

Scanning

We used an Agfa Horizon scanner, which uses a tungsten light source with characteristics that are similar to the light source used in the experiment. We checked the calibration of the scanner to be sure that it was linear with respect to percent-reflectance. We used a Colortron light-trap to set the absolute zero, and we checked the scanner response with the MacBeth color checker chart gray-scale ramp.

We scanned in a subset of nine cards of each type. To isolate the stimulus from the halftone texture pattern, we computed the difference between scanned halftone texture pattern with no line, and the scanned halftone texture pattern with the line. We found that the contrast of the lines were quite close to the smallest interval we could measure with the scanner, so we repeated the scanning procedure for 9 cards of each type and we computed the average. To average between scans, we first needed to put the scans in register with each other, and to do this we followed the procedure described below.

Localization of the Fiducial Crosses

We used a multi-scaler technique to localize the fiducial crosses. We first sub-sampled the scanned image, and then we convolved it with a cross-shaped kernel of the appropriate size. This produced 4 maxima that indicated the approximate centers of the fiducials. We then repeated the convolution procedure on the corresponding regions of the full resolution image to find the pixel closest to the center of each region. This information was used to extract each of the four limbs of each fiducial. We then used a non-linear regression to fit a Gaussian distribution to the reflectance profile of each limb. The mean of the fit was used as our sub-pixel estimate of the center of the limb. We then use the limb centers to estimate the center of the fiducial.

Resampled Affine Transformation

After we had determined the centers of the fiducials, each scanned image of a card was transformed by an affine transformation into register with all the other cards. For each card in turn, we found the affine transformation that produced the least-squared error transformation from that card's set of fiducial positions to the fiducial positions of the previous card. The entire image of that card was then transformed and resampled by bicubic interpolation. After all the scans were resampled into register with one another, we were able to compute the average of each stimulus type, and to subtract out the halftone noise.

Line Contrast Units

We model our line stimulus as a Gaussian blurred line. We found a least-squares fit of a Gaussian reflectance profile to the scanned stimulus. This allows us to describe our stimulus in units of percent minute (%min) and Gaussian blur. The unit of line-strength we used, % min is the combination of line width (in units of minutes of visual angle) and percent contrast. So, a line that subtended 1 min of angle and had 1% contrast would have a strength of 1%min.

References

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Biography

Amnon Silverstein has a degree in computer science from Oberlin College in Ohio, and a degree in Vision Science from the University of California at Berkeley. He joined Hewlett-Packard Laboratories in 1996. He is working on image quality for display devices.