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Halftone Dot Size Variation in Offset, Electrophotographic, and Flexographic Printing and Its Perception

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Abstract. *In digital halftone technology, dot reproducibility is an important factor because our perception and recognition of an image depend on the characteristics of the printed dot. Halftone dot size variations reproduced by typical printing technologies, such as electrophotography, offset, and flexography, were investigated to determine their dot reproducibility. The investigation found that offset, flexography, and electrophotography can produce halftone dot sizes with a percentage coefficient of variation (%CV) at 8.88, 19.64, and 13.93 consecutively in the highlight image areas (small dot size), while the %CV of halftone dot size variations tend to decrease when the dot size increases in the midtone and shadow image areas. The perception of simulated halftone dot size variations was then studied experimentally under set observation distance and halftone frequency conditions in order to analyze the relation between human perception and halftone dot size variations. It was determined that human perception detects nonuniform halftone image dot patterns when the %CV of the halftone dot size variation is greater than 6.72.* **©** *2008 Society for Imaging Science and Technology.*
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INTRODUCTION

Dot reproducibility is one of the most important factors influencing the quality of a halftone image. Reproducibility includes the characteristics of halftone dot size variations, dot position, and sharpness.[1–3] Dot reproducibility depends on the printing technology, the characteristics of the ink or toner used, and the properties of the printed media. Currently important printing technologies include electrophotography, offset, and flexography printing. Electrophotography is a dry photocopying method in which an image is transferred on the basis of the attractive forces of opposing electric charges. Electrophotographic toner is normally a powder, which may vary in properties according to composition, and which may contain colorants in the form of pigments. Offset produces printed dots by indirectly transferring ink to the printed media. In a conventional offset printing process, ink is prevented from transferring onto nonimage areas by use of a dampening solution. In the flexography process, the reproduced dot is transferred directly to the printed media. The conjunction of the low viscosity ink utilized and the elasticity of the flexography printing plate permit printing on nonabsorbent and rough-surfaced printed media. Furthermore, flexography requires only a slight contact pressure to enable reliable ink transfer from the printing plate to the printed media.[4] The differences between the printing technologies mentioned above lead to the production of halftone images with different halftone dot size variations.[2]

Halftone dot size variations affect the tone reproduction and quality of a halftone image because the way humans perceive a halftone image depends on the size variations of the printed dot. In this study, halftone dot size variation can be defined as interference that prevents the printed dot from blending smoothly into the intended image. Halftone dot size variations occur when an irregular fluctuation alters a dot shape into an irregular unclear pattern. Development of technology that reduces such interference is a major challenge for the printing industry.[5]

Among the studies that have been conducted on factors affecting image quality has been research on the relation between the coefficient of variation and the perceived quality of uniform density. These studies provide evidence for the effects halftone dot size variations have on image quality and indicate that the effect of halftone dot size variations, as a halftone dot noise, is one of the most important factors governing the production of high-quality halftone images.[6] A number of studies investigating factors that impact print quality[7,8] have been conducted. These research efforts have tended to focus on electrophotographic printing in order to simulate noise characteristics based on printer models and to evaluate the results on printed halftone image quality. Recent studies also show the result of empirical studies into the factors that influence image quality. The studies compared the shape of printed dots produced by electrophotography and ink jet printing[9,10] and the halftone dot size variation as a halftone dot noise,[1] and concluded that they are important factors governing the production of high-quality halftone images. The study results also show that the uniformity of the shape and size of dots printed by electrophotography printing increases in proportion to the cluster size. However, with ink jet printing, the increase in uniformity is

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relatively less obvious. Another research effort, focusing on electrophotography, established a correlation between image quality parameters and the measured attribute, defined as the printed dot size. The variations of halftone dot sizes when printed by offset, flexography, and electrophotography were observed, and the results show that dot variations tend to decrease when the dot cluster increases.[2]

This article aims at investigating human perception of halftone dot size variations. The characteristics of halftone dots reproduced by representative printing technologies were measured in terms of halftone dot size variations, and halftone dot quality was evaluated on the basis of human perception. The relation between human perception and halftone dot size variation is then discussed.

EXPERIMENTAL

Experiments were performed to analyze the halftone dot size variations of typical printing technologies and to determine the threshold level at which human perception can detect halftone dot size variation. The technologies used in this experiment were electrophotography, offset, and flexography printing. The perception of halftone dot size variations in this experiment was denoted as halftone dot noise perception.

Materials and Equipment

In the experiment, halftone imagery was generated by MATLAB® 7.0 software produced by MathWorks. We generated 11 square-shaped patterns. These patterns consisted of an image series, comprising an isolated dot (a cluster of $1\times1=1$ pixel/dot), a cluster of two horizontally adjacent dots (a cluster of $1\times2=2$ pixels/dot), a cluster of $2\times2=4$ pixels/dot, a cluster of $3\times3=9$ pixels/dot, up through a cluster of $10\times10=100$ pixels/dot. The number of halftone dots were ten dots per pattern. We then output the generated halftone dots as 1 bit TIFF with a resolution of 400 dpi, and printed it via the three selected printing technologies.

The technologies selected for use in this experiment, were flexography, offset, and electrophotography printing. The printing specifications were as follows.

- Offset press: The plate was output by Computer-to-Plate technology (Luxel V-6). The plate substrate was Fuji Digital Brillia™ type LP-NV plate. It was output at a resolution of 2540 dpi with 175 lpi, and printed by a proofing machine (SCREEN).
- Flexography press: The plate was output with Computer-to-Plate technology (ESKO type CDI Spark 4835). The plate substrate was Nyloflex® FAH No.114 DII. It was output at a resolution of 2540 dpi with 120 lpi and printed by a proofing machine (JM Heaford).
- Electrophotography: The study substrate was printed by a standard electrophotographic printer (Canon type 2710) at a resolution of 9600 dpi.

All dots examined during this experiment were printed on one side of 80 g/m^2 white bond paper. Each printed halftone dot was digitally measured by MATLAB® 7.0 software produced by MathWorks and QEA image processing software. We used an EPSON ES-2000 charge coupled device scanner set at a resolution of 1600×1600 dpi to import printed halftone imagery into the computer as digital data. The size and shape of the dots were then measured.

Method

The size and gain of printed halftone dots were measured and then calculated as a percentage coefficient of variation ($\%CV_p$). The percentage coefficient of variation is the ratio of the coefficient of variation for a halftone dot size, as reproduced by electrophotography, offset, and flexographic printing, to a normalized measure of dispersion for a probability distribution. For the analysis of halftone printed dot variations, the percent coefficient of variation $\%CV_p$ was calculated as shown in Eq. (1),[11]

$$\%\mathrm{CV}_p = \frac{S}{\bar{x}} \times 100, \tag{1}$$

where the standard deviation of the entire halftone printed dot for each pattern, $S=1/N\Sigma_{i=1}^{N}(x_i-\bar{x})^2$, and the mean of these halftone printed dot for each pattern, $\bar{x}=1/N\Sigma_{i=1}^{N}x_i$; x is the number of pixels within a halftone printed dot and N is the number of halftone dots per pattern.

Halftone dot noise was simulated in order to analyze the effect of halftone dot size variations on human perception. The percent coefficient of simulated halftone dot noise ($\%CV_n$) which is the ratio of coefficient of variation of the simulated halftone dot size variation, was then calculated in order to compare it with the percent coefficient of variation of the print, $\%CV_p$. The relation between human perception and halftone dot size variation was then discussed based on the evaluation results. The experimental procedure is shown in Figure 1.

Halftone Dot Reproduction via Three Printing Technologies

The printed halftone dots reproduced by offset, flexography, and electrophotographic printing are shown in Figures 2–4. The measuring device used was unable to detect an isolated dot (halftone dot patterns at 1×1 pixels/dot) produced by flexographic printing. Otherwise, all other halftone dot patterns could be detected. Furthermore, the edges of printed halftone dots reproduced by flexography printing were vague, and the shape of the printed halftone dots did not form a rectangular cluster when the cluster size was small. Figure 5 shows the dot size reproductions for offset, flexography, and electrophotography printing. The printed dots were measured in the form of pixels, after which the scale was transformed into microns.

During comparisons with original halftone dot sizes, it was found that offset printing produced the halftone dot size that most closely matched that of the original cluster. The halftone dot size produced by flexographic printing for the same cluster was greater than any of the others.

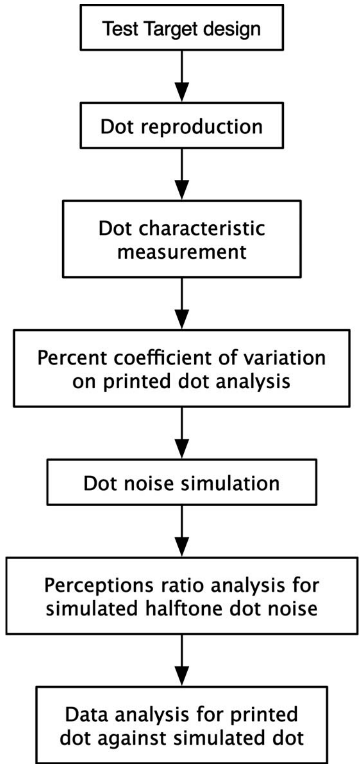


Figure 1. Halftone dot size variation analysis procedure.

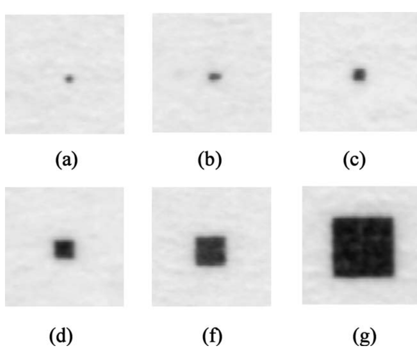


Figure 2. Halftone dot printed by offset: (a) isolated dot a cluster of $1\times 1 = 1$ pixel/dot; (b) cluster of two horizontally aligned dots in a cluster of $1\times 2=2$ pixels/dot; (c) a cluster of $2\times 2=4$ pixels/dot; (d) a cluster of $3\times 3=9$ pixels/dot; (f) a cluster of $5\times 5=25$ pixels/dot; and (g) a cluster of $10\times 10=100$ pixels/dot.

Figure 6 shows the relations between area coverage of the original halftone image and the area coverage in the printed media in terms of dot gain. Dot gain is a printing phenomenon, whereby printed dots are actually printed and perceived larger than intended. The dot gain resulting from offset printing is relatively constant, while flexography and electrophotographic printing tend to reproduce images in which dot gain increases as the halftone dot size increases.

Table I shows $\%CV_p$ for halftone printed dots reproduced by offset, flexography, and electrophotographic printing. It was found that offset printing produces halftone dots with the least variation while flexography printing produces halftone dots with the greatest variation. Figure 7 illustrates the relation between the $\%CV_p$ and the dimensions of the halftone dot pattern. The graph shows that $\%CV_p$ tends to decrease when the cluster dot increases. Since $\%CV_p$ represents the fluctuation of printed halftone dot size, we investigated the relation between these variations and halftone image quality. In order to determine the relation between halftone dot size variations and image quality, human vision,

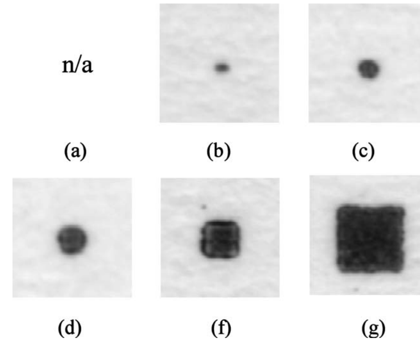


Figure 3. Halftone dot printed by flexography: (a) isolated dot a cluster of $1\times 1=1$ pixel/dot; (b) cluster of two horizontally aligned dots in a cluster of $1\times 2=2$ pixels/dot; (c) a cluster of $2\times 2=4$ pixels/dot; (d) a cluster of $3\times 3=9$ pixels/dot; (f) a cluster of $5\times 5=25$ pixels/dot; and (g) a cluster of $10\times 10=100$ pixels/dot.

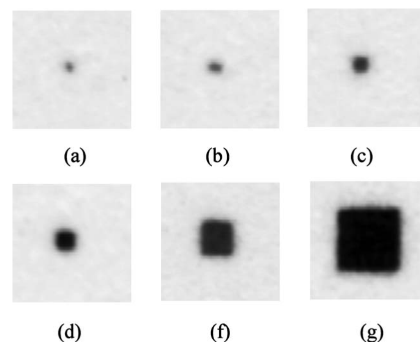


Figure 4. Halftone dot printed by electrophotography: (a) isolated dot a cluster of $1\times 1=1$ pixel/dot; (b) cluster of two horizontally aligned dots in a cluster of $1\times 2=2$ pixels/dot; (c) a cluster of $2\times 2=4$ pixels/dot; (d) a cluster of $3\times 3=9$ pixels/dot; (f) a cluster of $5\times 5=25$ pixels/dot; and (g) a cluster of $10\times 10=100$ pixels/dot.

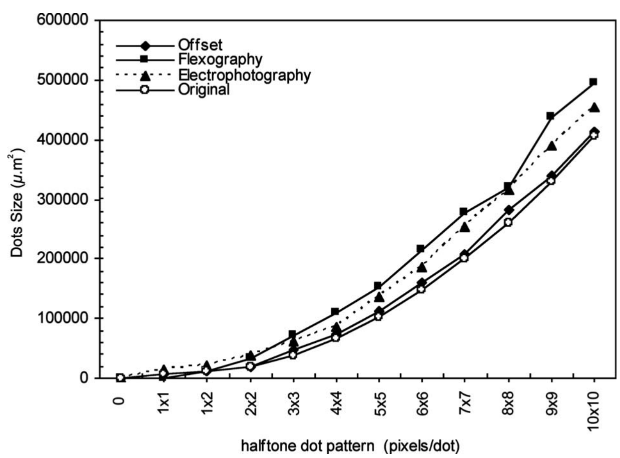


Figure 5. Printed halftone dot size.

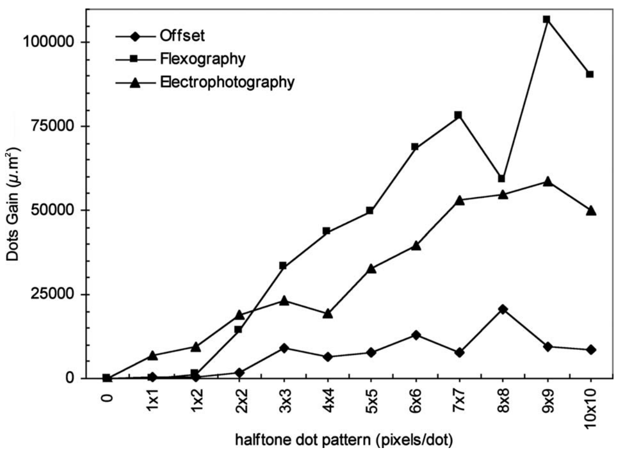


Figure 6. Printed halftone dot gain.

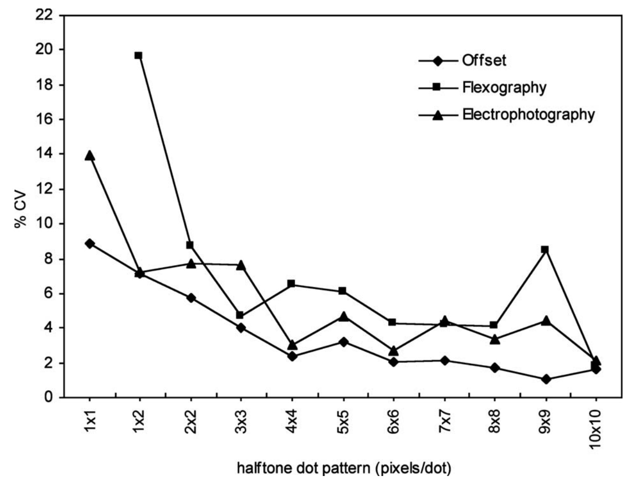


Figure 7. Percent coefficient of variation of printed dot size.

Table I. $\%CV_p$ of printed halftone dots.

Halftone dot pattern (pixels/dot)	$\%CV_p$		
	Offset	Flexography	Electrophotography
1×1	8.88	N/A	13.93
1×2	7.13	19.64	7.26
2×2	5.71	8.68	7.69
3×3	4.04	4.68	7.6
4×4	2.41	6.46	2.99
5×5	3.17	6.08	4.69
6×6	2.04	4.29	2.69
7×7	2.09	4.15	4.4
8×8	1.74	4.08	3.39
9×9	1.03	8.45	4.4
10×10	1.61	1.76	2.1

which is one of the typical approaches used to evaluate image quality, was considered an effective tool.

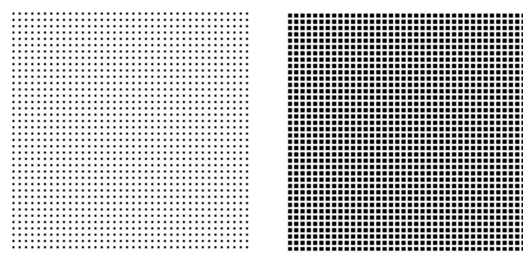
Halftone Dot Noise Simulation and Subjective Estimation Method

Halftone dot noise was simulated as part of investigations into the effects of halftone dot size variation on human perception. A number of subjects were asked to evaluate the quality of halftone imagery that contained embedded halftone dot noise. The halftone dot noise was converted into a percent coefficient of variation and compared with $\%CV_p$ to determine its relation. Halftone dot noise was generated according to Eq. (2) while the noise value was calculated by Eq. (3),

$$\mathrm{HT}'_{(x,y)} = \mathrm{HT}_{(x,y)} + N_{(x,y)}, \tag{2}$$

$$N_{(x,y)} = \alpha(R-p). \tag{3}$$

Here, $\mathrm{HT}'_{(x,y)}$ is the halftone dot noise, $\mathrm{HT}_{(x,y)}$ is the original halftone dot, $N_{(x,y)}$ is the noise value, α is the percent of noise in a halftone dot coverage area, R is a random number (0–1), and p is the coarseness parameter ($p=0.5$).



(a) (b)

Figure 8. Illustration of dot clusters: (a) the cluster of 5×5 pixels/dot; (b) the cluster of 10×10 pixels/dot.

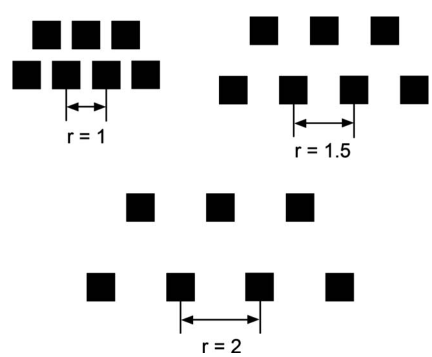


Figure 9. The distance between halftone dots.

Halftone images with dot noise were generated in clusters of $5\times5=25$ pixels/dot and $10\times10=100$ pixels/dot as shown in Figure 8. The distances between each dot, r, can be divided into three levels: 1, 1.5, and 2. The normalized distance between two dots was 1.0 whereas 1.5 and 2.0 were the extended distances. Figure 9 shows the distance pattern for the halftone dot noise simulation.

For this experiment, we generated halftone dot noise with $\alpha=\{2,4,6,8,10,12\}$. All halftone dot noise for this experiment was generated by MATLAB® 7.0 software pro-

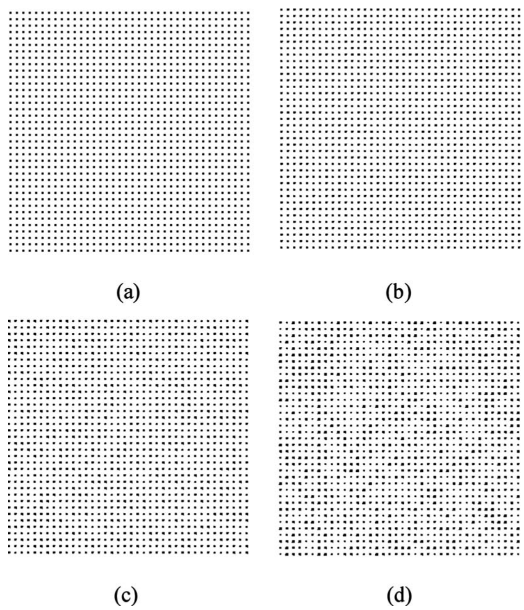


Figure 10. Test samples showing various percentages of dot noise for evaluation: (a) original; (b) 4% noise; (c) 6% noise; and (d) 12% noise.

duced by MathWorks and then printed on one side of 80 g/m^2 white bond paper. Figure 10 shows a sample image containing simulated halftone dot noise that as used for the evaluation. Ten subjects were asked to evaluate the fluctuation of simulated halftone dot noise at two observation distances: 1 m and free observation. The perception ratios were obtained as the ratio of the number of subjects who perceived halftone dot noise (responded "yes") versus the total number of subjects. The subjects who could not perceive halftone dot noise responded "no."

RESULTS OF PERCEPTION OF SIMULATED HALFTONE DOT

Figure 11 shows the relationship between the perception ratio and the simulated halftone dot noise. The perception ratio of simulated halftone dot noise at 5×5 pixels/dot increased as the percent of noise (α) increased. Similarly, the perception ratio of simulated halftone dot noise at 10×10 pixels/dot increased when α increased. On average, the subjects first detected the effect of halftone dot noise for an image when $\alpha=2$ and such noise was unmistakable when $\alpha=4$. The subjects detected the simulated halftone dot noise at the free observation condition easier than when the observation distance was set at 1 m. Fig. 11(b) shows that the distance between two halftone dots, r, affects perception. Human vision finds it easier to detect the fluctuation of a halftone image when dot distances increase. The degree of simulated halftone dot noise variation was converted into %CV in order to compare it with $\%CV_p$.

Table II shows the percent coefficient of variation for a simulated halftone dot ($\%CV_n$). It was found that $\%CV_n$ increases when α increase. Based on the results of Fig. 11, which show that human perception detects the effect of simulated halftone dot noise for an image when $\alpha=4$ on the average, it can be expressed as $\%CV_p=6.72$, i.e., human perception can detect the simulated halftone dot noise since $\%CV_n$ is 6.72. By considering the $\%CV_n$ against $\%CV_p$, it was determined that human perception can detect the fluctuation of a halftone image when the halftone pattern used is the small dot cluster, and that human perception tends to decrease when the dot cluster increases.

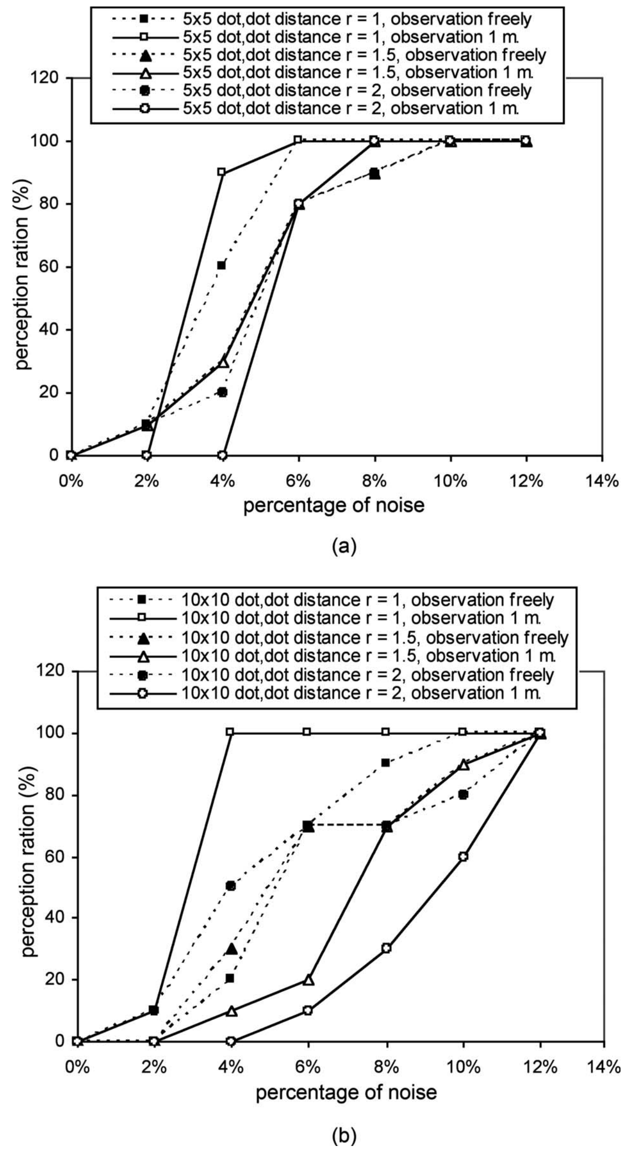


Figure 11. Perception ratios corresponding to various noise levels t two observation distances: (a) 5×5 pixels/dot; (b) 10×10 pixels/dot.

Table II. $\%CV_n$ of simulated halftone dots.

$HT_{(x,y)}$ (α)	$\%CV_n$
2	5.21
4	6.72
6	9.85
8	13.37
10	17.59
12	21.45

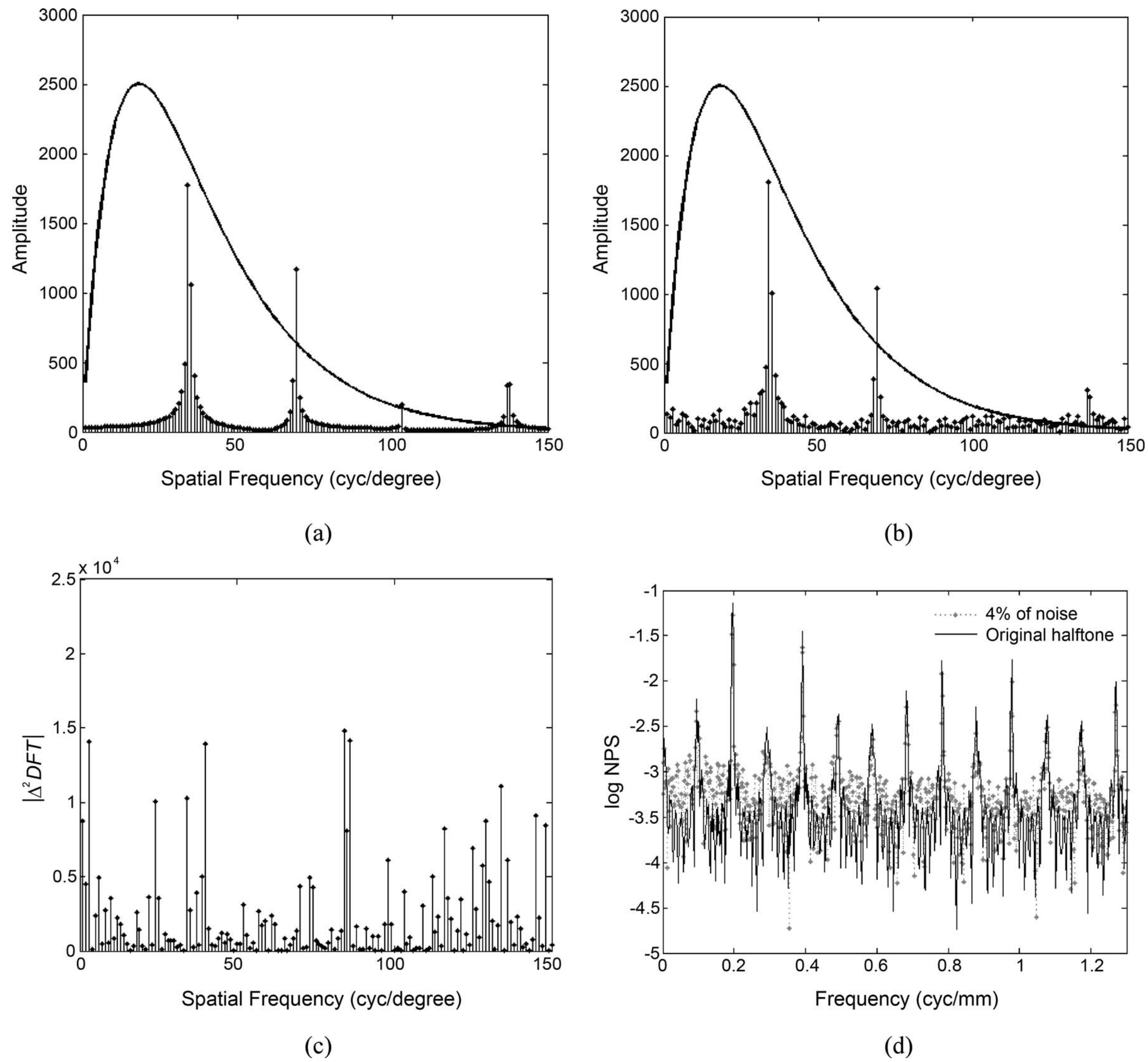


Figure 12. Relationship between DFT of halftone frequency and MTF of human visual system: (a) original halftone image; (b) 4% noise; (c) delta DFT between original halftone image and halftone image with 4% noise; and (d) log (noise power spectrum).

DISCUSSION

The modulation transfer function (MTF) of the human visual system (HVS) has been used in order to confirm the influence of halftone dot noise on human perception. The MTF describes the frequency characteristics relating to the sensitivity of human eyes, as given by Dooley,[12,13] and as expressed in Eq. (4). In this study, we used MTF to provide an explanation regarding the influence of halftone dot noise on human perception

$$\mathrm{MTF}(\omega) = 5.05(e^{-0.138\omega})(1.198 - e^{-0.1\omega}), \qquad (4)$$

where ω is the spatial frequency (cycle/degree) for the human eye.

Figures 12(a) and 12(b) show the discrete Fourier transform (DFT) of original and simulated halftone dots and the MTF of the HVS. They show the peak of the respective halftone frequencies[14] and the analysis of the effects simulated halftone dot noise, in order to assist in understanding how human perception reacts to the fluctuations in halftone dot size. Fig. 12(a) depicts the halftone frequency at $\alpha=0$ (original halftone image), and it was found that the shape of the halftone frequency could be determined distinctly, while the shape of halftone frequency at $\alpha=4$ in Fig. 12(b) was unclear because of the halftone dot size irregularity. This result indicates that perception of halftone dot size variations becomes easier as the nonuniformity of the halftone dot pattern increases. Fig. 12(c) shows the difference between the DFT of the original halftone image and that of the image with simulated halftone dot noise, $\alpha=4$, as the delta DFT value (Δ_{DFT}). It describes the effect of halftone dot size variation on Δ_{DFT} and shows that Δ_{DFT} tends to increase when the differential between original and printed halftone dot size variations increases. This result implies that human vision detects this difference with increasing ease when the Δ_{DFT} increases.

Fig. 12(d) depicts the relation between the DFT of the original and simulated halftone dot noise at $\alpha=4$ in the form of the log of the noise power spectrum (Log_{NPS}). The noise power spectrum was calculated by QEA image processing software. It utilizes the Fourier transform of noise in an image to determine the relative magnitude of noise appearance at each spatial frequency.[15] It can be used to characterize object perceptibility for a particular size and shape of an object of interest. In this plot the characteristics of the halftone dot pattern remain unclear at simulated halftone dot noise with $\alpha=4$, while the variation in the original halftone is unambiguously apparent. This comparison demonstrates that increasing halftone dot noise affects the perception of the halftone image. The perception of halftone dot noise becomes easier with increases to the dot size variations that serve as components of a halftone image.

Since $\alpha=4$ is equal to $\%CV_n=6.72$, an important result for printing technology users has been revealed. That is the fluctuation of a halftone image based on halftone dot size variation can be detected more easily in highlight areas than in other areas due to the small cluster of dots produced in highlight image areas. When the results of perception for a simulated halftone dot pattern are considered, we recognize that human perception can detect halftone dot size variations when the halftone pattern is a small cluster, and that this detection ability decreases when the number of dots in the cluster increases. Based on the result of percent of coefficient of variation for the representative printing technologies (offset, flexography, and electrophotographic printing), it indicates that human perception more easily detects nonuniformity in the dot patterns of a halftone image produced by flexography printing than for printing by other typical technologies.

CONCLUSIONS

This work investigated the variations of dot sizes produced by three representative printing technologies and the relationship between human perception and the nonuniformity of the dot pattern of a halftone image, based on halftone dot size variation, %CV. Experiments were carried out to analyze the halftone dot size variations produced by typical printing technologies; offset, electrophotography, and flexography. The results show that offset printing produces halftone dot sizes with the closest similarity to the expected dot size. Flexographic printing, on the other hand, produced halftone dot sizes with the least similarity to the expected dot size. The uniformity of the dot pattern has a possible impact on halftone dot size variations.. In Fig. 7, it was shown that the three printing technologies show %CV that is greater than 6.72 in the highlight area. If %CV is less than 6.72, human perception cannot reliably detect halftone dot size variations. An analysis of halftone dot size variations indicates that the characteristics of printing technology affect dot size reproducibility.

Simulated halftone dot noise was generated in order to confirm the influence of halftone dot size variations on human perception. The result of the experiment shows that perception of halftone dot size variation decreases when the dot cluster size increases. Human perception could detect the simulated halftone dot noise when the percent of noise was $\alpha=4$, which corresponds to $\%CV=6.72$ on average. By considering the percent coefficient of variation for simulated halftone dot noise against printed halftone dots, we determined that human perception detects halftone dot noise most readily in small dot clusters and that perception tends to decrease when the dot cluster size increases. Based on these results, we also determined that the flexographic printing method produced the most variation of halftone dot sizes in the highlight area. It is anticipated that further development of the algorithm for halftone generation will be directed towards reducing this error.

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