An Evaluation Method for the Images Obtained by Multi-Level Error Diffusion Technique

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In this article, we evaluate the qualities of images obtained by the multi-level error diffusion method and propose objective parameters for evaluation of image quality. The results of the subjective evaluation experiments show that the image quality is improved as the number of output levels increase, but the improvement is saturated at 8 levels in 400 dpi resolution and 24 levels in 200 dpi. The objective parameters proposed in this study are rms (root mean square) granularity and SNR (signal to noise ratio). The results of the subjective evaluation show that these parameters are useful to evaluate the quality of the images obtained by the multi-level error diffusion method.

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Introduction

Color printers can be classified into two categories according to their printing characteristics. One is a multi-level printer that can produce many levels in each pixel. The other is a bi-level printer that represents a pixel by an ON or OFF state. This ON or OFF characteristic depends on the digital halftoning method used to represent a halftone. In general, the multi-level printer can produce a hardcopy with high quality as the number of output levels increase, however, the price and the operating cost of the printer become more expensive. A hardcopy printed by the bi-level type has poor image quality compared with multi-level printers, but the advantage of low price. Recently, many studies have been carried out to improve the quality of the images printed by bi-level-type printers. For example, Pappas and coworkers introduced an image quality improvement method by their circular dot overlap model for the bi-level error diffusion method.[1] The multi-level error diffusion method was also introduced to improve the image quality.[2]

It is necessary to evaluate the quality of the digital halftone image successfully to improve the image quality effectively. In the evaluation of the quality of continuous tone images, many kinds of physical parameters have been proposed and used to evaluate the image quality.[3–6] In the multi-level error diffusion method, the subjective image quality will increase as the number of output levels increase, however, the relationship between the subjective image quality and the number of output levels has not been represented quantitatively and objective parameters to represent this relationship have not been proposed.

In this article, we focus on the multi-level error diffusion method that is a modified form of the conventional error diffusion technique.[7] We examine the relationship between subjective image quality and the number of levels used in the method based on subjective evaluation experiments. Furthermore, we evaluate the subjective image quality by using the objective parameters rms (root mean square) granularity and SNR (signal to noise ratio). In the experiment, we produce multi-level error diffusion images with 11 kinds of output levels printed in 400 dpi and 200 dpi.

Our goals were to establish the relationship between subjective image quality and the number of output levels used in the multi-level error diffusion method and to evaluate the subjective image quality by objective parameters. First, we describe the subjective evaluation experiments and then we try to evaluate the quality of the images by the objective parameters.

Experiments for Subjective Evaluation

Multi-Level Error Diffusion Method. As an example of the multi-level error diffusion method, we describe a tri-level error diffusion method for one-dimensional data as shown in Fig. 1. In this figure, the horizontal axis represents location and the vertical axis represents the value of the data at the location. The variables L_1, L_2 , and L_3 on vertical axis are output values after the error diffusion process and T_1 and T_2 are thresholds used to determine each output value. The process of error diffusion is essentially the same as the bi-level error diffusion method. In Fig. 1, multi-leveling has been applied to one-dimensional data, but it can be applied to two-dimensional image data as follows.

Let $f(x,y)$ be the original value at pixel location (x,y), $g(x,y)$ be an output value, $e(x,y)$ be an error value produced by the thresholding, and $f'(x,y)$ be the value that is made from the error added to the original value. Subscripts i and j are the row and column numbers of the weight matrix w_{ij} at corresponding location (i,j). Then, the algorithm of tri-level error diffusion method is written as follows:

$$g(x,y) = \begin{cases} L_1 & f'(x,y) < T_2 \\ L_2 & T_1 \le f'(x,y) < T_2 \, , \\ L_3 & T_2 \le f'(x,y) \end{cases} \tag{1}$$

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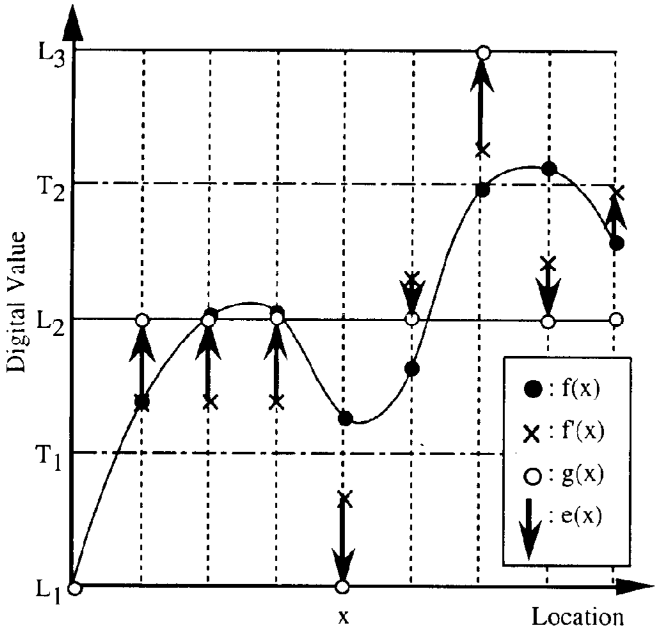


Figure 1. Tri-level error diffusion in one-dimensional data.

where

$$f'(x,y) = f(x,y) + es(x,y),$$

$$es(x,y) = \frac{\sum w_{ij}\, e(x+i, y+j)}{\sum w_{ij}},$$

$$w_{ij} = \begin{bmatrix} 1 & 3 & 5 & 3 & 1 \\ 3 & 5 & 7 & 5 & 3 \\ 5 & 7 & * & & \end{bmatrix},$$

where * is the present pixel and $e(x,y) = f'(x, y) - g(x,y)$.

There are 3 output levels in Fig. 1, but this process can be applied to more than 3 output levels. The values of output levels and thresholds are very important in the multilevel error diffusion method, because the tone scale reproduction is greatly influenced by the value of output (e.g., L_1, L_2 , and L_3 in this case). However, we don't consider the influence of the values in this study the output values L_i and the thresholds T_i are calculated from Eqs. 2 and 3, respectively.

$$L_i = dL(i-1) \quad (1 \le i \le n), \qquad (2)$$
$$dL = (L_{max} - L_{min}) / (n-1),$$

$$T_i = (L_{i+1} + L_i) / 2 \quad (1 \le i \le n-1), \qquad (3)$$

where

n	=	number of output levels
i	=	i'th output value
L_{max}	=	maximum output value
L_{min}	=	minimum output value.

In Eq. 2, we set $L_{max} = 255$ and $L_{min} = 0$ because the printer used in this study has a tone scale reproducibility of 8 bit for each primary color channel. The original image consists of R, G, and B primary colors, and the above method is applied to each color plane, independently.

(a)

(b)

Figure 2. Original images used in the experiments: (a) image No. 1 (SCID F1 portrait); (b) image No. 2 (SCID F5 bicycle).

TABLE I. Evaluation Experiments

	Experiment 1	Experiment 2
Resolution	400 dpi	200 dpi
Levels	2,3,4,5,6,7,8,12,16,24,32	
Method	Method of successive categories	
Observers	28*	26†
Images	Original image 1 and 2	
Print size	Width: 130 by height: 163 mm	

* 14 observes times two sessions.
† 13 observers times two sessions

Table II. Viewing Conditions

Light source	D65 fluorescent lamp
Illuminatiion	1400 lx
Adaptation	5 min
Length	About 400 mm
Time	Arbitrary

Samples for Experiments. Two images in SCID (standard color image data) shown in Figs. 2(a) and 2(b) are used as the original images in this study. The number of pixels in the images is 2048 × 2560 pixels, and the quantization level is 8 bit for each primary color R, G, and B.

We print 11 samples with different output levels by the multi-level error diffusion method for each original image. The output levels are 2, 3, 4, 5, 6, 7, 8, 12, 16, 24, and 32 levels, respectively. The color printer used in this study is a silver halide type Pictrography3000 (Fuji Photo Film Co., Ltd.) that has 400 dpi resolution and supports 256 levels for each primary color. We use this as a halftone printer to represent digital halftones.

The quality of hardcopy strongly depends on the printing resolution, therefore we produce samples in low-resolution to consider the effect of the resolution. The low resolution samples are made as follows: First, we make a reduced image, which has 1024 × 1280 pixels, from the original image by averaging over a 2 × 2 pixel region. Next, the multi-level error diffusion method is applied to this reduced image. Third, this image is enlarged two times by using the nearest neighbor interpolation method and printed by the printer.

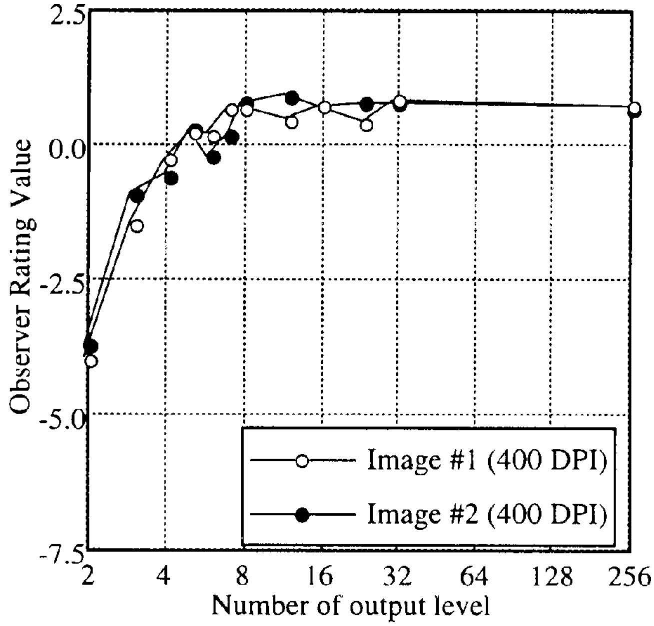
Method of Subjective Evaluation. The image quality is evaluated by using four sets of 12 images: 11 error diffusion images and 1 original image. The two kinds of evaluation experiment are summarized in Table I, and Table II shows viewing conditions for these experiments.

In these experiments, the observer is asked to classify the image quality into one of five categories: excellent, good, fair, poor, and bad. The viewing time for each sample is not restricted, viewing distance is 400 mm, and the viewing order is random for each session. The observer views a sample in the viewing booth that illuminates samples with a D65 equivalent fluorescent lamp.

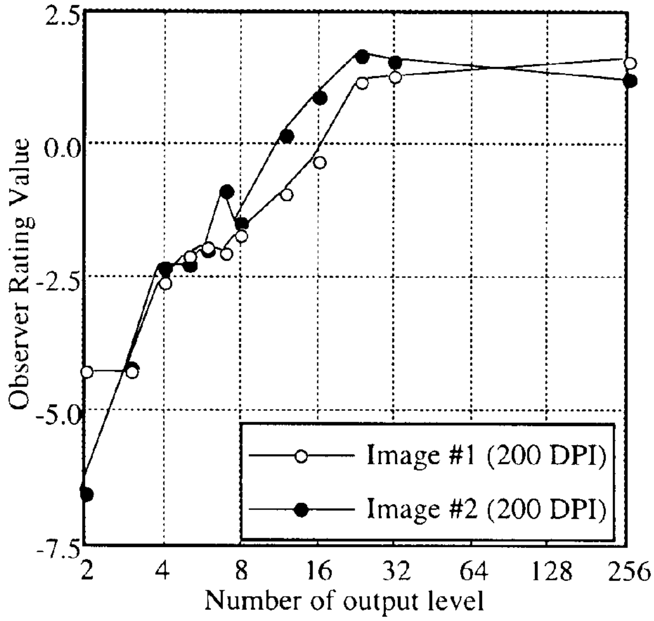
Results of Subjective Evaluation. The results of the subjective evaluation are shown in Figs. 3(a) and 3(b). Figures 3(a) and 3(b) show the results for 400 dpi and 200 dpi resolution. The vertical axis of these figures is the observer rating values calculated by a statistical method[8] and the horizontal axis is the logarithm of output level to the base two.

In Fig. 3, there is a sharp increase in the observer rating values from 2 to 3 output levels. The increase continues until the output levels reach 8 in the case of 400 dpi and 24 levels in the case of 200 dpi. The reason for the image quality being saturated at each level are that some artifacts and pseudocontours appear in 200 dpi images compared with 400 dpi images. In Fig. 3, we can see that the observer rating value at 256 output levels in 200 dpi is higher than that in 400 dpi. However, it does not imply that the image quality at 256 levels in 200 dpi is better than in 400 dpi. Because the subjective evaluation experiments are performed individually, we derived observer rating values in 200 dpi and 400 dpi, respectively. Therefore, the observer rating values in 200 dpi are not able to be compared with the observer rating value in 400 dpi.

In this study, two original images were used. The original image No. 1 is a portrait scene and the original image No. 2 contains several charts to evaluate the quality of the images objectively. From the results of observers'



(a)



(b)

Figure 3. Results of subjective evaluation: (a) experiment 1 (400 dpi); (b) experiment 2 (200 dpi).

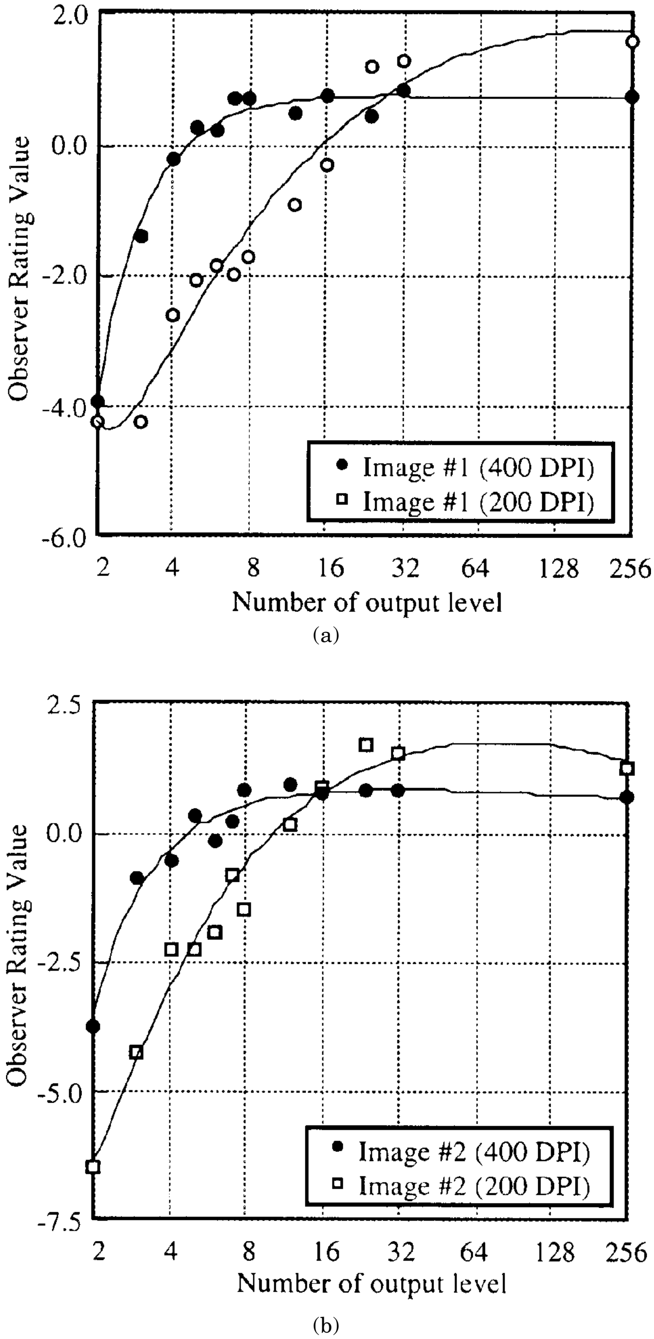


Figure 4. Results of curve fittings: (a) image No. 1; (b) image No. 2.

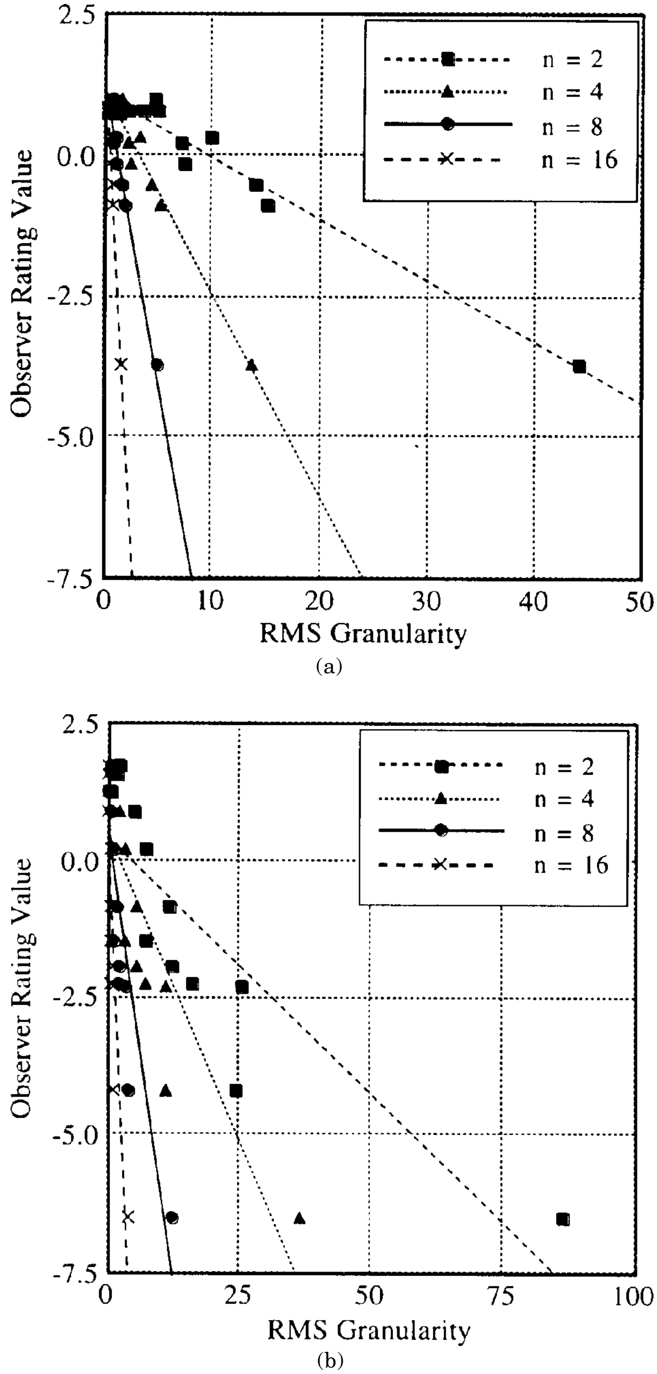


Figure 5. Relationship between the observer rating value versus calculated rms granularity: (a) 400 dpi; (b) 200 dpi.

interview, we found that the artifacts and pseudocontours of the skin color regions such as the face and arms are the main cause of the image quality decrease in image No. 1. In image No. 2, the sharpness of the resolution chart and smoothness of the fruits and textiles strongly influenced the image quality. From the results of this interview, it was suggested that the perceived smoothness of tone scale reproduction and the artifacts are very important for the subjective image quality of the error diffusion method.

Evaluation by Objective Parameters

Curve Fittings of the Experiments. We applied the curve fitting method to the results obtained from the experiments for subjective evaluation. The following function resulted from fitting the data to a power series in natural logarithm of the number of output levels, and coefficients were calculated by the method of least squares.

$$V = A + B \ln(N) + C\{\ln(N)\}^2 + D\{\ln(N)\}^3, \qquad (4)$$

where V is the observer rating value; N is the number of output levels; and A, B, C, and D are coefficients of the curve fitting. Figures 4(a) and 4(b) show the results of the curve fitting, and Table III shows the coefficients of each curve fitting, where r is the correlation coefficient for each fitting. From Eq. 4 and Table III, we can calculate the number of output levels that give the same image quality for each resolution.

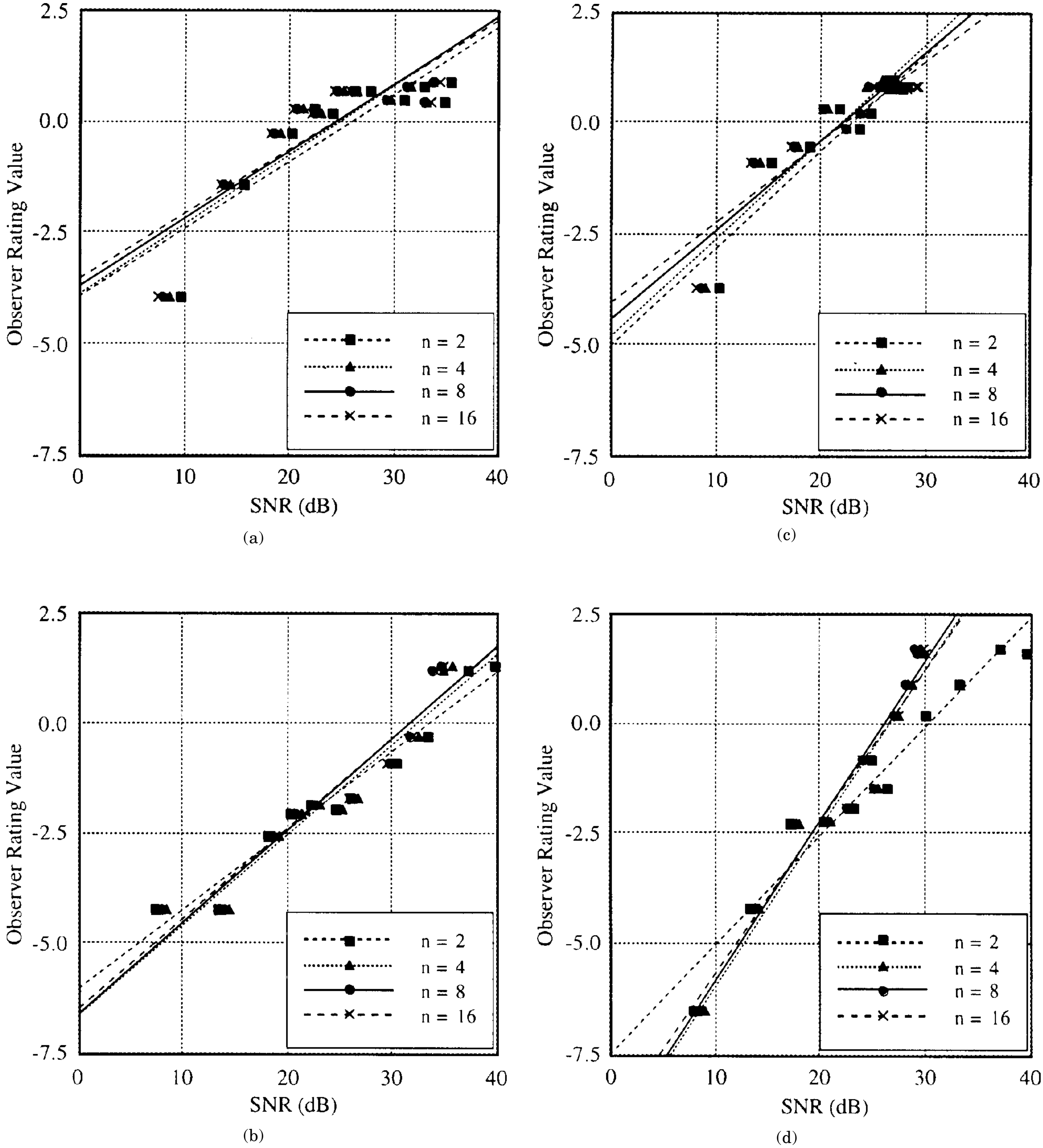


Figure 6. Relationship between the observer rating value versus SNR: (a) image No. 1, 400 dpi; (b) image No. 1, 200 dpi; (c) image No. 2, 400 dpi; (d) image No. 2, 200 dpi.

TABLE III. Coefficients of Curve Fittings

	A	*B*	*C*	*D*	*r*
Image No. 1 (400 dpi)	–3.66	6.92	3.38	0.514	0.985
Image No. 1 (200 dpi)	–6.37	2.92	4.01	–1.74	0.979
Image No. 2 (400 dpi)	–4.03	8.24	–4.67	0.869	0.992
Image No. 2 (200 dpi)	–4.22	–1.65	5.91	–1.79	0.987

Evaluation by rms Granularity. Objective parameters for evaluation of image quality have to be measured from printed images. However, we calculate rms granularity from the data in the digital image directly. In the error diffusion method, the characteristic of tone reproduction is determined by the modulation of the number of printing dots in a unit area, and the value of rms granularity depends on the size of the measuring aperture.[9] Therefore, we change the size of the averaging window to consider the effect of low-pass filtering resulting from averaging window. We use four windows, namely, in the $n \times n$ pixel regions, where n =

2, 4, 8, and 16. The rms granularity is calculated at gray charts in image No. 2 by the following steps:

Step 1. Pick up 80 × 80 pixels at the gray chart.

Step 2. Average over an $n \times n$ pixel region in the picked up area, where n = 2, 4, 8, and 16.

Step 3. Calculate rms granularity Rg by Eq. 5.

$$Rg = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(D_m - D_i)^2}, \quad (5)$$

where N is the number of data after the averaging process, N = 1600 (n = 2), 400 (n = 4), 100 (n = 8), and 25 (n = 16); D_m is the mean value of the data, and D_i is the value of the i'th data.

Figures 5(a) and 5(b) show the relationship between the observer rating value and the rms granularities calculated by four averaging windows.

The rms granularity and observer rating value are well correlated with each other. Particularly, the correlation coefficient of rms granularity calculated by using an 8 × 8 pixel window and the observer rating value was approximately 1.0. This result means that the rms granularity is a significant parameter for the evaluation of image quality by the multi-level error diffusion method.

Evaluation by SNR. The SNR is also calculated from data in the digital image directly. We calculate SNR by the following steps:

Step 1. Produce averaged image data $f'(x,y)$ and $g'(x,y)$ from the original image $f(x,y)$ and multi-level error diffusion image $g(x,y)$, respectively, using an $n \times n$ pixel window region, where n = 1, 2, 4, 8, 16, 32, 64, and 128.

Step 2. Calculate SNR by Eq. 6.

$$SNR = 10\mathrm{Log}_{10}\left(\frac{255^2 XY}{\sum_{y=1}^{Y}\sum_{x=1}^{X}\{f'(x,y) - g'(x,y)\}^2}\right), \quad (6)$$

where X and Y represent the number of pixels of the image in the horizontal and vertical directions.

Figure 6 shows the relationship between the observer rating value and SNR calculated with window size n = 2, 4, 8, and 16. In this figure, the horizontal axis shows SNR and the vertical axis shows the observer rating value. Each line shows the result of linear fitting between the observer rating value and SNR with each averaging window, respectively. In Figs. 6(b) and 6(d), we can see that the observer rating value has a linear relation to SNR in the case of 200 dpi. However, this linearity is decreased in the case of 400 dpi shown in Figs. 6(a) and 6(c).

Figure 7 shows the correlation coefficient of each linear fitting with different sizes of averaging window from n = 1 to 128. From this figure, it is shown that SNR has a linear relation in any window size in 200 dpi. But for 400 dpi, the correlation coefficient is relatively low with respect to 200 dpi and depends on the size of the window. In low resolution such as 200 dpi, SNR is very useful parameter to evaluate the quality of the images, however, this usefulness will decrease with increase in resolution. To discuss this in more detail, experiments using samples printed in higher than 400 dpi resolutions are needed. We will discuss this problem in the future.

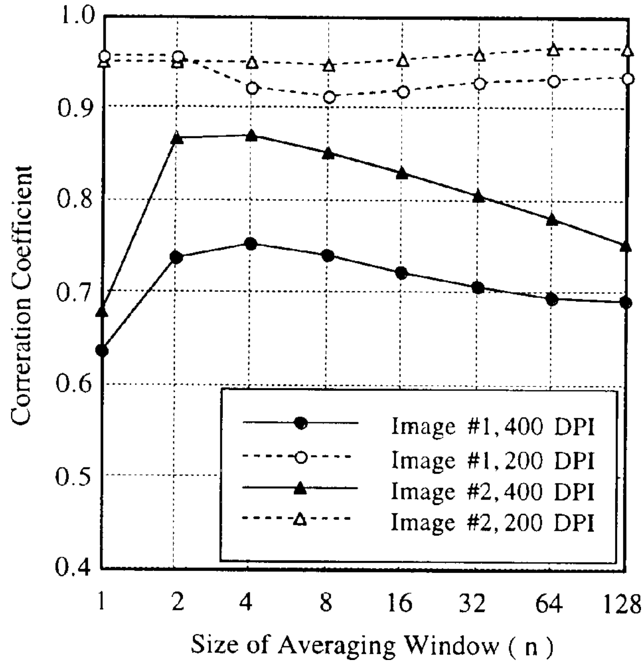


Figure 7. Correlation coefficient with respect to size of averaging window.

Conclusions

We introduced the multi-level error diffusion method and evaluated the qualities of images obtained by this method using rms granularity and SNR. The results of this study are as follows:

1. The image quality improves with increase in the number of output levels, but the quality is saturated at 8 levels in 400 dpi resolution and 24 levels in 200 dpi.
2. The rms granularity and SNR used in the experiments are useful parameters to evaluate image quality by the multi-level error diffusion method. However, the experimental results also show that the effectiveness of SNR depends on the resolution.

Digital halftoning methods such as error diffusion use characteristics of the human visual system. Therefore, we will relate these experimental results to the human visual system in our future problems. Furthermore, we will use other parameters such as MTF and tone reproductivity for more accurate evaluation of the image quality.

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References

1. T. N. Pappas and D. L. Neuhoff, Printer models and error diffusion, *IEEE Trans. Image Proc.* **4**, 66–80 (1995).
2. I. Katsavounidis, Y. C. Lin and C. C. Jay Kuo, Multiscale error-diffusion digital halftoning with local intensity quality measure, in *Proc. SPIE* **2298,** 224 (1994).
3. J. C. Dainty and R. Shaw, *Image Science,* Academic Press, London, 1974, Chaps. 3–10.
4. Y. Miyake, S. Inoue, M. Inui, S. Kubo, An evaluation of image quality for quantized continuous tone image, *J. Imaging Technol.* **12,** 25–34 (1986).
5. Y. Miyake, Evaluation of image quality for hardcopy, *Inst. Telev. Eng. Jpn.* **43,** 1212–1217 (1989).
6. M. A. Kriss, Image quality requirements for a multimedia environment, *J. Soc. Photogr. Sci. Technol. Japan*, **59,** 186–211 (1996).
7. R. W. Floyd and L. Steinberg, An adaptive algorithm for spatial greyscale, *Proc. SID,* Santa Ana, CA **17**, 75–77 (1976).
8. J. P. Guilford, Psychometric Methods, McGraw-Hill, 1954, Chap. 8.
9. K. Miyata, M. Saito, and M. Ohnishi, A method to evaluate the image quality of halftone images in color hardcopy, in *IS&T's 48th Ann. Conf. Proc.*, IS&T, Springfield, VA, 1995, pp. 526–529.