Graininess Metric for Digital Halftone Images

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Abstract

A conventional metric proposed by Dooley & Shaw[1] is well known and has been used for graininess evaluation. Recently, another method has been proposed by Kenji Kagitani et al.[2] Both methods use a monotone decreasing function as the visual-sensitivity representation for image density. However, their results may not always agree with the experience that a visual system would be most sensitive to a granularity on 18% to 30% area coverage for halftone images. To resolve this disagreement, we made a subjective test using a test chart which has precise tint gray scales with various screen rulings to find a just noticeable difference (JND) curve for graininess.

As a result, we have found the graininess JND curve that has a peak sensitivity at the patch of about 20% area coverage and have derived a new representative function for visual sensitivity to image density from this JND curve, and have defined a new graininess metric. Furthermore, we applied this metric to some samples of commercially available digital copiers. The results have almost agreed with their graininess as a subjective image quality.

Introduction

It is well known that image noise produces poor impressions of hard copy images. Graininess is one type of image noise and some methods to objectively evaluate the graininess have been proposed. For example, GS using the Dooley & Shaw algorithm[1] is a conventional metric for quantitatively evaluating the graininess. It is based on the integration of the Wiener Spectrum, which is moreover multiplied by the transfer function of a visual system (VTF) and the empirically derived function, exp(-1.8*D*), is a visual-sensitivity representation for image density. This empirically derived function is a monotone decreasing function. The reason for using a monotone decreasing function is that it is generally considered that the visual sensitivity to image density would be increased in highlighted images rather than in shadowy images.[3]

However, in digital images with periodic ruling, for example, images from off-set printing and electro-photographic printers, our visual system for graininess would be most sensitive to granularity on 18% to 30% area coverage of halftone images. Therefore, the purpose of this paper is to resolve this disagreement and to describe a new graininess metric for digitized images. Throughout this paper the term graininess is extended to cover the notion of the visual sensation for image fluctuations by the periodic pattern of the halftone screen itself.

A New Graininess Metric

We made a subjective test using a test chart to determine just noticeable difference (JND) patches for graininess. Using the measured value of these JND patches, we then derived a new visual-sensitivity representation for image density. Based upon this representation, we established a new graininess metric for digital halftone images, and applied it to commercially available digital copier images.

A Test Chart

To examine the relationship between graininess and area coverage of images, we used Test Chart No. 4 (1986) published by the Society of Electrophotography of Japan (SEPJ). This test chart has halftone tints ranging from 65 to 200 lines per inch, 11-step gray scales (5% to 95% area coverage), and can be regarded as the ideal image because it has little noise. (i.e., the allowance for area fluctuation of each dot on each patch is under 2%.)

Just Noticeable Difference for Graininess

Based on observational evaluation, we determined the Just Noticeable Difference (JND) for graininess (i.e., the threshold whether or not observers can discriminate the graininess on each patch of this test chart). We thought that there exist a fairly large ambiguity in the case when observers subjectively select patches which could be of equal graininess, but there exist little ambiguity in the case when observers subjectively select border patches whether or not they can discriminate the graininess. For this purpose, three observers tried to select border patches which were beginning to feel graininess at a viewing distance of 300 mm under the illuminated conditions of a general office environ-ment (about 500 *lx*). As a result, we obtained the border patches as the bases of the graininess JND. In these patches, the 20% area-coverage patch has the highest-frequency screen ruling (200 lpi) as shown in Figure 1.

Measurement of Patch Images

To analyze the micro-structure of each patch, the measurement of patches on the test chart was carried out using a Drum-scan densitometer (Model 2606), which Abe Sekkei Inc. manufactured and improved according to our request. This system scans and measures the reflection density with a set sampling rate on the images. The sampling conditions and spatial frequency in FFT are shown in Table 1.

Calculation of gs

Graininess is regarded as a visual perception for the fluctuation of lightness.[4] Lightness, *L*, in CIE 1976

L*a*b* color space is converted using Equation (2) from the reflection density, D, which is calculated using Equation (1) from the value d measured by the Drum-scan densitometer. Measured data have a 12-bits depth, so that in the worst case on the highlight ranges the resolution of at least 0.04 will be maintained. Digital halftone images by LBP, etc. are formed on high-reflectance substrates such as white papers with low-reflectance toners, therefore, it requires reversal processing with Equation (3) to analyze the structure of a granular appearance with toners.[5]

$$D = 0.03 + 2.00 \times \frac{d}{4095} \qquad (1)$$

$$\mathrm{L} = 116 \times (10^{-D})^{1/3} - 16 \qquad (2)$$

$$L' = 100 - L \qquad (3)$$

Two-dimensional (2-D) fast Fourier transform (FFT) is then implemented for the image data, converted to reversal lightness, L', with Equation (3), and the Wiener spectrum $\mathrm{WS}(u_{x,y})$ is calculated. We multiplied $\mathrm{WS}(u_{x,y})$ by the well-known visual transfer function (VTF) at a viewing distance of 300 mm as expressed by Equation (4) to reflect the spatial characteristics of vision. We then calculated the value of gs for each patch using Equation (5).

$$\mathrm{VTF} = 5.05\exp(-0.723u)\{1 - \exp(-0.524u) \qquad (4)$$

where: u = spatial frequency in cycles per mm.

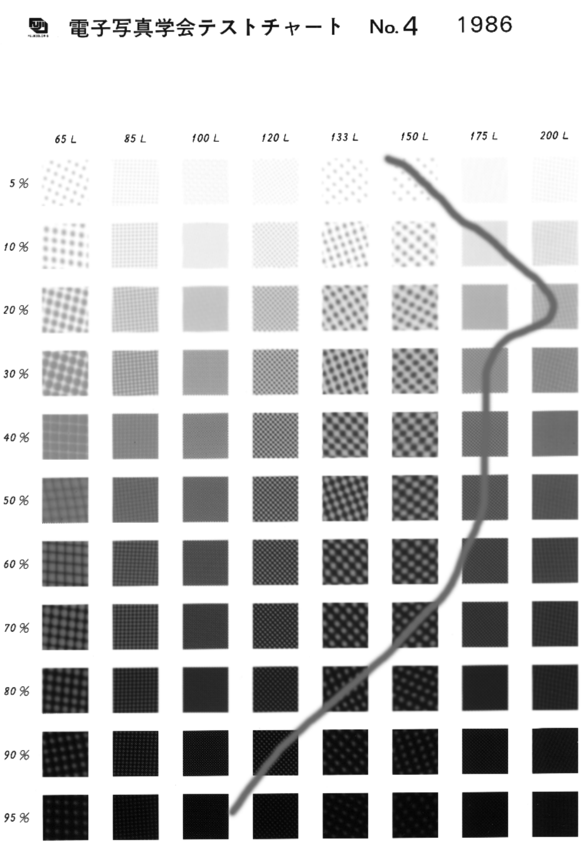

Figure 1. Test Chart No. 4 (SEPJ) used to determine JND patches for graininess.

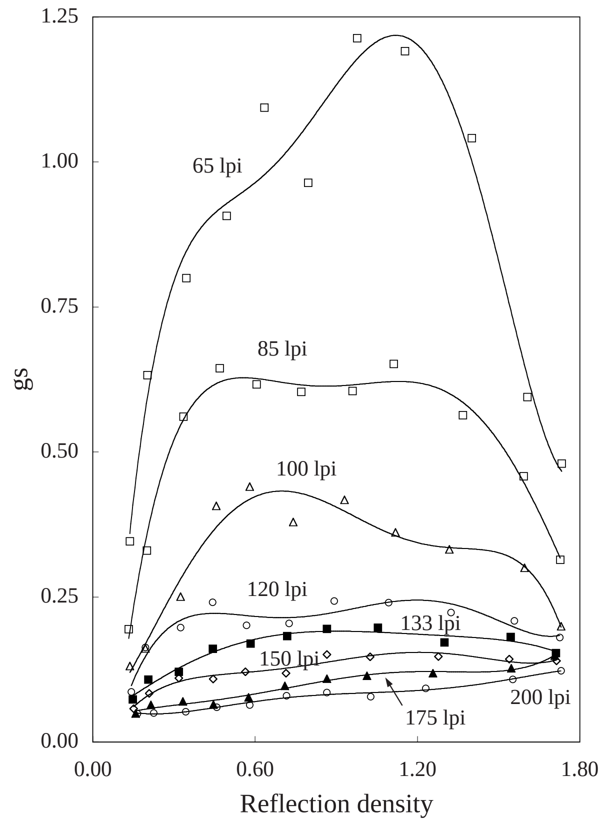

Figure 2. The gs of each patch plotted versus the mean reflection density according to each screen ruling.

$$\mathrm{gs} = \sum\sum\left\{\sqrt{\mathrm{WS}\left(u_{x,y}\right)}\mathrm{VTF}\left(u_{x,y}\right)\right\} \qquad (5)$$

The value of gs for each patch is plotted in Figure 2. In this figure, the x-axis is mean reflection density of each patch measured by the Drum-scan densitometer and the y-axis is calculated gs. It would be possible to compare each one on the same reflection density, but as human visual sensitivity for graininess is also dependent on image density, it is necessary to add a visual-sensitivity representation for the image density for matching with the subjective evaluation.

Visual-Sensitivity Representation for Image Density

As human visual sensitivity for graininess is dependent on image density, it is necessary to add the sensitivity representation to the gs. In the conventional metric, shown in Equation (6), GS by Dooley & Shaw, the term of $\exp(-1.8D)$[1] is used as the visual-sensitivity representation for image density. Recently, the application of a sigmoid function ($p_1(D)$ & $p_2(D)$), shown in Equation. (7), EGY by Kagitani et al.[2], has been submitted as a new method. But, both are essentially a monotone decreasing characteristic for the visual sensitivity of image density.

$$\mathrm{GS} = e^{-1.8D}\int\sqrt{\mathrm{WS}(u)}\mathrm{VTF}(u)du \qquad (6)$$

$$\mathrm{EGY} = \left\{1 + e^{-p1(D)} \int \sqrt{\mathrm{WS}(u)}\,\mathrm{VTF}(u)du + p_2(D)\right\}^{-1} \quad (7)$$

It has been empirically said that human visual sensitivity for granularity is most sensitive to the halftone of 18% to 30% area coverage, which has also been reported.[6] The main reason is that granular appearance would not be detected on an area of very low area coverage (less than 15%) because of its brightness and on the area of high area coverage because of its filling of inks. This tendency can be easily observed at low-frequency screen ruling on this test chart. We have confirmed that we feel a strong graininess to the patches of about 20% to 30% area coverage on this test chart.

Figure 3 shows the calculated gs of border patches plotted versus the mean reflection density. As the gs is a weighted value by a visual sensitivity function of VTF (against spatial frequency), we can consider that the gs is to be processed with only a visual-sensitivity representation for the reflection density in order to obtain the same graininess value. But it seems that the conventional sensitivity representation as explained above is not good enough, because there is an increase in the amount of the gs in the middle- to high-density range, but in the low-density range, there is a slight decrease as shown in Figure 3. Therefore, we assumed that the visual-sensitivity representation for image density should have a peak sensitivity to the patches of about 18% to 30% area coverage on halftone images like VTF.

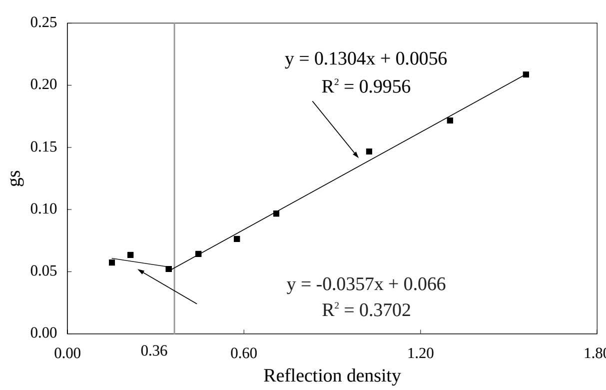

Figure 3. The gs for graininess JND patches plotted versus the mean reflection density and two regression lines.

For easy calculations, we approximated the gs for border patches into two regression lines as shown in Equations (8) and (9). In Figure 3, because there are some data in the low-density range, or under a reflection density of 0.36, the regression line may not be creditable, but in the middle- to high-density ranges, or over a reflection density of 0.36, we have a very close correlation. Both lines intersect at the point with a reflection density of 0.36, as shown in Figure 3.

$$y = 0.1304x + 0.0056 \ (x \geq 0.36) \quad (8)$$

$$y = -0.0357x + 0.066 \ (x \leq 0.36) \quad (9)$$

The reflection density of 0.36 is roughly equivalent to a 20% area coverage of the digital halftone images. So, it seems reasonable to approximate the gs versus the image density into two regression lines. Consequently, the points on these two regression lines indicate same graininess. The equivalence in the other areas except for these two regression lines must then be taken into account. As previously mentioned, it would be difficult to subjectively select patches having the same graininess. Therefore, we have formed two hypotheses, Model 1 and Model 2, as shown in Figure 4. In the first model, we assumed that the same graininess would be on lines which are parallel to the JND regression lines. In the second model, we assumed that the same graininess would be on lines which have an x-intercept of -0.04 and 1.85. But, in Model 1, it is predicted that if the gs is lower than the JND line in the shadow area, it can be a negative value. And, it is also predicted that the maximum graininess in a low-frequency screen ruling by Model 1, for example, 65 lpi, will tend to shift to the higher-density range. We considered that Model 1 does not always match with the subjective evaluation.

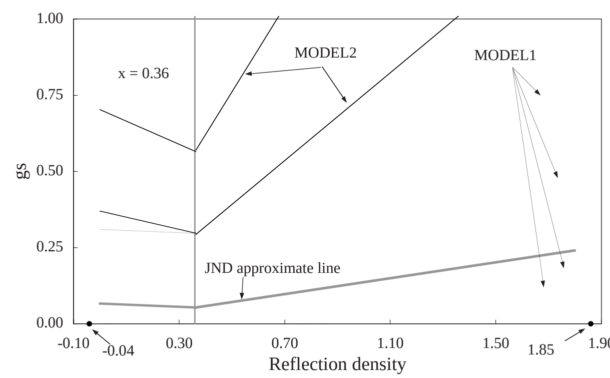

Figure 4. Two models assumed for equivalent graininess.

In Model 2, it is predicted that there is a clear peak sensitivity at the patches of about 20% area coverage in the low-frequency screen rulings and the gs curve becomes almost flat in high-frequency screen rulings. We considered the results would match with the subjective evaluation. Therefore, we have adopted Model 2 for the subjective sensitivity representation, that is, the same graininess would be on lines which have an x-intercept of -0.04 and 1.85, intersecting at a reflection density of 0.36 as a border as shown in Figure 5. That is to say, the value mapped on a line which is parallel to a vertical axis (y-axis), x = 0.36, will represent the same graininess for each reflection density.

Results and Discussion

We applied this model to the patches in the test chart, the electrophotography images made by Digital Plain Paper Copiers (PPC) and photography images. The results are shown in Figure 6 and Figure 7. There is a clear peak sensitivity at the patches with about 20% area coverage on the low-frequency screen ruling in Figure 6 as predicted. Also the graininess curve becomes flatter as the screen frequency becomes higher. Therefore, it will match with the subjective evaluation. In Figure 7, it tends to have a clear peak sensitivity for images that we feel have bad graininess by subjective evaluation, so we consider that this new method would match with any subjective image quality.

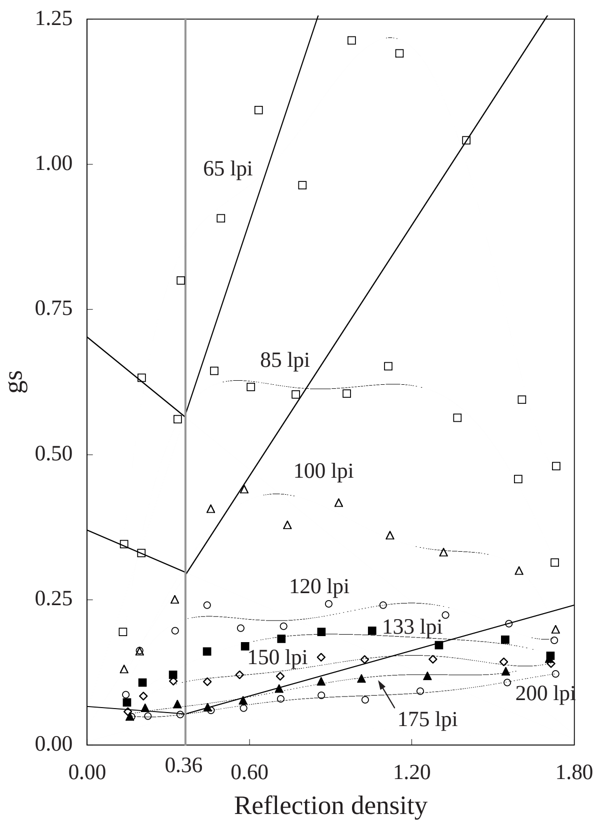

Figure 5. Relationship between equivalent graininess lines by MODEL 2 and the measured gs.

Conclusions

We have developed a new method of the graininess metric for digital halftone images. The new metric reflecting the visual sensitivity to image density agrees with the subjective evaluation. This sensitivity representation for image density is based on experience that it would be most sensitive for granular patches of about 18% to 30% area coverage, and we have decided the JND for the graininess of digital halftone images using the Test Chart No. 4 (SEPJ). As a result, it is possible to make a quantitative analysis for graininess which matches with subjective evaluation.

In this method, we have considered that the graininess is also dependent on its specific frequency structure in the digital images such as screen rulings, so that the gs has been calculated without removing the regular periodic component of the halftone screen itself. However, we did not examine the influence of noise by positioning error or the area fluctuation of each dot. In this evaluation method, such image noise components are included in the calculation of the gs as its increase. Therefore, this method needs more quantitative investigation on the correlation between the increase in the gs by noise and the subjective evaluation.

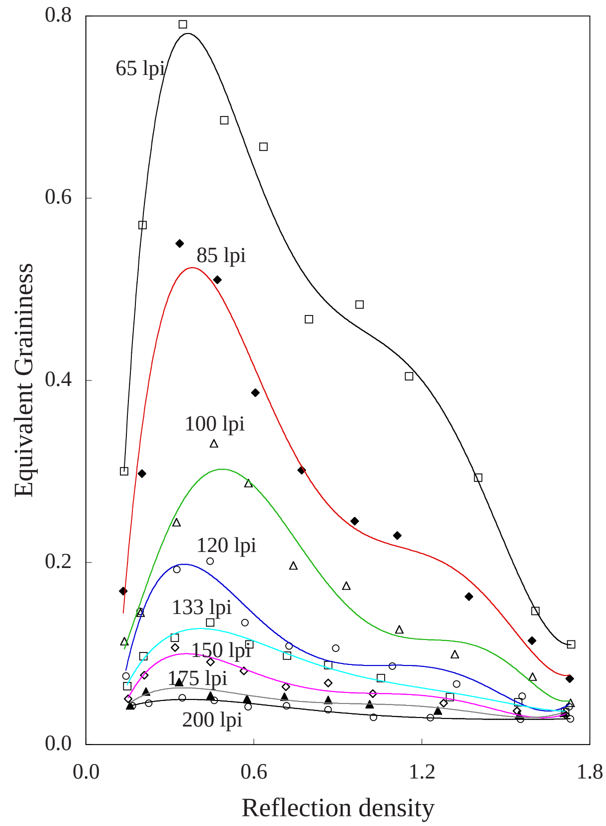

Figure 6. Equivalent graininess applied to all the patches on Test Chart No. 4.

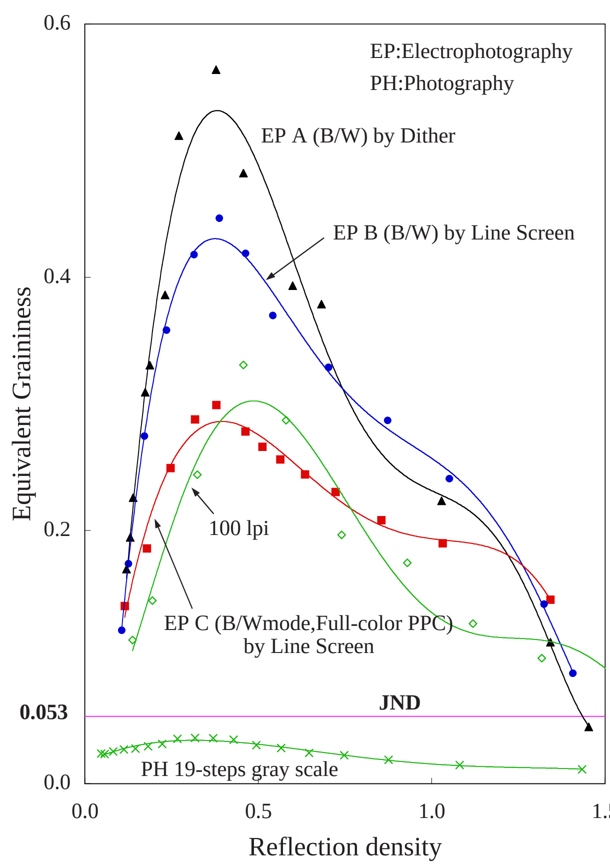

Figure 7. Equivalent graininess applied to gray-scale images by electrophotography and photography.

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Appendix

In the model 1, we assumed that the same graininess would be on lines which are parallel to the JND regression lines. As shown figure A, the result of this model was that if the gs is lower than the JND line in the shadow area, it can be a negative value. And, it was also that the maximum graininess in a low-frequency screen ruling, for example, 65 lpi, will tend to shift to the higher-density range. Therefore we considered that Model 1 does not always match with our visual sensation, and consequently we have adopted Model 2.

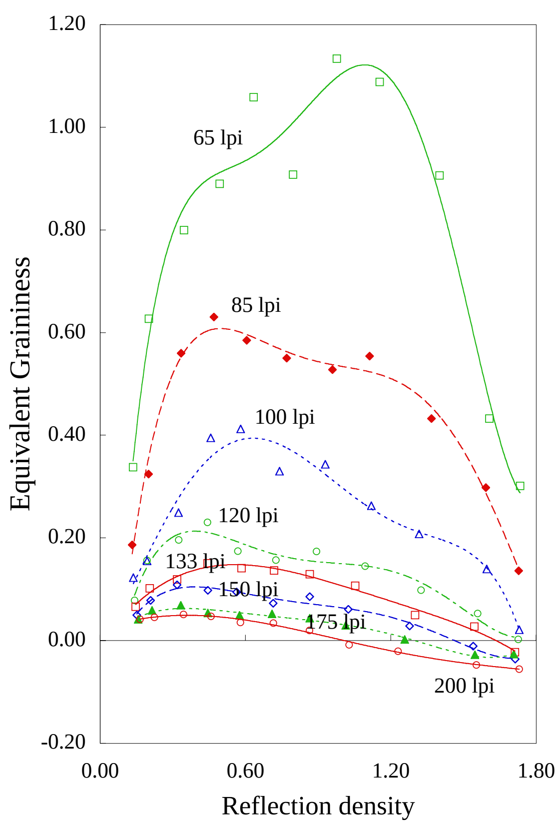

Figure A. Equivalent graininess (by Model 1) applied to all the patches on Test Chart No.4.

As human visual sensitivity for graininess is dependent on image density, it is necessary to add the sensitivity representation to the gs. Figure B shows the results of application for the conventional metric to the gs. In the conventional metric, the term of exp(-1.8*D*) is used as the visual-sensitivity representation for image density. Compared with Figure 7, which shows the results of application for our model to the gs, it is recognized that there are some differences. For example, it can be seen that the result of PH (19-steps gray scale by photography) has no peak sensitivity.

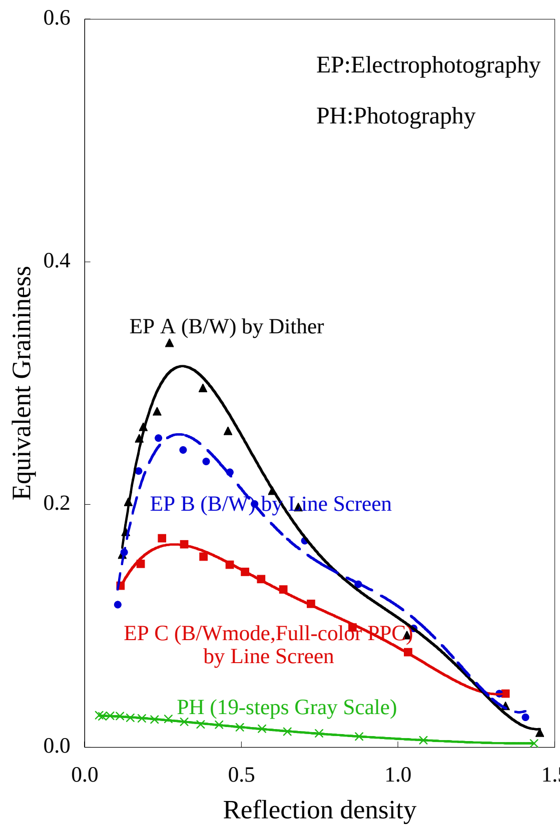

Figure B. Equivalent graininess (by conventional metric) applied to gray-scale images by electrophotography and photography.

We made subjective assessment for those test chart patches and various patches from analog copiers and printers. We applied Scheffe's method of paired comparisons. For ease of research, we used 46 of the 88 patches of Test Chart No.4 (SEPJ) and 29 other patches from samples made by electrophotographic analog copies and printers. Five panels of observers assessed these patches under the typical office environment. The mean preference was calculated from the assessment results. The analyzed results are shown in Figure C. The solid line indicates the regression line. The correlation coefficient is r=0.8, which means a strong relationship exists between the equivalent graininess and the subjective evaluated level.

The author(s) have provided Auxillary information via this Appendix

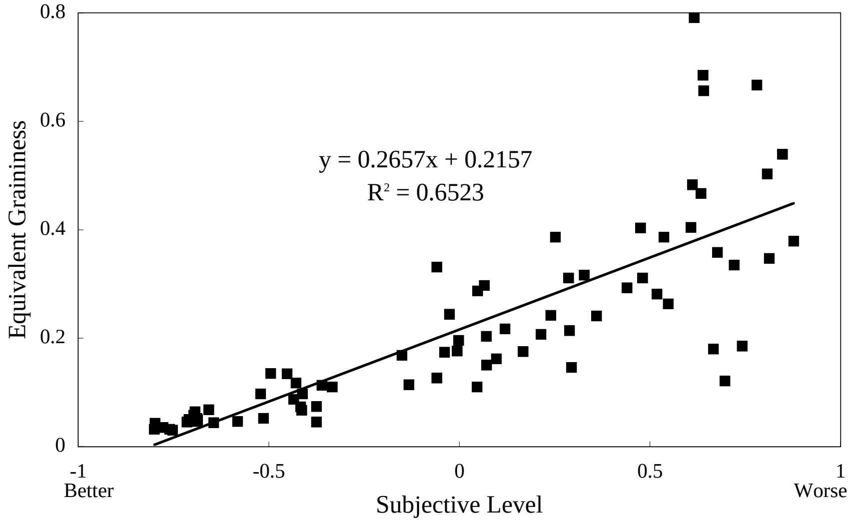

Figure C. The relationship between the equivalent graininess for selected patches and their subjective level.