An Evaluation of Image Quality for Hardcopy Based on the MTF of Paper

Shinichi Inoue,▲* Satoshi Yamazaki,† Norimichi Tsumura▲† and Yoichi Miyake▲†

** Process Development Laboratory, Corporate Research Center, Mitsubishi Paper Mills Limited, Tokyo, Japan*

† Department of Information and Computer Sciences, Chiba University, Chiba-ken, Japan

Image quality of hardcopy is significantly influenced by paper properties. In this article, two kinds of image, a hardcopy and an image projected onto paper, are analyzed using a function based on the Modulation Transfer Function (MTF) of paper, and evaluated by observer rating experiments. As a result, good correlation was obtained between the function values and the observer rating values. It is shown experimentally that the reflectance and MTF of paper are of significant importance in the image quality of hardcopy.

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Introduction

Image quality of hardcopy is influenced by paper properties. On the other hand, the image quality is defined by its sharpness, graininess, tone reproduction, and color reproduction characteristics. Various criteria have been suggested to evaluate the image quality. For example, Modulation Transfer Function (MTF), Tone Reproduction Curve, Wiener Spectrum, Chromaticity value, Information Capacity, and so on. Some evaluation functions based on the MTF have been introduced for evaluating image quality of photographic images.[1–5] It has been reported that these evaluation function values, i.e., figures of merit, have good correlation with observer rating experimental results. However, most of these studies were for conventional photographic systems using film and lens, and relatively little has been directed to the imaging characteristics of paper. In a previous article, we introduced a new method for measuring the Modulation Transfer Function (MTF) of paper.[6] In this article, the relationship between image quality and the MTF of paper are discussed.

Two types of image are used for evaluation. One is a hardcopy, such as a print or a photographic print. The other is an image projected onto paper. The MTF of each type is discussed. The image quality is evaluated by an image quality function based on the reflectance and MTF of paper. The Subjective Quality Factor (SQF) which was introduced by Granger and Cupery[1] is used as the image quality function in these experiments. Simultaneously the images on sample papers are analyzed by observer rating. Good correlation was obtained between the image quality function values and the observer rating values.

The Hardcopy and Projected Image

Two types of image, hardcopy and image projected onto paper, were prepared for analysis. Each image is evaluated on the same sample papers. However, it is considered that the effect of the MTF of paper may be different in each case. For discussion, we use a simple model of hardcopy. We assume that the hardcopy image consists of two layers, a transparent image layer and a diffuse reflection layer, as shown in Fig. 1. We may consider that the transparent image layer is an ink pattern and the diffuse reflection layer is paper, respectively. Each step in this model is explained as follows;

Step 1: Incident light is projected to the ink (the transparent image layer).
Step 2: The ink absorbs incident light.
Step 3: Incident light is also scattered and diffused in the paper (the diffuse reflection layer), and this phenomenon is represented by the MTF of paper.
Step 4: The scattered and reflected light from the paper is absorbed in the ink again.

We assumed that the incident light i_{in} and reflectance of paper r are uniform with the coordinates. These steps are linear processes and can be expressed as the following equation in the Fourier domain.

$$I_{out}(u,v) = [i_{in}T(u,v)rMTF_{paper}(u,v)]*T(u,v) \qquad (1)$$

where $I_{out}(u,v)$ and $T(u,v)$ at coordinate u, v are the spectrum of output intensity and transmittance. $MTF_{paper}(u,v)$ is the MTF of paper.

Next, we discuss the case of the image projected onto paper. It is modeled as shown in Fig. 2. It can be considered that these steps and the equation correspond to

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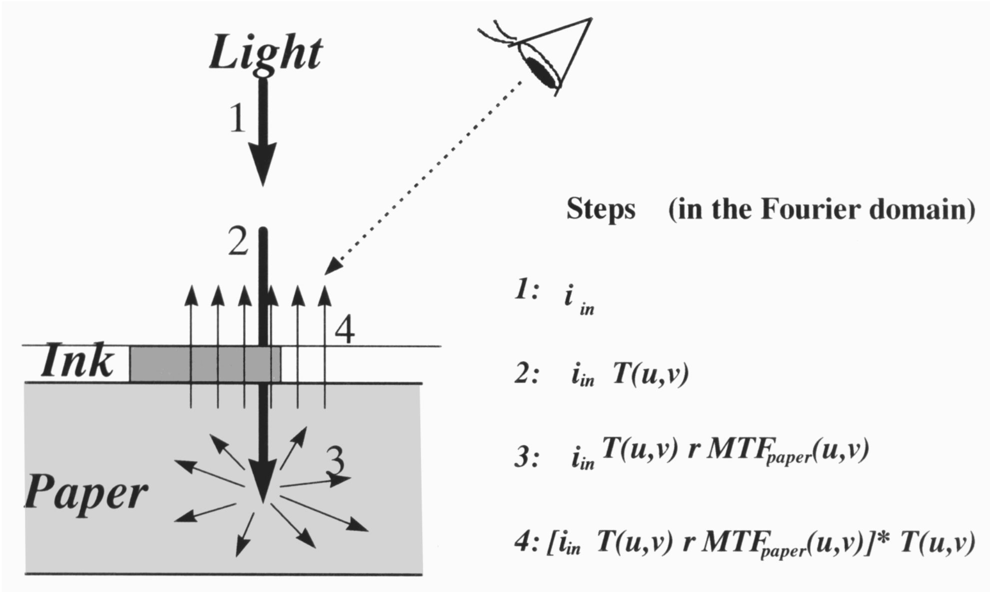

Figure 1. A schematic diagram of the observation of hardcopy.

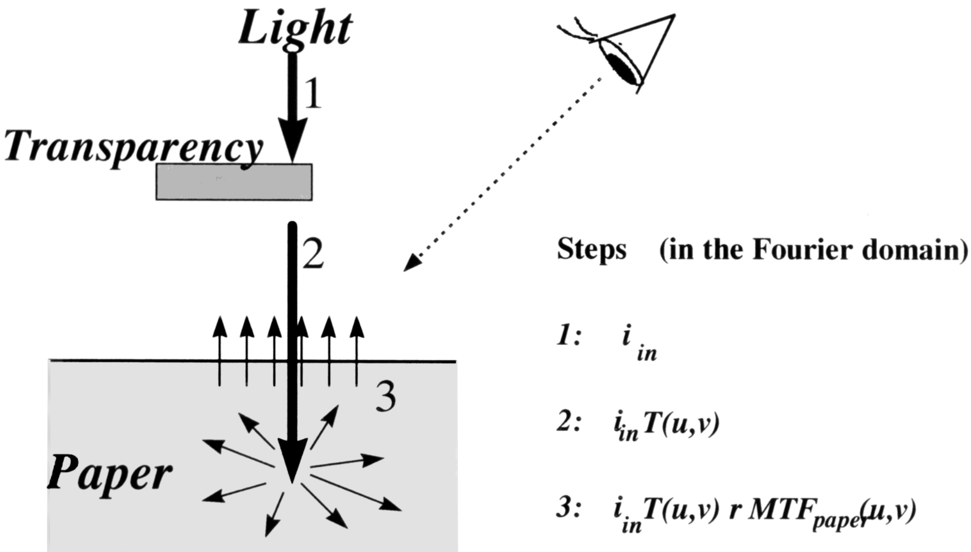

Figure 2. A schematic diagram of the observation of a projected image.

those of the hardcopy's. The image projected can be described by steps 1 to 3 as follows:

$$I_{out}(u,v) = i_{in}T(u,v)rMTF_{paper}(u,v) \tag{2}$$

CTF of Hardcopy and MTF of Paper

MTF is an input–output function. MTF has been used for analyzing and evaluating photographic images.[1–5,7] It should be noted that the process of the image projected can be analyzed mathematically in terms of the MTF. The MTF of paper is the input–output function of the image projected onto paper. On the other hand, the MTF of paper is not the input–output function of the hardcopy. We studied this question in a previous article[8] and introduced an alternate input–output function for the hardcopy. It is reviewed briefly here.

The process in the hardcopy corresponds to steps 1 to 4 of the model. In step 4, the light is absorbed in the ink again, and this process is expressed as the convolution integral in Eq. 1. Equation 1 shows that the MTF of paper is different from the input–output function of the hardcopy. We introduced the Contrast Transfer Function (CTF) of hardcopy instead of MTF. We define the CTF of hardcopy as in Eq. 3. The contrast c is given by the difference of the maximum and minimum intensity in as follows.

$$c = i_{\max} - i_{\min} \tag{3}$$

where $i_{\max}$ and $i_{\min}$ denotes the maximum and minimum output intensity. We define the CTF of hardcopy, $CTF_{hardcopy}$, in Eq. 4.

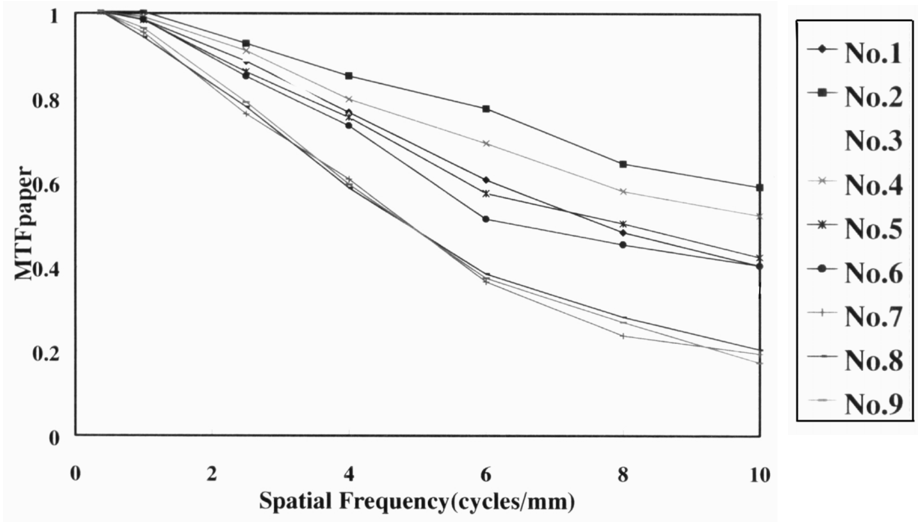

Figure 3. The measured MTF's of sample papers.

$$CTF_{hardcopy} = c_{out} / c_{out,u=0} \tag{4}$$

where c_{out} denotes the contrast of output and $c_{out,u=0}$ denotes the contrast of output when the spatial frequency, u, equals zero. It is assumed that the input intensity is sinusoidal.

According to the definition, the relationship between the CTF of hardcopy and the MTF of paper can be analyzed mathematically. The CTF of hardcopy can be expressed by the simple function as follows:

$$CTF_{hardcopy}(u) = \frac{1 + MTF_{paper}(u)}{2} \tag{5}$$

In this article, the CTF of hardcopy is used for the input–output function of hardcopy instead of the MTF.

An Evaluation of Image Quality for Hardcopy Based on the MTF of Paper

We consider that the image quality is dependent on the MTF of paper. Therefore, we examined several image quality functions which could include the MTF of paper. Some evaluation functions based on the MTF have been introduced for evaluating image quality of photographic images.[1–5] Granger and Cupery[1] developed the Subjective Quality Factor (SQF) which would correlate with subjective rank regardless of MTF form. They have reported that the SQF is able to predict the image quality within normal reader error and was correlated (r = 0.988) with the measured data. We apply the MTF of paper to the SQF.

After a brief review of the SQF, we introduce an evaluation function based on the MTF of paper. The SQF is defined as follows:

$$SQF = K\int_{10}^{40} MTF_{system}(u)d(\ln(u)) \tag{6}$$

where $MTF_{system}(u)$ is the system MTF. u is the spatial frequency at the retina and K is a normalizing constant obtained by performing the above integration with MTF_{system} = 1.

To examine an approach to the evaluation of image on paper, it is assumed that the same image is projected onto various papers as shown in Fig. 3. In SQF, according to the assumption, the MTF of system in Eq. 6 is divided into the MTF of paper and the MTF of imaging system except for the MTF of paper. The MTF of imaging system except for the MTF of paper can be ignored because the projected image is same and the calculated spatial frequency area is in low frequency area. Therefore, the MTF of paper is only used in the equation.

Granger and Cupery[1] pointed out that the loss of contrast also reduces the image quality. The effect on the subjective quality rating would be a reduction in quality, proportional to the contrast ratio. In the case for the image on paper, contrast depends on the reflectance of paper. So it is considered that the product of the MTF and the reflectance is appropriate for the evaluation. According to these approaches, we propose an evaluation function for the imaging characteristics of paper based on the MTF as follows:

$$SQF_{paper} = K\int_{10}^{40} rMTF_{paper}(u)d(\ln(u)) \tag{7}$$

where K is a normalizing constant obtained by performing the above integration with $rMTF_{paper}$ = 1.

In the hardcopy, the input–output function is altered by the CTF of hardcopy according to Eq. 5. Therefore the SQF of paper in the hardcopy is defined as follows:

$$SQF_{paper} = K\int_{10}^{40} r\left[\frac{1 + MTF_{paper}(u)}{2}\right]d(\ln(u)) \tag{8}$$

The SQF of paper incorporates both reflectance and MTF of paper. We consider that it evaluates the imaging characteristics of paper, especially sharpness on paper. It varies from 0.0 to 1.0, where 1.0 means perfect response.

Experiments

The MTF's and the reflectances of various sample papers were measured. The figures of merit for sample papers were calculated as SQF_{paper}. On the other hand, the observer rating experiments were done for a pro-

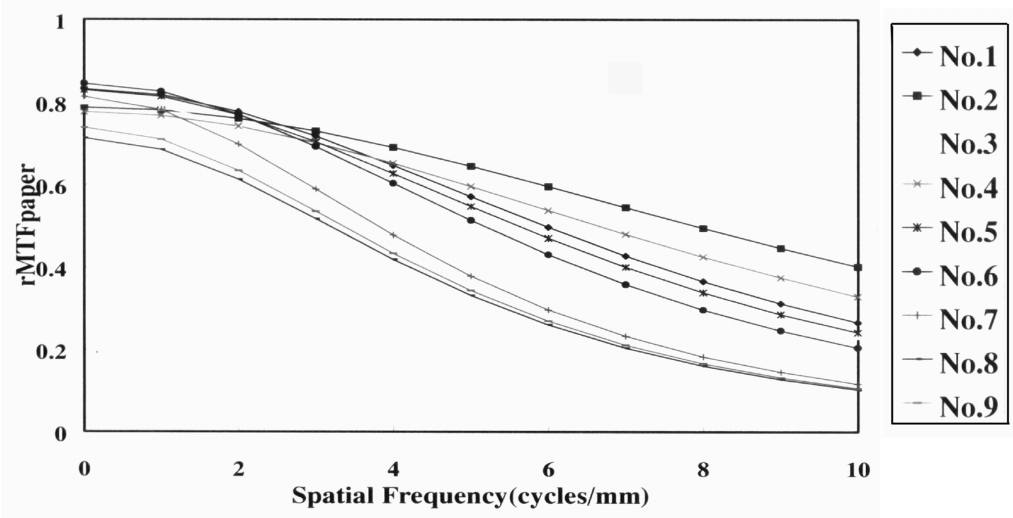

Figure 4. The MTFs of paper multiplied by reflectance of the sample papers.

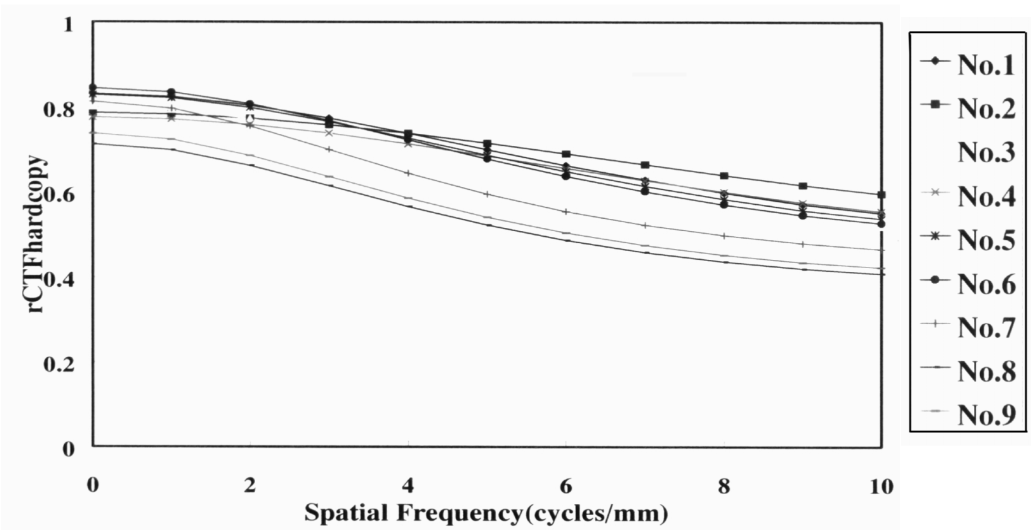

Figure 5. The CTFs of hardcopy multiplied by reflectance of the sample papers.

TABLE I. Characteristics of Sample Papers

	Specific	Sample No.	Basis weight	reflectance ratio	coefficient *d* at the MTF_{paper}
Coated Paper	Art	1	104.7	0.831	0.017
	Coat(+TiO2)	2	64.0	0.787	0.012
	Coat(gloss)	3	104.7	0.802	0.018
	Coat(gloss)	4	73.3	0.776	0.014
	(no calendar)	5	104.7	0.829	0.018
	Coat(mat)	6	104.7	0.845	0.020
Uncoated Paper	for printing	7	104.7	0.813	0.026
	paper for coat	8	67.7	0.713	0.026
	ppc	9	64.0	0.739	0.026

jected image and two hardcopies. Each relationship between the figures of merit and the observer rating values are discussed.

Evaluation by SQF of Paper

The sample papers were evaluated by SQF of paper. The experiments were done as follows.

Sample Papers. The nine sample papers are coated or uncoated papers with different basis weight, pigment and coating weight as shown in Table I. These papers are usually used for printing.

Measuring MTF of Paper by Sinusoidal Test Pattern Projection. In our previous article, we introduced

TABLE II. Experimental Results with Sample Papers (O.R.V. denotes Observer Rating Value)

Sample No.	Projected image experiment portrait		Contact image experiment portrait		Contact image experiment landscape
	SQF paper	O.R.V.	SQFpaper	O.R.V.	O.R.V.
1	0.78	0.80	0.80	0.48	0.53
2	0.76	0.62	0.77	0.16	0.33
3	0.74	0.71	0.77	0.37	0.37
4	0.74	0.32	0.76	–0.30	–0.01
5	0.77	0.37	0.80	0.58	0.46
6	0.77	0.35	0.81	0.56	0.44
7	0.70	–0.34	0.76	–0.26	–0.46
8	0.61	–0.68	0.66	–0.80	–0.93
9	0.63	–0.77	0.69	–0.78	–0.73

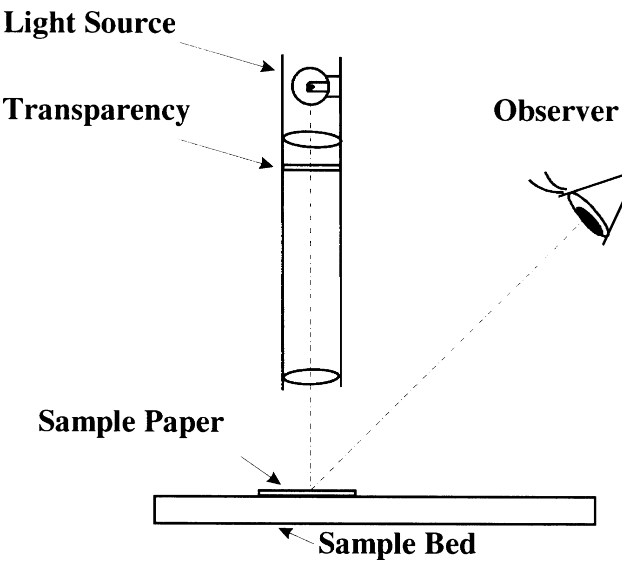

Figure 6. The schematic diagram of the observer rating experiment for the image projected onto the sample papers.

a method for measuring the MTF of paper.[6] The MTFs of the sample papers were measured by this method. A sinusoidal test pattern is projected onto paper, and this reflection intensity distribution is measured with a modified microdensitometer(UNION Optical, Japan). The MTF is calculated from the output sinusoidal image. Measured MTFs are shown in Fig. 3. In the previous paper,[3] we found that the MTF of paper can be expressed approximately by Eq. 9.

$$MTF_{paper}(u) = \frac{1}{[1+(2\cdot\pi\cdot d\cdot u)^2]^{\frac{3}{2}}} \tag{9}$$

where d is a coefficient. Each coefficient d of the sample papers is given in Table I.

The Reflectance of Paper. The reflectance of each sample paper was measured as the lightness against a black background by PF-10 (Nihondensyokukogyo, Japan). The results are also given in Table I.

The SQF of Paper. Figure 4 shows the MTF curves multiplied by reflectance of the sample papers. Figure 5 shows the CTF curves multiplied by reflectance of the sample papers. The SQF_{paper} for hardcopy was calculated from Eq. 7. The SQF_{paper} for image projected onto paper

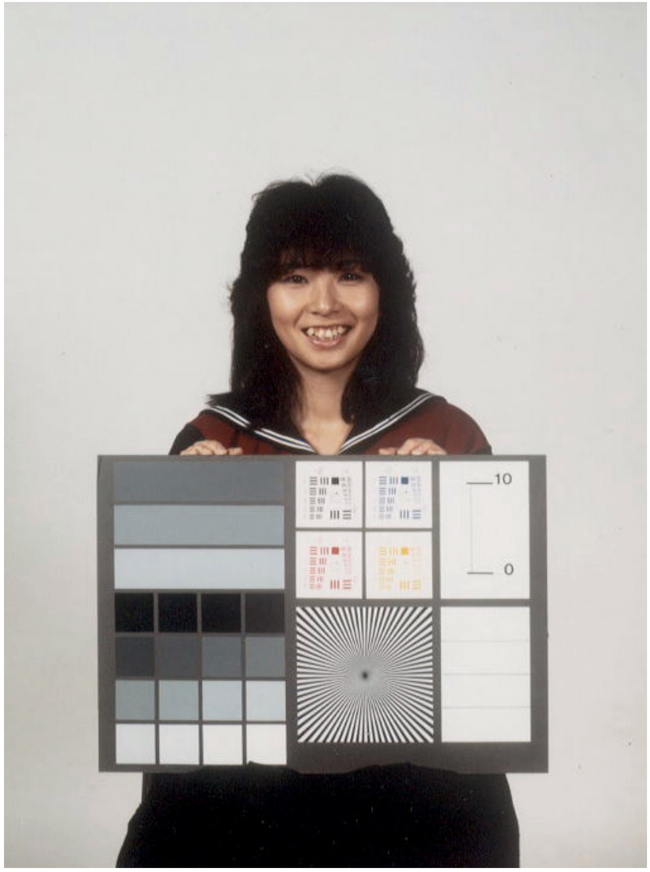

Figure 7. The original picture used in the projected image experiments. (*Supplemental materials—Figure 7, in color, can be found on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication*)

was calculated from Eq. 8. The results are shown in Table II.

The Observer Rating Experiments

The observer rating experiments were done for a projected image, a portrait, and two experimental contact images, a portrait and a landscape, on the sample papers.

Projected Image. Figure 6 shows the observer rating experiment for the projected images. A photographic image in Fig. 7 was projected onto the sample papers. A 4 × 5 inch color transparency was used as the original. The circle area 20 mm in diameter of a face was projected. The projected image size is same as the original film. The sample bed is coated black. The sample pa-

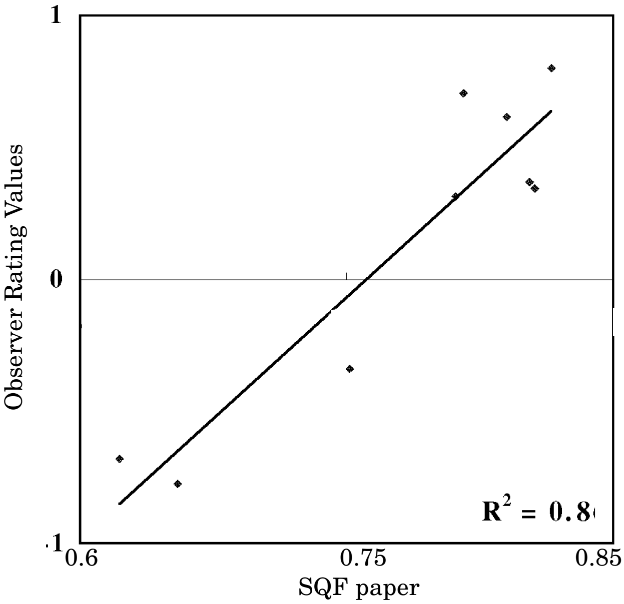

Figure 8. Relationship between SQF_{paper} and observer rating values in the projected image experiments.

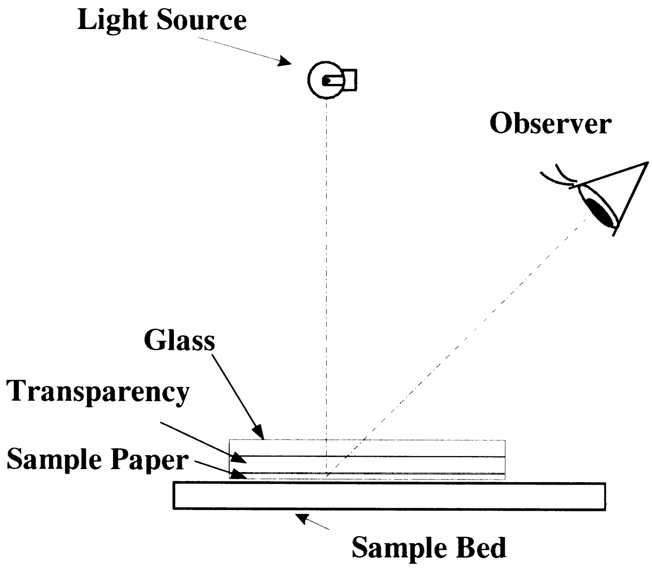

Figure 9. The schematic diagram of the observer rating experiment for the contacted images.

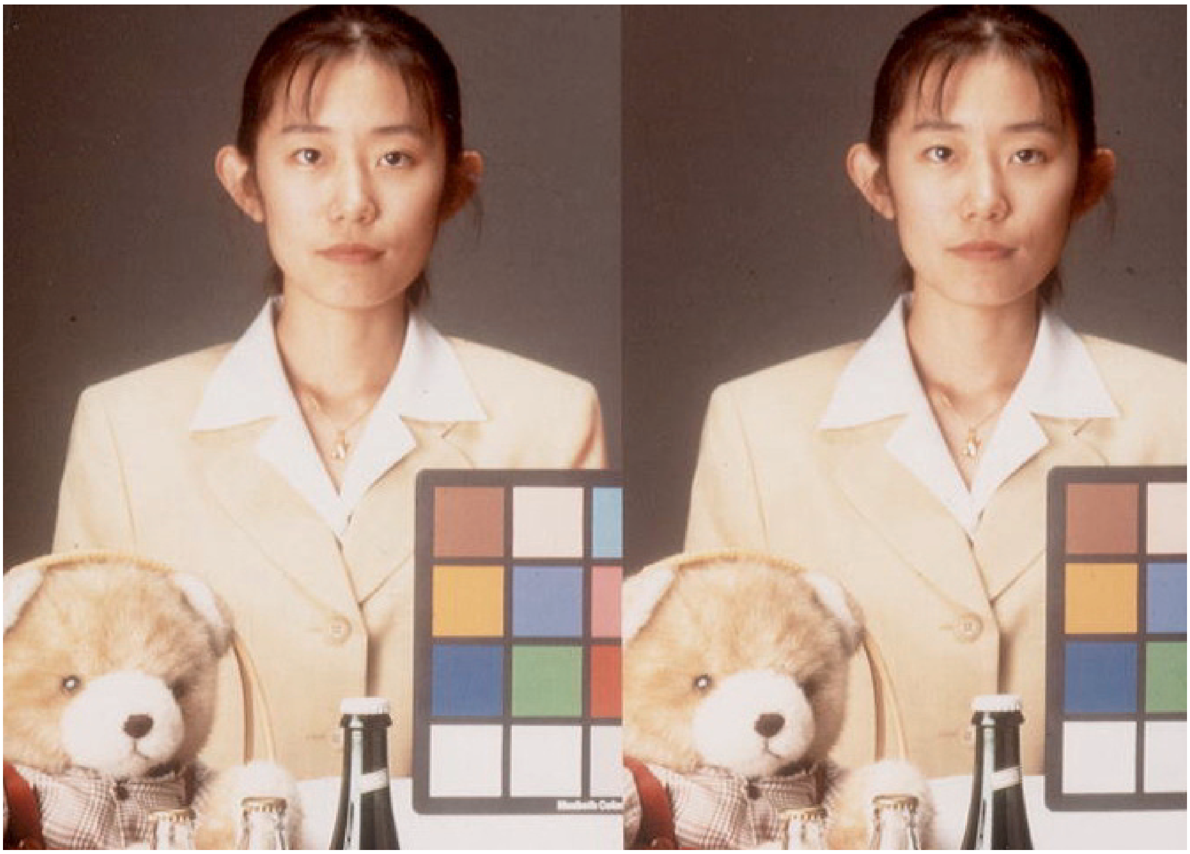

Figure 10. The original picture used in the contacted image experiments (portrait). (*Supplemental materials—Figure 10, in color, can be found on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication*)

pers are arranged randomly and rated by 6 observers who are members of the research staff. The samples were observed at an angle of 45 degrees at 200 mm distance. Then the subjective evaluation values were calculated based on the psychometric scaling method. The observer rating values are shown in Table II. Figure 8 shows the relationship between the values of the SQFs of paper and observer rating values. The correlation coefficient between them was 0.86.

Contact Image. Figure 9 shows the observer rating experiment for the contact images, i.e., hardcopy. Each transparency image in Figs. 10 and 12 were placed in contact with the sample papers. The color transparency

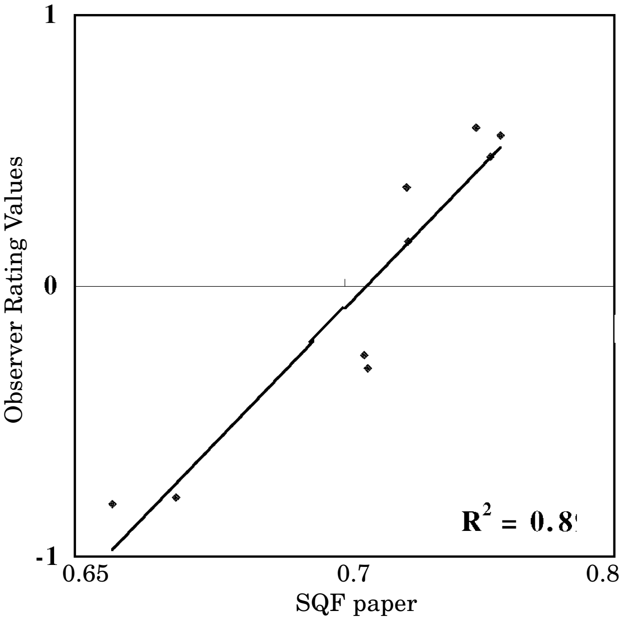

Figure 11. Relationship between SQF_{paper} and observer rating values in the contacted image experiments (portrait).

was made on the 4 × 5 inch color reversal film by the film recorder (Imapro QRZ) from digital data to be half the gamma of the normal tone reproduction curve. The same two images were made on one film. Two different sample papers were placed under the film on the right and the left side. The set-up was then observed and judged. The sample papers are arranged randomly and rated by 8 observers who are members of the research staff. The samples were observed at an angle of 45 degrees and at 200 mm distance. The observer rating values are shown in Table II. Figures 11 and 13 show the relationship between the values of the SQF of paper and observer rating values. The correlation coefficient between them was 0.89 for the portrait and 0.88 for the landscape.

Discussions

The experimental results show good correlation between the SQFs of paper and the observer rating values in both type of images. It is shown experimentally that the reflectance and MTF of paper are important factors for hardcopy image quality.

Other evaluation functions based on the MTF were examined. Those showed similar results. The correlation coefficient between the figures of merit and observer

Figure 12. The original picture used in the contacted image experiments (landscape). (*Supplemental materials—Figure 12, in color, can be found on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication*)

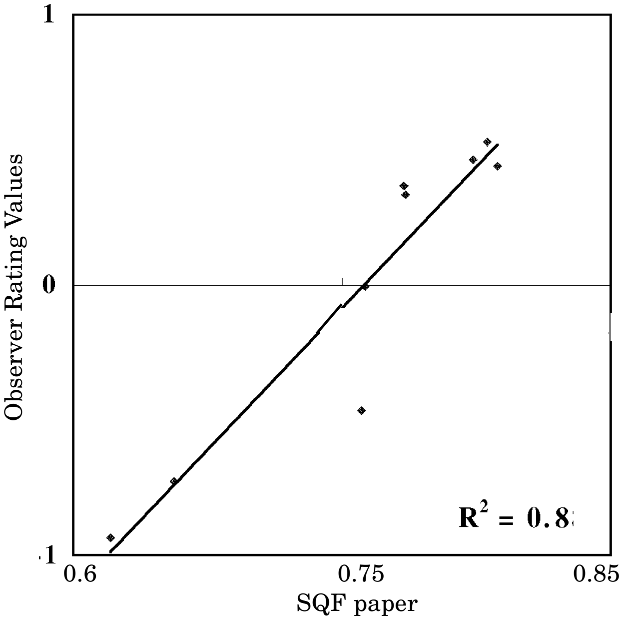

Figure 13. Relationship between SQF_{paper} and observer rating values in the contacted image experiments (landscape).

rating values depends on the bandpass area (or visual MTF) of the evaluation function. A better evaluation function will reduce the error of correlation; carrying out the observer rating experiments with more observers may also reduce the error of correlation.

The CTF of hardcopy was used as the alternative input–output function for hardcopy in this experiment. We would like to point out two problems. The first one is that the final output signal is not sinusoidal even though the input signals were sinusoidal.[8] For example, if the MTF of paper becomes 1.0, the output signal becomes $\sin^2$. This occurs in the low spatial frequency regime. The second one is that the macro intensity is reduced according to the increasing of spatial frequency. This is the same phenomenon that has been known as optical dot gain in halftone image.[6,9] Therefore, by using the CTF of hardcopy as the input–output function, the calculated evaluation value might be little different from that evaluated by observation.

The SQF of paper in the contacted images is higher than in projected images on the same sample paper. This phenomenon is a consequence of the difference of their input–output functions. Equation 5 shows that hardcopy is able to have information even if the MTF of paper becomes zero. We consider that the image quality of hardcopy is better than that of an image projected onto the same sample paper. However it is difficult to compare a hardcopy with a projected image because the projected image is observed in a dark room and the hardcopy is observed in a light room. Therefore, we are planning computer simulation experiments, wherein the images will be simulated by the functions of Eqs. 1 and 2. They will then be compared on a display and evaluated by observers.

Conclusions

In this article, we discuss the relationship MTF of paper and image quality. Two types of images, a hardcopy and a projected image, were analyzed by both the evaluation function and observer rating experiments. The evaluation function is based on the MTF of paper. Good correlation was obtained between the evaluation function values and the observer rating values. It is shown experimentally that the reflectance and MTF of paper are significantly important to the image quality of hardcopy.

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