IMAGE QUALITY ASSESSMENT OF INK-JET PRINTERS

Yigal Gur,* Francis X. D. O'Donnell*

Abstract: A method for assessing the print quality of an ink-jet printer is described. The ink-jet printer is a binary machine which can either put a dot at a particular location on a sheet of paper or leave it blank. It is the binary nature of the printer which prevents the direct use of the classical Modulation Transfer Function (MTF) which is used with great success in the study of optical systems. A Reflectance Transfer Function (RTF) is defined which can be used to assess the print quality of a binary printer. The RTF is obtained by reflectance measurements of a test target which consists of checkerboards of various frequencies. This is then cascaded with the MTF of the human eye to give a Subjective Quality Factor (SQF). This SQF has been shown to correlate well with the subjective assessment of print quality by a panel of observers. Thus, the objective measurement of RTF may be used to assess the print quality of the printer.

Introduction

It would not be incorrect to say that the problem of print quality appeared together with the first prints. Even today, it is still a problem, at least from the metrology point of view. The reason for this lies in the complexity of human perception, the last judge of the quality of a picture. Our understanding of all "mechanisms" involved in this perceptual chain (eye-nerve-brain) is less than sufficient. The process in itself is extremely subjective, especially if we ask "which picture is better?" It is not valid to try to answer this question, when comparing pictures of Dega, Monet and Reubens with a modern advertizing brochure. It should be clear that the question as posed cannot be answered objectively.

It is possible to change the question slightly to "which picture is better printed?" and this in the majority of cases relates to the enigma of print quality.

To try to answer this question, one should compare the picture just obtained with the original. In some cases, the original exists only in our memory as a rendition of 3-D reality as in the case of a photograph. In the case of printing, it could be an artwork or its "proof" impression. Still, human perception will be involved in this case, but on a less absolute level. Rather, it will work in a comparison mode trying to rate the imperfections of the picture relative to the original master. The subjective character of human perception shows too in the rating procedure itself.

The conversion of the question "which picture is better?" to "which picture is better printed?" is an important point in understanding of print quality. It connects

*Diconix, A Kodak Company, Dayton, Ohio.

the meaning of quality to the way the picture is produced. In other words, print quality starts to be a characteristic of the process by which the picture was obtained and, presented in this way, can be connected with components, parameters and their interactions in the printing process, as shown in Fig. 1. Once the connection

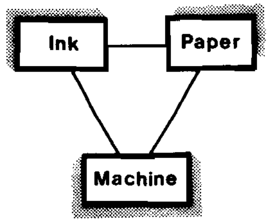

Fig. 1 The major contributors to print quality which depends not only upon the properties of the components (machine, ink, paper), but also upon the interaction between them.

is found, the more complex but practical problem can arise—optimization of the components and the parameters of the printing process to achieve maximum print quality. This print quality then starts to serve the purpose of the objective function in the problem of process optimization. However, the subjectivity in the print quality evaluation is an obstacle for using it as an objective function. Attempts were made in the past to overcome this subjectivity by the substitution of human vision by a computerized vision system using digital image processing. It was soon found that such a system requires quite a high level of intelligence to simulate human perception. This requirement has two origins: first, the task of comparing the images is one of the most difficult in digital image processing; second, a model should be established to connect the imperfections observed with the human perception of them. One of the results in using such systems is that there is no unique model like that: the model itself depends upon the image. The practical realization of this system leads to a wide variety of test images (text, halftone, line picture) and a large number of parameters (contrast, stroke width, edge raggedness, etc.) tied up into an infinitely large number of models of human perception. Not to mention the costly character of the system itself (about $200K), this, by virtue of its logics, overwhelms all the advantages of the objective estimation of print quality.

The printing business was not the first to encounter the problem of image quality.
In the early 50's, an attempt was made in optics to rate the quality of images. An important role in the understanding of this was played by the Optical Transfer Function (OTF) as was shown by Schade (1955). With the introduction of contrast as a carrier of information in images, the Modulation Transfer Function (MTF), being a part of OTF, was connected with quality of images by judging the ability of the optical system to produce images. A perfect review of these methods can be found in the book by Linfoot (1964). Information volume was introduced by K. Sayanagi (1956) as an area beneath an OTF curve. He showed that the lens imperfection could be related to information volume.

The next significant step was made by E. Granger (1972). He cascaded the MTF of the system with the MTF of human eye and using the Weber law of perception, introduced the Subjective Quality Factor (SQF). He established a direct correlation between the quality of images and SQF of systems that had been used to produce them. More recently, the concept of SQF has been widely used by Kodak in a variety of products ranging from the disk camera to a unique microimaging system, as described by Drayo et. al. (1985).

E. Granger's SQF method is expanded here for use by ink-jet printers. Such printers are restricted by printing single drops of ink, very small in size, anywhere on a printed page with a given spatial resolution. The images created by such printers are binary in their origin and halftones can be simulated by changing the frequency of dot placement.

A special target design will be explained together with the main principles for the determination of SQF which has been correlated with the human perception of print quality for text (characters). Once this correlation has been established, the SQF may be used to judge the overall performance of an ink-jet printer relative to its components (ink, paper, machine) and their interaction.

Pixel Reflectance Model

An image is defined here as an information message coded on paper by changing the paper's reflectivity. This is done by placing a drop of ink in a given picture element (pixel). The ink drop is absorbed by the paper; the dye is precipitated onto the fibers changing three dimensionally the properties of the paper. The sizing of the paper is used to localize, at least partially, the dye precipitation in the surface layer of the paper. The reflectance of light by a single dot of ink is schematically presented in Fig. 2, left. The spatial dependency of the reflected light can be seen from the upper photomicrograph of a single ink dot. The lower photomicrograph is a cross-section of the paper and the dot made with a razor blade and pictured with the same magnification as the ink dot.

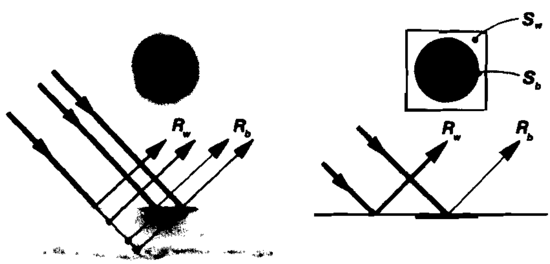

Fig. 2 Actual (left) light scattering by an ink spot on a sized paper. Right diagram presents an idealized pixel model. Reflected light is shown as specular only for simplification of drawings.

Incident light is partially reflected back by the paper's surface. Some of it penetrates into the paper and will be scattered by paper fibers. This scattering is complex in character. The light, reflected by an uncovered part of the paper ("white") will consist of diffuse and specular reflections from the paper's surface plus additional scattering from the main body of the paper. In the vicinity of the ink dot, part of this scattering will be eliminated by the phenomena of light entrapment by the ink dot as described by J. Yule and K. Neilsen (1951). The reflectance of the "white" part R_w will be a complex unknown function:

$$R_w = R_w(\Lambda, r) , \tag{1}$$

where Λ represents the spectral and r represents the spatial dependencies. The same will be true for the ink dot itself:

$$R_b = R_b(\Lambda, r) , \tag{2}$$

The spatial dependence of the reflectance can be accounted for by introducing the luminous reflectance Y, one of the CIE 1931 tristimulus values. For definitions of Y, see for example Wyszecki et. al. (1966).

While the calculations of the spatial dependencies of R_w and R_b present a real challenge, it is unnecessary for the body of current work. The actual reflectance of a pixel can always be approximated by an ideal case: assuming completely diffuse reflectance of paper surface only. It is equivalent to the substitution of the paper by a tarnished aluminum mirror with Y_w and Y_b the same as for uncovered and fully ink covered paper, respectively. Because of the linearity in the definition of Y, the resultant reflectivity of a pixel will be

$$Y = \frac{Y_w S_w + Y_b S_b}{S_w + S_b} , \tag{3}$$

where S_w - uncovered, S_b - covered areas of a pixel.

With these approximations, if the distribution of pixels in the binary image is known, the reflectance measured as luminance can be predicted. Similar formula (3) can be applied for such predictions if S_b and S_w are treated as total areas of covered and uncovered paper in any image.

Checkerboard Reflectance

The distribution of pixels in an image of a checkerboard is known. This image is used as a target here and could be characterized by its period T. When printed in portrait or landscape mode on an ink-jet printer, the period of the checkerboard T is a multiple of the machine period λ. ($1/\lambda$ is resolution of the printer, for example, in dot/inch):

$$T = 2n\lambda , \tag{4}$$

where $n = 1, 2 \ldots$ is the number of a checkerboard and is the size of the checker element in pixels, see Fig. 3.

One of the important properties of the checkerboard is the fact that if the pixels are squares, the reflectance of the checker will be independent of its period. Because the areas of white and black are equal for any period, the luminance of any checker will be

$$Y_a = \frac{Y_w + Y_b}{2} . \tag{5}$$

When the checkerboard is assembled with round pixels, as in the case of the ink-jet printer, this independency disappears and the luminance of a block becomes a function of the period of the checker. This is presented in Fig. 4 where actual patches of checkerboards are shown.

The decrease of the luminance for small T is obvious. When the period increases

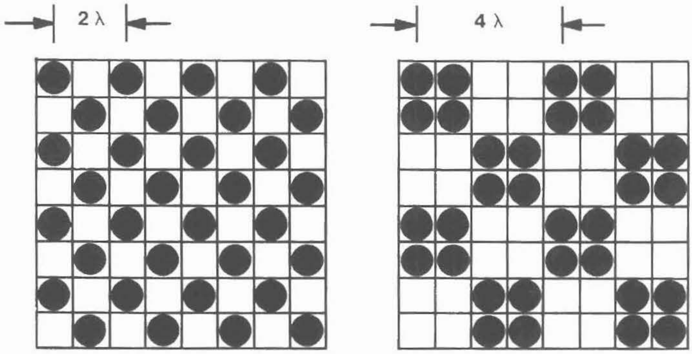

Fig. 3 Principle of the checkerboard target design for two spatial periods *T*.

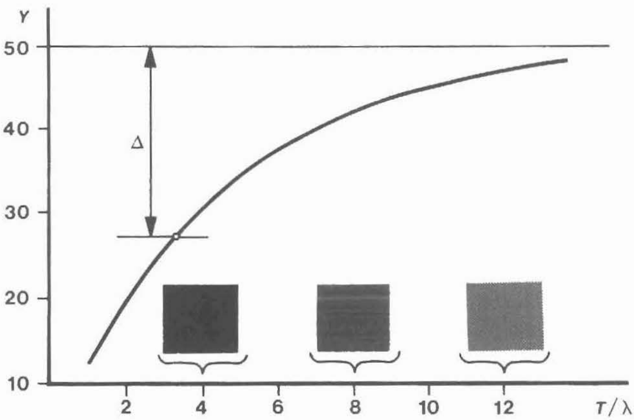

Fig. 4 The integrated reflectance of the checkerboard target depends upon the spatial period of the target. The three patches shown were printed on 300 DPI Dijit® 1 ink-jet printer.

the luminance of the checker asymptotically approaches the value of $Y_a = 50$ in Fig. 4. The difference

$$\Delta = |Y_a - Y| \tag{6}$$

can be a measure of the degradation of the printer when considered as a function of the checkerboard's spatial frequency. The process of printing the checkerboards with different spatial frequencies can be equated to a general transfer of information, coded as differences between black Y_b and white Y_w. The value that is actually transferred is the contrast:

$$c = \frac{Y_w - Y_b}{Y_w + Y_b}. \tag{7}$$

This same value is used in optics, so the concepts of optics can be applied to the process.

Reflectance Transfer Function

Optical systems (the eye, for example) are characterized by a Modulation Transfer Function (MTF). The word "modulation" in optics means "contrast," so the quality of a system is described by its ability to convey (deliver) contrast. In the case of the eye this contrast, initially on paper, is projected onto the retina. The ratio of contrast on the retina to the contrast on the paper is the modulation transfer. Unfortunately, imperfections of the eye diminish the contrast on the retina. The degradation starts to be significant (low modulation transfer) for high spatial frequencies of the checkerboard (or any other image). This is reflected in the curve in Fig. 5

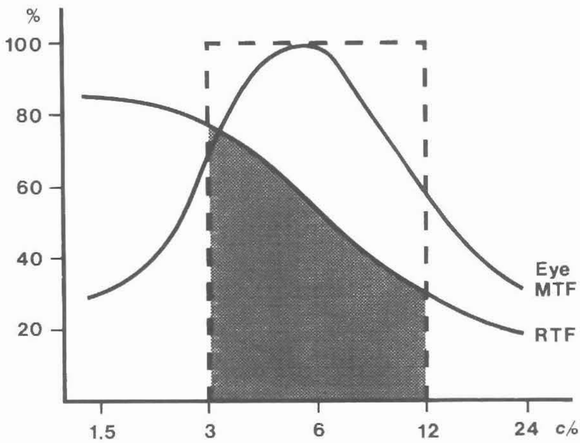

Fig. 5 The MTF of a human eye and its band-pass approximation (dotted line). SQF is defined as the ratio of the shaded area to the total area of the band-pass.

and this is why the modulation transfer becomes a function - MTF. The MTF of the eye has been studied by many investigators. The most detailed was that of A. P. Ginsburg (1978). E. Granger (1972) suggested a band-pass approximation of the MTF of the eye, which is plotted in Fig. 5.

One of the wonders of MTF is the so called cascading property: when the MTFs of the components are known, the MTF of the whole system can be found by multiplication of all sequential MTFs (cascades). Applying this property, one can estimate the quality of the system by the total area (information volume) beneath the cascaded MTF.

In the case of the eye, not all the frequencies are perceived as the same. E. Granger found that the human perception of visual information approximately follows Weber's law: it is logarithmical relative to spatial frequencies. The area beneath the system's MTF, cascaded with the eye's MTF and plotted in log coordinates, was called the Subjective Quality Factor (SQF) reflecting its perceptual character. E. Granger correlated the perception of images produced with an optical system with known MTF and SQF. He found that the correlation is better than 0.92 for a wide variety of images.

However, the MTF of an ink-jet printer cannot be determined by the same approach as in optics. The reason for this is in the strong nonlinearity of the printer. After all, it is only a binary device. Nevertheless, the effective Reflectance Transfer Function (RTF) can be introduced, as was shown by Y. Gur and F. O'Donnell (1987). This function can be determined for an idealized printer - paper - ink combination (a printer with an absence of placement errors, ink and paper as in the elementary model of a binary image) as

$$RTF = c\left(1 - \frac{\Delta}{Y_a}\right). \qquad (8)$$

As shown by Gur and O'Donnell (1987), the function (8) is close enough to an MTF and with some modifications can be measured by a colorimeter with wide aperture.

A study was run at DICONIX to find the correlations between the perception of the quality of text printed by Dijit® 1 and the SQF of the printer calculated from RTF. The results shown in Fig. 6 confirm that the text is perceived in the same

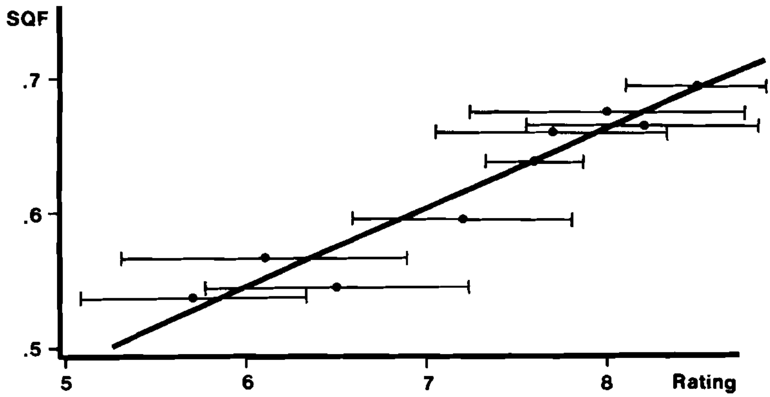

Fig. 6 The correlation between the SQF of the printer Dijit® 1 and the text quality ratings. The ratings were collected from 12 trained individuals (Print Quality Panel). Horizontal bars present differences in opinions between individuals (95% confidence limits).

way as an image. The result of this experiment, confirmed by the use of multidimensional scaling, permitted the organization of a control system for every machine using SQF to assure the required print quality of the product. It is well known that the overall performance of the printer depends on the setting of its operational parameters. Fig. 7 presents the dependence of the printer's SQF on two of the most vital parameters: deflection voltage and ink pressure. This figure confirms the existence of an optimal set of parameters from a print quality standpoint (maximal SQF).

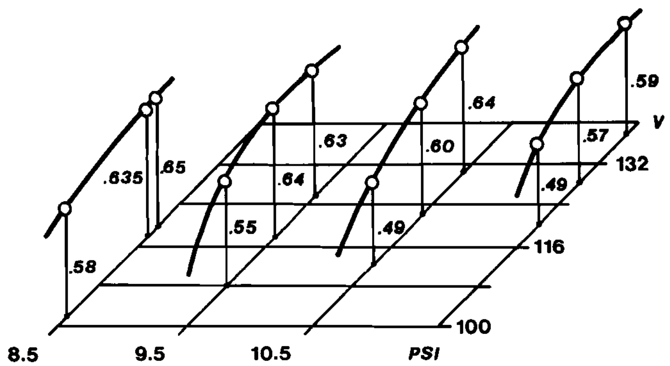

Fig. 7 SQF as a function of ink pressure and deflection voltage of Dijit® 1 printer.

SQF and Binary Image Parameters

It is important to trace the behavior of SQF for the general case of a binary image. The concrete operational parameters of printers can then be connected to the parameters of a binary image. This study was done theoretically by direct calculations of the checkerboard's luminance using the period of the target, geometrical calculations of the black area, determinations of noncovered area of paper and applications of equation (3). The value Y was then used in (6) and (8).

The size of the ink spot has a major influence on the quality factor, Fig. 8. There are three distinct areas which need to be considered. In region *a* - the diameter

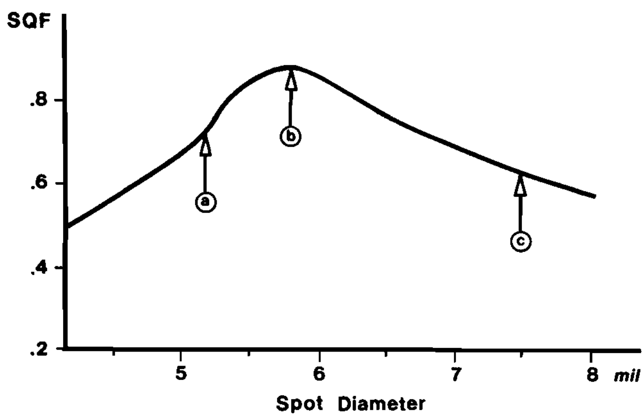

Fig. 8 SQF as a function of ink spot size. Data are calculated for a 192 DPI printer, paper Y_w = 90, ink Y_b = 5. Dot sizes pointed are: a = 5.2, b = 5.8, and c = 7.5 mils.

of the spot is smaller than the spatial resolution λ. Increasing of the spot size then will increase the SQF. This increase is observable up to a region of small overlays about 1.1λ - region *b* of Fig. 8. In this area, the maximum SQF is obtained.

Further increase of the overlap, region *c* in Fig. 8, leads to decrease of SQF for the digital printer.

The behavior of RTF as a function of spatial frequency is different for the regions *a*, *b*, and *c*. As presented in Fig. 9, the nonoverlapping spots lead to a straight line for the RTF curve. In the case of small overlaps, region *b*, the RTF curve has a

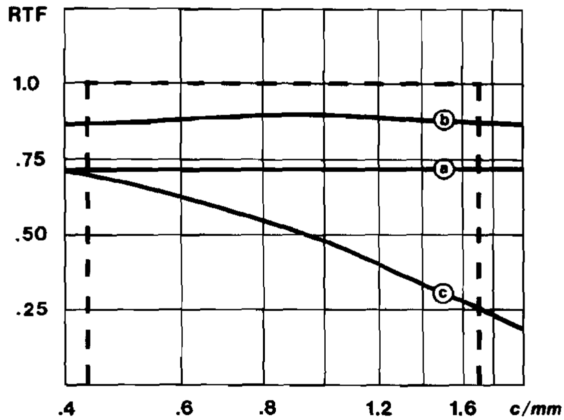

Fig. 9 RTF's calculated for the same printer as in Fig. 8.

slight maximum. The position of the maximum depends upon the overlap and with increasing overlap the maximum moves toward lower frequencies. In the case of strong overlaps, region *c*, the RTF curve becomes a monotonically decreasing function.

Fig. 10 presents a family of SQF curves plotted as functions of the spot overlap

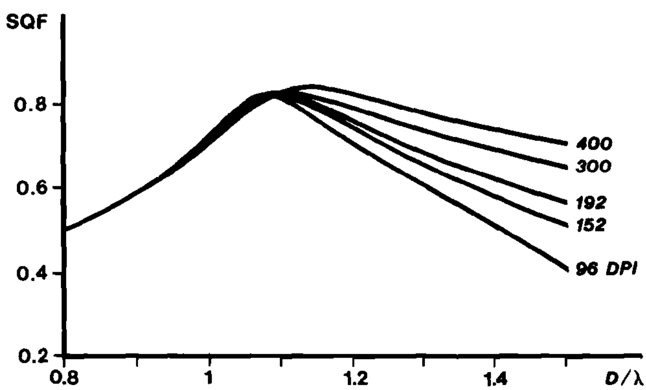

Fig. 10 Dependence of SQF upon spot size ratios (overlap) D/λ, calculated for printers with different resolutions. Paper and ink were with Y_w = 90 and Y_b = 5, respectively.

D/λ for different spatial resolutions. All curves have approximately the same maximal value in the region of D/λ ~ 1.1. The practical importance of this fact is in the ability to predict the best diameter for a spot for a printer with a given spatial resolution. The influence of the blackness of the ink and the whiteness of the paper on SQF is reflected at Fig. 11. Any decrease of the whiteness of the paper, or a decrease of the blackness of the ink obviously diminishes the SQF of the printer.

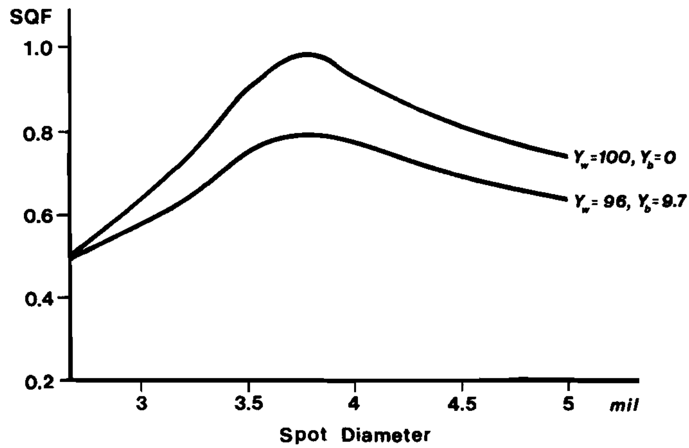

Fig. 11 Paper and ink reflectances in SQF behavior. Data were calculated for a 300 DPI printer.

The spot diameter is a very complex function of the drop size, physico-chemical properties of the ink (viscosity, surface tension, etc.) and the paper (size of the fiber capillaries, pH, etc.). The drop size, is responsible for the total volume of ink delivered and is a constructive parameter of the ink-jet printer. The properties of the ink can be modified together with its blackness to achieve the given

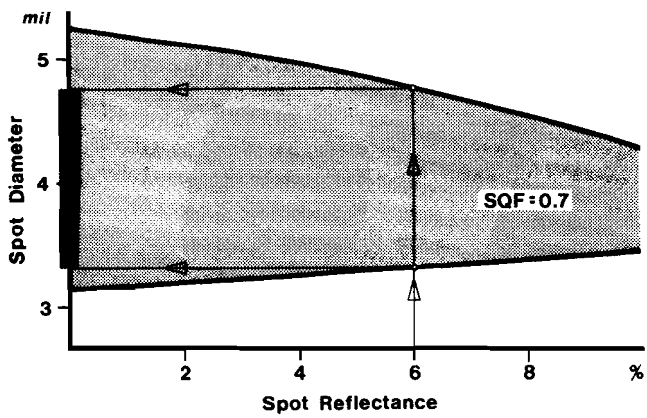

Fig. 12 An application of the SQF for a 300 DPI printer design. Shaded area is a region of SQF ≥ 0.7. Heavy shaded area is a "safe" range for ink spot sizes using an ink with Y_b = 6.

target SQF, as presented in Fig. 12. If the given batch of papers is known, the experiments can be performed to establish the possible span of the spot diameters. This span can be connected with the reflectances of the spots needed to achieve the targeted SQF. Another way to use Fig. 12 is to start from the spot reflectance and determine possible variations of the spot size that will not degrade SQF of the printer more than the targeted value for SQF.

Conclusions

A pattern consisting of a series of checkerboards of different spatial frequencies has been discussed. This pattern may be used to evaluate the Reflectance Transfer Function of a printer. This function is similar to the Modulation Transfer Function used in optics to assess the quality of optical systems.

The Reflectance Transfer Function may be obtained from the checkerboard pattern either by a series of luminance measurements or by calculation (pixel model of binary images).

The Reflectance Transfer Function, being cascaded with a band-pass approximation of the Modulation Transfer Function of the human eye gives the Subjective Quality Factor of a printer. Studies performed at Diconix have shown high correlation between the Subjective Quality Factor and the subjective assessment of print quality of text by a panel of individual observers. We believe that the use of the method described is a simple and cost effective way for instrumental measurements or theoretical analysis of the print quality of a printer.

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