# PRINTED IMAGE QUALITY THRESHOLDS

Gary G. Field*

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Abstract: The categories of tone and color reproduction, image definition, and interference patterns were used as a framework for exploring aspects of the perceptual quality and the physical characteristics of printed images. The findings included: approximately 1,500,000 distinct colors may be reproduced by 4-color process printing; the halftone screening process should generate about 144 tone steps; screen rulings of 250 lines per inch produce optimal single color resolution for conventional screens; graininess and moiré patterns may be minimized, respectively, by conventional and stochastic screens; and, the human visual process loses both color discrimination ability and visual acuity with age. In order to realize optimum quality, it is necessary to balance the production conditions (materials and methods) to suit the characteristics of the original image, and the economic and production requirements of the printed product.

## Introduction

The primary factors that influence the quality of printed images have been arranged in a framework developed by George Jorgensen (1955); they are:

1. Tone and Color Reproduction. The hue, saturation and lightness of areas in the printed image.
2. Image Definition. Sharpness and resolution of fine detail in the image.
3. Interference Patterns. These unwanted effects may be random (graininess and mottle) or periodic (moiré).
4. Surface Characteristics. Texture of the substrate and gloss are the main aspects of this category.

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*Graphic Communication Department, California Polytechnic State University, San Luis Obispo, California 93407.

The particular combination of print quality factors for optimal reproduction is not known beyond some general guidelines (Field, 1985). In the absence of universal specifications, companies generally strive to improve individual performance characteristics of imaging systems in the belief that such improvements will raise the overall level of image quality.

In practice, however, it is useful to know the limit or boundary conditions for particular print quality factors in order that unnecessary "improvements" are not introduced. Such knowledge can also be of use when writing quality specifications and making print quality factor tradeoffs during production.

This exploratory study considers aspects of the visual process as they relate to the performance constraints of printing systems; notably:

1. Visual Processes. The age of the observer influences color perception and visual acuity. Such factors are also affected by the viewing conditions; in particular, the intensity of the light source. Color vision abnormalities are related to the observer's sex and, to some extent, his or her racial heritage.

2. Printing Systems. Such factors as substrate whiteness and brightness, colorimetric properties of inks, ink transparency, substrate surface characteristics, and the ink transfer mechanism will influence the color gamut and other aspects of a printed image. Resolution, graininess, moiré, and tonal discrimination will be influenced by the halftone screening process.

Some key questions concerning the evaluation of an imaging system's performance could include: What is the maximum number of colors a human can discern? What is the finest screen ruling that is practical to use? What is the optimal number of tonal values between white and black? When should extra colors be used to supplement the process colors? and, What subjects, or images are best suited to particular screening techniques? The answers to these questions must be based on a consideration of both the visual process and the capabilities of the printing system.

## The Human Visual System

The human visual system is extremely complex and is only partially understood. Textbooks by Hurvich (1981) and Wandell (1995) provide a good introduction to the complexities and theories of this subject. The following discussion covers specific topics that are relevant to the evaluation of printed image quality.

1. Number of Discriminable Colors. The exact number of individual colors the human eye is capable of discriminating is not known with any certainty, but a number of noted authorities (Carl Foss, Deane Judd, and Gunther Wyszecki) agree that the number is probably around 10,000,000

or more (Burnham et al., 1963). In the case of surface colors (colors viewed by reflected light), Nickerson and Newhall (1943) have deduced that the number of discriminable colors is about 7,500,000 under ideal conditions. This latter number, therefore, represents the theoretical maximum number of colors in a reproduction that is viewed by reflected light. Nickerson and Newhall do suggest, however, that "under the more usual observational conditions of visual color matching work" the theoretical maximum number of surface colors that the eye can distinguish falls to about 1,875,000.

2. Color Vision Abnormalities. About eight percent of the male population and about 0.6 percent of the female population have abnormal color vision because they have inherited defective genes (Hurvich, 1981). The most common form of color vision abnormality is red-green confusion. The incidence of abnormal color vision is highest in Caucasian races (about 8.1 percent), next highest in Asian races (about 4.9 percent), and lowest in other races (about 3.1 percent).

3. The Effects of Age on Color Perception. The lens in the eye tends to yellow as we grow older. This gradual yellowing can affect out ability to distinguish between the greenish yellow to purplish blue tray (caps numbered 43 to 63) of color samples in the Farnsworth-Munsell 100 hue test (Ancona, 1986). The lens also transmits less overall light as we age: the 80-year old lens transmits about one half of the light transmitted by the 25-year old lens (Lerman, 1987).

4. Visual Acuity. The ability to discriminate between fine details is termed visual acuity. The five million cones that are concentrated in the fovea of the eye are the primary photoreceptors responsible for resolving detail and color under good illumination conditions. The center-to-center distance of individual cones is about 2.5 microns, which means that a cone is able to resolve about 0.5 minutes of visual angle (Wandell, 1995).

5. The Effects of Age on Visual Acuity. As we age, the pupils of the eye become smaller for a given illumination level which, in turn, reduces the brightness of the retinal image. This effect can be countered by using higher intensity illumination. Another effect of aging is the decreased efficiency of the photoreceptors in the retina. In general, a 100 score relative visual acuity at age 20 declines to 90 at age 40, to 74 at age 60, and to 47 at age 80 (Luckiesh, 1944).

6. Illumination. The intensity, spectral quality, color temperature, and other properties of illuminants will influence color perception and visual acuity.

In theory, however, perceptual differences caused by illuminant variability should be low because of the standard light sources used by the photographic and printing industries (ANSI, 1989, for example).

## Printing Process Capabilities

The performance limits or capabilities of the photomechanical reproduction system are initially constrained by the properties of the inks and substrate, and by the ink transfer and image carrier characteristics of the printing process. In practice, performance limits are highly variable because of the great variety of inks and substrates that are used for printed products. The selection of substrate and ink are often dictated by economic factors or product form considerations (e.g., newspapers vs. folding cartons). The number of inks used is often determined by the nature of the original; greeting card companies, for example, often use supplementary pink and pale blue inks to improve the color fidelity of light tonal areas. It is possible, however, to offer some general guidelines regarding printing system performance:

1. Color Gamut. As stated earlier, the color gamut of a reproduction system is highly dependent on materials selection. Such press operational factors as ink trap, color sequence, and individual ink maximum densities will also exert a powerful influence on color gamut. The CIELAB values for a set of eleven inks in an ink mixing system have been published (Field, 1987). These values describe the gamut of a typical high density and high saturation ink set. Different inks would be required for maximizing the gamut of lighter colors.

2. Maximum 4-Color Density. A color survey of the printing industry has revealed a considerable variation in the maximum 4-color density that may be achieved (Field, 1972). The maximum values recorded for coated paper in the survey were fairly consistent with the data in Table 1. The maximum 4-color density of a process determines image sharpness characteristics as well as the tonal scale.

3. Tonal Separation. The 1972 introduction by Hell of a laser recording system (Gast, 1974) for halftone images meant that the halftone scale took on a digital rather than an analog structure. The halftone cell was represented by a 12x12 grid, the elements of which were exposed or not exposed according to the tonal and screen requirements. Today, virtually all halftone color images are formed by this principle. The number of grid elements (plus one for unprinted paper) determines the tonal separation. For a 12x12 grid there are 145 tonal steps and for 16x16 there are 257 steps.

Table 1
Single Copy 4-Color Density Maxima for Two Magazines

| | National Geographic | | Australian Geographic |
|---|---|---|---|
| Printing Process | Gravure | | Lithography (web) |
| Issue Date | April 1995 | | April-June 1995 |
| Number of Measurements | 40 | | 37 |
| Mean 4-Color Dmax | 2.215 | | 1.888 |
| Standard Deviation | 0.066 | | 0.059 |
| Maximum Reading | 2.30 | | 2.02 |

4. Fine Detail Rendition. A study by Jorgensen (1967) of the lithographic process reported that detail as small as an 8 micron spot could occasionally be recorded. He suggested that an element size of about 10x10 microns should be considered for practical purposes. A 10x10 micron element prints more consistently than an 8 micron element and, if placed within a 12x12 micron area, will contain an allowance for graininess-induced variation.

   There are no known studies on the theoretical limits of fine detail rendition in other processes, but it is believed that the minimum printable element is considerably larger than that achieved by the lithographic process. The fact that lithography uses a photochemical process for forming the planographic plate image, whereas the other processes use a physical or chemical process to literally remove material from the image carrier, is the partial basis for this belief.

5. Moiré Patterns. Any overlap of halftone screen images on different angles will produce a pattern. If the angles are not properly chosen, the resulting pattern may be objectionable. The optimal angles for a given number of colors and screening condition will still produce a rosette pattern that will be more noticeable at certain screen rulings and tone values. The use of multi angle screens, as opposed to the difficult-to-control same angle screens, will also lower the resolution of the reproduction (Rich, 1982). Patterns between the halftone screen and detail in the subject ("subject moiré") are also possible with conventional halftone screens. The use of stochastic halftone screens will reduce moiré and improve resolution; but, sometimes at the expense of an increase in graininess.

6. Graininess. Image graininess in lithography has also been investigated by Jorgensen (1956). He found that normal images typically have a density variation in their microstructure that becomes more noticeable with finer screen rulings and higher ink densities. A scanning microdensitometer with a 0.0033" diameter aperture was found to give the best correlation to an observer's evaluation at a distance of 12 inches.

7. Density Variation. Density variation across the press; from gripper to tail; as a result of ink ductor action; and as a function of drift over time were studied by Hull (1972). Leaving aside across the press variation, he found a maximum density variation under the best conditions of about 0.02 to 0.03. The across the press variation was considerably higher than this range, but such variation is probably not typical of modern ink-key setting systems.

## Performance Evaluation and Requirements

### 1. Tone Scale and Screen Ruling Considerations

One starting point for establishing imaging requirements is the smallest recordable spot. If this spot is taken as 10x10 microns it can serve as the lightest printable tonal value for a given screen frequency. In the case of course screen rulings, a 10 micron increment in halftone dot size will result in a large number of tonal values between the limit points. In the case of fine screen rulings, however, the same 10 micron increase in halftone dot size will produce a much lower number of tonal values between the limits of black and white. In other words, there is a tradeoff between screen ruling fineness and tonal step increments when digital halftoning techniques are employed.

A rough estimate of required tonal step increment may be derived from measurements of printed halftones of known values. A five percent-increment color chart was used for the measurements. A Hunterlab Labscan Spectrocolorimeter and FMC-2 color difference software were used to evaluate the difference between each step of the yellow, magenta, and cyan tone scales. Each step was, in turn, used as the reference for evaluating the color difference of the next step. The results are presented in Table 2.

The $\Delta E$ shifts were mostly considerably higher than the $\Delta L$ shifts because of such factors as proportionality failure. The Table 2 magenta values should be considered the most valid because, unlike cyan and yellow, the magenta samples were certainly free of press-induced variability.

Table 2
ΔL Differences Between 5 Percent Halftone Tints

| | Yellow | | Magenta | | Cyan |
|---|---|---|---|---|---|
| $\bar{x}$ | 1.273 | | 4.801 | | 4.095 |
| $\sigma$ | 0.583 | | 1.325 | | 1.330 |
| Minimum | 0.460 | | 1.290 | | 2.010 |
| Maximum | 2.780 | | 7.230 | | 7.120 |
| | | | | | |
| Dmax | 1.10 | | 1.15 | | 1.13 |
| Overall ΔL (vs. substrate) | 22.72 | | 109.46 | | 94.04 |

It seems, in general, that a 5 percent halftone difference for the magenta scale is approximately equal to 5.0 ΔL units. A 12x12 halftone grid, therefore, will produce tonal values that differ from each other by 0.69 percent, a value that will produce about seven steps between 5 percent tone values.

A 12x12 grid of 10 micron elements results in a screen ruling of about 83 lines per centimeter or about 212 lines per inch. A 10x10 grid of 10 micron elements equates to a 100 lines per centimeter ruling (~250 L.P.I.) and a 12x12 grid of 8 micron elements equates to a 105 lines per centimeter ruling (~265 L.P.I). It seems, therefore, that a 100 lines per centimeter (about 250 lines per inch) screen represents a good compromise value for the screen ruling-tone increment tradeoff that is a characteristic of digital imaging systems.

## 2. Maximum Number of Printable Colors

It is difficult to estimate the number of colors that may be produced by a given ink-substrate combination. A simple raising to the power 4 of the number of tonal steps will not produce a useful estimate: the black printer contributes considerable redundancy, and for some colors an incremental tone step is far less than a perceptible difference (the yellow solid in Table 2, for example, has a ΔL value, compared to unprinted paper, of only 22.72). The Dmax, number of colors, substrate characteristics, printing conditions, colorant spectral characteristics, and ink transparency will all influence the maximum number of colors that may be printed.

A crude estimate of the maximum number of printed colors for a given set of conditions may be derived by using ΔL values as surrogates for tone steps, and to specifically exclude the gray component of YMC combinations by considering only paired combinations of primaries prior to applying the contribution of the black printer. Table 3 presents the results of such a calculation where a 1.42 density black ($\Delta L$ 90.24) is combined with the sum of paired combinations of the yellow, magenta, and cyan from Table 2.

Table 3
An Estimate of Maximum Printable Colors for a Given Set of Conditions

| Color Combinations | | $\Delta L$ (from Table 2) Products |
|---|---|---|
| Yellow and Magenta | | 2,486.931 |
| Yellow and Cyan | | 2,136.589 + |
| Magenta and Cyan | | 10,293.618 |
| | | 14,917.188 |
| Black Contribution ($\Delta L$) | | x 90.24 |
| Estimate of Total Colors | | 1,346,123 |

The estimate does not include the contribution of black to the near-100 percent 3-color areas but, on the other hand, it probably overstates (due to additivity failure) the products of the primary color pairs. In general, therefore, it is reasonable to suggest that the average 4-color printing system can produce somewhere between 1,200,000 and 1,500,000 distinct colors. Gravure will be at the higher end of this estimate, while lithography will be at the lower end.

### 3. Interference Pattern Minimization

The issue of graininess and halftone screening patterns has been addressed by Schläpfer (1994). He reported the results of an UGRA evaluation of several screening techniques (regular, random, and frequency modulated). It was found that noise (graininess) varied significantly, but was lowest for the regular screens. Frequency Modulated (FM) screens with the smallest spot sizes (about 20 microns) exhibited the lowest graininess for that class of screen. Kruse (1994) and Schläpfer both point out the superior resolving power of the stochastic or FM screens as compared to regular screens.

Schläpfer and Widmer (1994) stress the virtues of FM screening in avoiding moiré patterns, and in also circumventing the need for ultra fine (154 lines/cm) conventional screens to minimize halftone rosette patterns. They point out that such patterns have an inner diameter twice as large as the edge of a 50 percent dot for a given screen ruling. Dot array phase shift techniques as a method of minimizing rosette patterns in conventional screens have been described by Daels and Delabastita (1994), and Yuasa and Mishina (1994).

## Conclusions and Recommendations

The following conclusions are advanced for the factors that influence color reproduction, image definition, and interference patterns in printing:

1. Graininess. Very small spot sizes (probably below 20 microns) or software revisions are required in order to reduce FM or stochastic graininess to levels below the visual threshold for the critical light-to-medium smooth or flat tones. Regular halftone screens minimize screen-induced graininess effects; however, press-induced graininess will be more noticeable with finer screens than with coarser screens.

2. Moiré. Stochastic or FM screens eliminate moiré patterns of all types. Dot array phase shift techniques may be advantageous in minimizing rosette patterns when regular screens are used.

3. Resolution. A screen ruling of 250 lines per inch is sufficiently fine to give the appearance of continuous tone for a single color. In the case of multicolor printing, however, screen rulings of 380 lines per inch or higher may be required in order to minimize the rosette patterns in critical areas. It would be extremely difficult to consistently reproduce the small spot sizes (about 6 microns) that are required for a 380 LPI screen with at least 100 tone steps. A stochastic or FM screen is capable of producing continuous tone appearance, but the recording resolution must be high enough (probably around 2500 dpi) to minimize graininess and to produce a satisfactory number of tonal steps per unit area.

4. Tonal Steps. A 12x12 grid producing 144 different dot levels seems to provide a satisfactory tonal scale transition.

5. Color Reproduction. Good 4-color process printing may be capable of reproducing about 1,500,000 distinct colors. The use of supplementary colors will expand this range, but it will still be below the 7,500,000 theoretical limit for surface colors.

6. Color Variation. Statistically normal intra and inter image color variation probably amounts to an absolute value of 0.03 density.

7. Visual Discrimination. The lens of the eye becomes yellower and more cloudy with age. The pupil of the eye loses some of its ability to open, and the retina becomes less efficient at recording images. In sum, there is a marked decline in visual acuity, and in the ability to discriminate between colors in the blue and adjacent ranges. The visual acuity effects become more pronounced after age 60, but may be countered to some extent by using higher intensity illumination for critical viewing situations.

The conditions (materials and methods) for optimal reproduction will vary from situation to situation because of the tradeoffs that exist between various print quality factors. Color gamut enhancement requirements will depend on the key colors in the original, and the graininess-resolution-sharpness-moiré requirements will be determined by the relative proportions of busy detail and smooth tones in the original (Field, 1990).

The recent developments in digital imaging have made higher quality reproductions more feasible. Stochastic screens allow moiré-free reproductions when using any number of colors. These screens also produce higher resolution images for a given recording resolution than is possible with regular screens. Stochastic screen graininess can be reduced to some extent, by software developments.

Quality of printed images is also a function of the human visual system and the lighting conditions. A 50-year old person will not see some of the defects in a reproduction that a 20-year old will, but it may not be practical to attempt to use this knowledge as a basis for establishing quality specifications or evaluation conditions.

Finally, markets, economic factors, and production considerations also help to define quality. The Unites States Government Printing Office (USGPO), for example, have published sets of specifications (1992) that establish the target values and tolerances for five different levels of printing quality. Such specifications recognize the use and life factors of the product in question and ensure that the production requirements have sufficient latitude to minimize waste and maximize production while meeting the quality requirements of a particular class of work. In other words, quality strategy is chosen to suit the circumstances.

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