

Perception of Spatial Color Variation Caused by Mass Variations about Single Separations

Nancy Goodman
Wilson Center for Research and Technology
Xerox Corporation, Webster, NY, USA

Abstract

When developing image quality specifications for a printer or copier, it is important to understand people's threshold and sensitivity for spatial color variation. Much information exists in the literature for thresholds for lightness variations about a neutral base color. There is much less information about thresholds for color variation about a neutral base color. The general question of thresholds for spatial variation in any direction in color space about an arbitrary base color is very complex and has yet to be answered. This work is part of the general study.

In tracking the behavior of a printer against process changes, it is useful to examine the quality of printed single separations. Visual thresholds to color variations representative of those caused by mass variations about 30% tints of cyan, magenta, yellow and black have been determined from psychophysical tests. Thresholds were determined in each of 3 common color difference metrics ($\Delta E_{CIE\text{-}Lab}$, $\Delta E_{CMC\ 2:1}$ and $\Delta E_{CIE\text{-}94}$) as a function of spatial frequency from 0.02 to 2.0 cycles/mm at normal reading distance of ~40 cm.

The actual ΔE values depend heavily on which metric is used, varying by a factor of two or more. In any of the 3 ΔE's used, there is a broad peak in sensitivity to spatial variation between 0.1 and 0.7 cycles/mm, with perceptibility thresholds in the neighborhood of ΔE~0.2 (twice as high for $\Delta E_{CIE\text{-}Lab}$). The exception is yellow, for which the peak is between 0.05 and 0.2 cycles/mm and the perceptibility threshold is ΔE~1 (again twice as high for $\Delta E_{CIE\text{-}Lab}$). This difference is because a yellow mass variation creates only a chroma variation, whereas for the other colors there is a significant lightness variation.

Introduction

The human visual system is finely tuned to detect patterns in objects. For a printed page, this translates into an ability to discern both the intended information and any other non-uniformities. Thus, an understanding of human sensitivity to spatial variations is important in determining the image quality of a document and setting specifications.

Much work exists in the literature[1-7] about the human response to monochrome variations as a function of spatial frequency, to color variations on a neutral base color and to color differences between solid patches. Although there is considerable scatter among researchers, the results show a peak sensitivity at 2-4 cycles/degree (about 0.3 - 0.6 cycles/mm at a normal reading distance of 40 cm).

There is much less information about color variation, but it is understood that human sensitivity to chromatic variation has a broader peak at a much lower spatial frequency than for lightness variation about the same base color. This peak is at approximately 0.5 cycles/degree (0.1 cycles/mm at 40 cm)[4,5]. If spatial variations exist simultaneously at multiple spatial frequencies, all are important since after the causes of some spatial variations are removed, the other frequency variations will be noticed if they are above their thresholds. Moreover, multiple variations can interact constructively to create an even more visible effect.

For color differences between solid patches, several measures have been developed which attempt to represent perceptually consistent color differences. Those measures in most common use are $\Delta E_{CIE\text{-}Lab}$ (the geometric distance between two points in L*a*b* space), $\Delta E_{CMC\ L:C}$[8] and $\Delta E_{CIE\text{-}94}$[9]. In $\Delta E_{CMC\ L:C}$ different pairs of values for L and C are used to vary the impact of lightness (L) and chroma (C) on the calculated color difference. Color differences are presented here in all 3 units since there is no direct conversion from one to another.

This paper begins to explore the general case of human sensitivity to color spatial variations about an arbitrary base color, focusing on color differences which would be produced by xerographic toner mass variations about 30% halftones of cyan, magenta, yellow and black. Although the colors used are for a specific set of xerographic toners and halftones, the results for human sensitivity to color variation can be applied to any printing technology. Work on the general case is still in progress. Other pieces of the general study have been published elsewhere[10].

Experimental and Analytic Procedure

Test samples were made using a well controlled lithographic proofing process (DuPont WaterProof®) on Image Series LX paper. This is a bright white uncoated paper used in xerographic printers. The base colors were matched to 30% area coverage for single separation prints from a xerographic breadboard. Color variations were matched to small mass variations about those colors. Sinusoidal variation was superimposed on each base color by varying the halftone level using a special dot with many very closely spaced levels around the colors of interest. Each patch contained at least three full cycles. Reference patches of the base and each extremum color were printed and measured. The uncertainty in the measurement of the colors is $\Delta E \sim \pm 0.2$ (except $\Delta E_{CIE\ Lab} \sim \pm 0.4$). The spatial period is the true distance between adjacent maxima.

Each subject was screened with the Ishihara color-blindness plates[11] and verified to have normal color vision before beginning the test. He or she was given directions to read and allowed to ask questions. The final instruction was to hold each sample at their normal reading distance *as established by reading the directions.* He or she was then shown 137 patches, each measuring 1" x 6" and glued to a white card and told to sort them into 3 piles: "no visible variation"; "variation is visible but subtle"; "variation is obvious". All observations were made under fixed fluorescent office lighting in a small room with a near-neutral surround and no windows. The samples were randomized before being shown to each successive subject.

All responses were combined in a Microsoft Excel® spreadsheet. The extremum to base color shift was determined at which 50% of the subjects rated each combination of color and spatial frequency either "visible but subtle" or "obvious". This resulted in 2 thresholds.

Results

Color differences for each threshold were calculated and plotted in terms of $\Delta E_{CIE\text{-}Lab}$, $\Delta E_{CMC\ 2:1}$ and $\Delta E_{CIE\text{-}94}$ versus spatial frequency. Each plot shows thresholds for both "visible but subtle" and "obvious" variations. These color difference metrics give values that differ by up to 1 unit for black, up to 1.5 units for cyan or magenta and up to 2.5 units for yellow. Thus, it is *crucial* that one specify *which* ΔE metric one is using when describing color variations.

The data shown in figure 1 reflect the responses of 7 people. More subjects would give better statistics, but the improvement for each successive subject is already quite small. The visible threshold in $\Delta E_{CIE\text{-}Lab}$ for black is obscured by identical values in $\Delta E_{CIE\text{-}94}$.

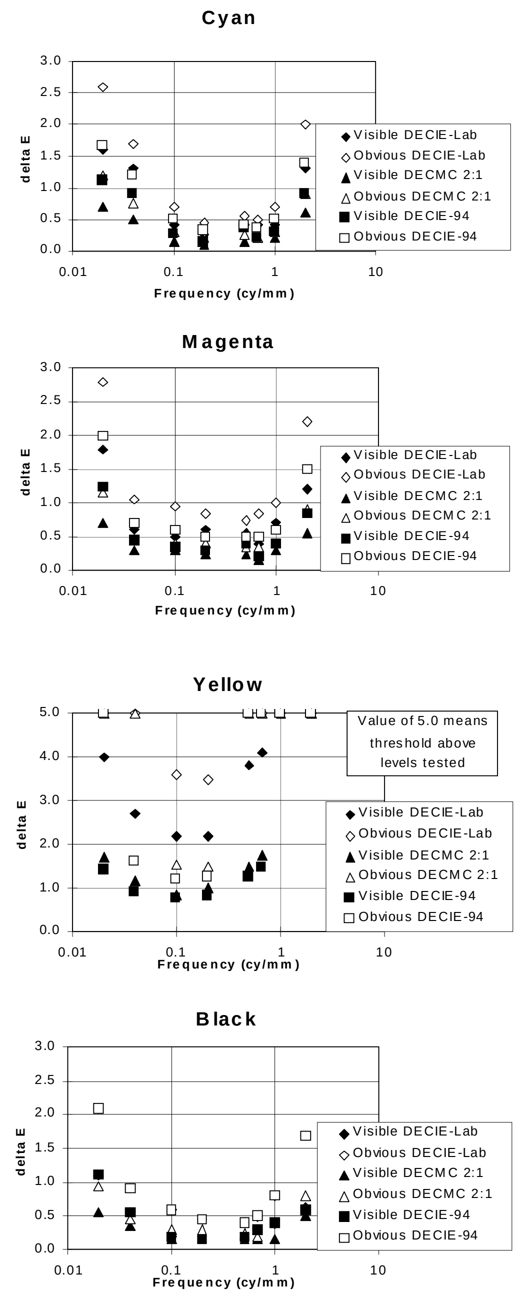

Figure 1: Plots of visual threshold to spatial variation in 30% tints of c, m, y, k as a function of spatial frequency. For black, values in $\Delta E_{CIE\text{-}Lab}$ and $\Delta E_{CIE\text{-}94}$ are the same; only 1 set of points is on the plot. Values are based on 7 observers looking at randomized colored strips with pure tone sinusoidal variations. (The scale is different for yellow.)

The response to yellow variations is qualitatively different from the others. Thresholds are higher (in all ΔE's) and the peak sensitivity is at a lower spatial frequency. Although enormous variation in the *amount* of yellow within a patch was used, in many cases all samples are below threshold. For those cases, an artificial value of $\Delta E=5$

was used in the plots. The different response to variations in yellow is because that color shift is purely in chroma due to the similarity in lightness between a 30% yellow tint and bare paper. The black (gray) variation is purely in lightness. The cyan and magenta variations are approximately equal in lightness and chroma, but the lightness variation dominates the visual response at the spatial frequencies tested.

All responses were given at normal reading distance. For the subjects tested, "normal" reading distance varied from 38 to 45 cm, except for one who is myopic, but with glasses is corrected to normal vision. This spread causes variation in the perceived spatial frequency in cycles/degree, which blurs but does not shift the thresholds. However, it is also representative of how people *view* documents. Moreover, people often *see* documents at an even greater variety of viewing distances and angles.

Guidelines for Specification for High Quality Printers

The data shown above represent thresholds for when a given pure tone sinusoidal color variation becomes visible or obvious. For a high quality color printer, the print quality specification should be *close to the onset of visibility*. Since visibility of spatial variation is such a strong function of spatial frequency, the print quality specification should be spatial frequency dependent. The visibility threshold for spatial variation is extremely low and very difficult to stay below, however the cost of underspecifying this important attribute is large. Product programs must make this trade-off when developing a print quality specification for within page color uniformity.

Figure 2 shows a ***guideline*** for a specification for a high quality color print engine. Each graph contains one curve for each color. The specification guideline is plotted in $\Delta E_{CIE\text{-}Lab}$, $\Delta E_{CMC\ 2:1}$ or $\Delta E_{CIE\text{-}94}$ versus spatial frequency. The specification guideline was obtained from the raw data by first taking a weighted average of the two thresholds. For each color and spatial frequency, a new level of { [1/3] x [(2 x "visible but subtle threshold") + ("obvious threshold")]} was established. The resulting curve was then smoothed slightly.

Then, at each spatial frequency a level was chosen that was the *minimum* of the value at that spatial frequency and at double that spatial frequency to account for people seeing documents from larger distances or at more glancing angles. Either of these acts increases the effective spatial frequency. Accounting for this up to 2x was deemed reasonable. In extreme cases somebody sees an image from across the room, but it was not considered necessary to have a specification cover those cases.

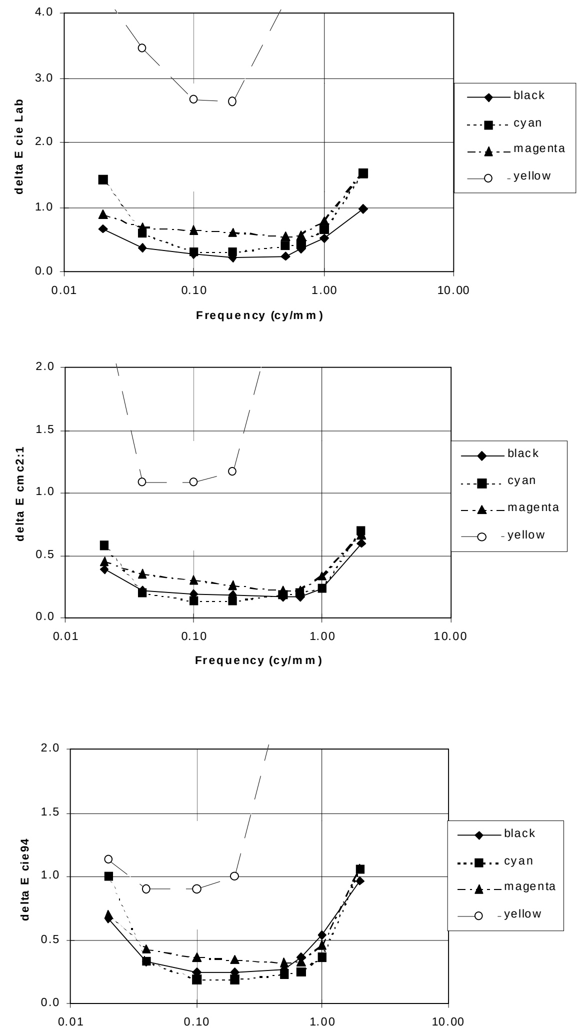

Figure 2: Guidelines for high quality printer specifications for 30% tints of c, m, y, k as a function of spatial frequency. Derived from a smoothed weighted average of visible and obvious thresholds (see text). The scale is different for $\Delta E_{CIE\text{-}Lab}$ than for $\Delta E_{CMC\ 2:1}$ and $\Delta E_{CIE\text{-}94}$.

Discussion and Conclusions

Visual thresholds to "mass" variations about 30% tints of cyan, magenta, yellow and black were determined from psychophysical tests. These thresholds were determined in each of 3 common color difference metrics ($\Delta E_{CIE\text{-}Lab}$, $\Delta E_{CMC\ 2:1}$ and $\Delta E_{CIE\text{-}94}$) as a function of spatial frequency from 0.02 to 2.0 cycles/mm. From these thresholds and with an understanding of how people view documents, a *guideline* for a macrouniformity specification was determined for single frequency variations about single separations using the same common color difference metrics.

The values of ΔE depend on which metric is used, varying by a factor of two or more. In any of the 3 ΔE's used, there is a broad peak in sensitivity to spatial variation between 0.1 and 0.7 cycles/mm, with perceptibility thresholds in the neighborhood of ΔE~0.2 (twice as high for $\Delta E_{CIE\text{-}Lab}$). This is near the limit of our ability to measure color differences. The exception is yellow, for which the peak is between 0.05 and 0.2 cycles/mm and the perceptibility threshold is ΔE~1 (again twice as high for $\Delta E_{CIE\text{-}Lab}$). This difference is because a yellow mass variation creates only chroma variation, whereas for the other colors there is significant lightness variation.

This guideline is for single spatial frequency variations which persist over at least three repeats. It does not cover variations which are either 2 dimensional in nature or that exist as single bands or streaks. Ideally, one would like a specification for color uniformity for arbitrary color variation about an arbitrary base color. Even after that information becomes available, the single frequency single separation acceptability curves will still be useful for tracking subsystem and/or system behavior since it is often easier to identify and solve a problem without the complication of interactions among multiple separations.

As the spatial frequency drops below ~0.1 cycles/mm (period>10 mm), people are more sensitive to chromaticity variations than to lightness variations. Chromaticity variations occur primarily in colors formed from multiple separations. Thus, although a given low frequency spatial variation in cyan alone may not be visible, the resulting spatial variation in the blue achieved by combining this cyan with even a uniform magenta may be quite visible. It is important to write specifications for spatial uniformity of the individual separations so that hue variations caused by having 2 or more separations' variations out of phase with each other are acceptable. This has *not yet* been taken into account in the above guidelines for specifications since it requires determination of perceptibility thresholds for hue variation, but the effect would be to make the specifications more stringent at low spatial frequencies.

The stress case for a digital printer is a large uniform area of a halftoned pale low chroma color. These depend on uniform printing of small dots in each of several colors. Moreover, the human eye is most sensitive to color shifts in that regime. Users are most sensitive to certain types of spatial variation and specifications must be tightest for these. Primary among these are lightness variations in light colors (20–30 % area coverage) at spatial frequencies of 0.1–0.7 cycles/mm.

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Biography

Nancy Goodman received her BA in Astronomy from Bryn Mawr College, and her MS and PhD in Physics from the University of Chicago. After a post-doctorate at the Max Planck Institute in Stuttgart, Germany, she joined Xerox Corporation in 1982, where she is now a Principal Scientist in the Wilson Center for Research and Technology. She has worked on many aspects of xerography, and her current focus is on understanding the causes of image quality degradation and its evaluation.

Author's e-mail: ngoodman@crt.xerox.com