The Legacy of Hans Neugebauer in Color Imaging: A Centennial Remembrance

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Abstract

Two of the most significant contributions of Hans Neugebauer to color imaging are examined, from both a historical perspective, and in light of solving today's problems.

Biographical Data

Hans E J Neugebauer was born in Berlin on 8 May 1905. In 1935 he completed his doctorate at Dresden. His interest in color imaging is evident in his dissertation, *Contributions to the Theory of Multicolor Printing;* the often-cited abstracted version appeared two years later in *Zeitschrift für wissenschaftliche Photographie.* In 1951, he emigrated with his wife and two children to Montreal, Canada, where he held several positions including one at the RCA Victor Research Laboratories. Neugebauer's work on Colorimetric Quality Factor and filter selection was performed while at RCA. In 1958, Neugebauer began a ten year association with Xerox and moved to Rochester, NY. After a retirement in California and a brief return to Germany, he died on 18 August 1987. [1]

During his lifetime, Neugebauer published 60 technical papers. These covered a diverse range of subjects. Of these papers, 36 covered color imaging and color science. Of the remainder, topics discussed included electrophotography, imaging science, and quantum mechanics. [2]

In the remaining two sections, two of Neugebauer's key contributions to color imaging will be discussed, especially in light of how they influenced the work of others. The two areas are the Neugebauer equations and the Colorimetric Quality Factor in color filter selection. There are several very worthy articles not mentioned below because of the desire to focus on material directly related to Neugebauer. The author regrets having left out more investigators than have been included!

The Eponymous Equations

Perhaps Neugebauer's most famous and enduring contribution to color imaging are the equations which bear his name. Like many great ideas, it was relatively simple to explain. In his 1937 paper, he wrote that in multicolor printing "one uses both additive and subtractive color mixing." [3, *author's translation*] The subtractive color mixing was the printing of one ink atop another, to produce eight of what are now termed "Neugebauer Primaries" in three-ink printing (or 2^k, in general, for printing with k inks). The Neugebauer primaries were the the primaries for the additive color mixing, each weighted according to its fractional area of coverage.

The fractional coverage areas of each primary were provided by equations derived by Demichel. [4, 5] These equations assume the form of probabilities of statistically independent events: if events **A** and **B** are statistically independent, then the probability of both **A** and **B** is the product of their individual probabilities. In terms of printing inks, if **A** is true when a particular point is covered with, say, Yellow ink, and event **B** is true when the same point is covered with, say, Magenta ink, then the situation in which both **A** and **B** are true corresponds to the point being covered with both inks. If the halftone patterns obey the assumptions of the Demichel equations, the fraction of points covered by both inks will be the product of their individual fractional coverages.

This statistical analogy has caused some to remark that the Demichel equations assume the halftone patterns are random. Actually, the Demichel equations, and the Neugebauer model which is based upon them, assume that the probability of finding all inks at a given point is the product of their individual coverage fractions. It has been shown that halftone patterns offset by 30 degrees exhibit this behavior. [6]

The tangent of 30 degrees is irrational. The behavior of halftone patterns offset by an angle whose tangent is rational, as is sometimes done with digitally generated halftones, will be slightly different. Moiré rosettes generated using rational tangent screens exhibit greater regularity, [7] though the error of the Demichel equations may still be small.

The Demichel equations will not hold when the halftone patterns are at the same angle. The case where the screens have co-located dot centers (so-called "dot-on-dot" screening) has been studied by Balasubramanian; [8] alternative equations are offered.

Neugebauer's concept of multicolor halftone printing as an essentially additive process whose primaries were formed subtractively was in stark contrast with the notions of Alexander Murray of the Kodak Research Laboratory, who approach color correction from a purely subtractive point of view. [9] Murray's outlook is easily understood, as photographic dyes function subtractively, and it is logical that he would apply (quite successfully) this approach to the problem of photomechanical color reproduction using halftones.

Applications of the Neugebauer Equations

One of the interesting applications Neugebauer investigated for his equations was the determination of printing gamut, anticipating the

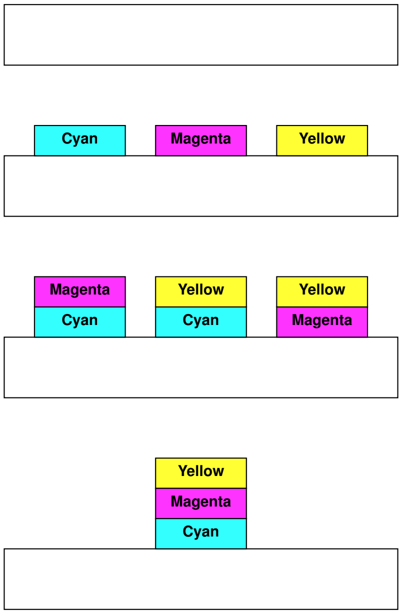

Figure 1: *The Neugebauer Primaries are formed by a subtractive mechanism, as illustrated by these simplified side views of prints.* ***Top:*** *the unprinted paper.* ***Second from top:*** *the Cyan, Magenta, and Yellow inks absorb ("subtract") light that would otherwise be reflected from the unprinted paper.* ***Second from bottom:*** *Cyan, Magenta, and Yellow inks are overprinted, resulting in Blue, Green, and Red, respectively; the top ink absorbs light which would otherwise be reflected from the ink below.* ***Bottom:*** *The Yellow ink is printed atop the Cyan-Magenta overprint, absorbing further light, resulting in the eighth Neugebauer Primary, the three ink "Black."*

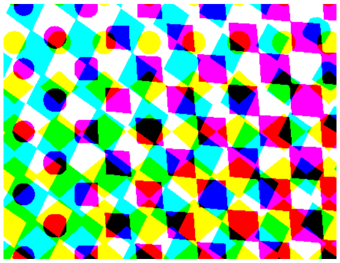

Figure 2: *The eight Neugebauer primaries appear side by side in this magnified view of a simulated print. Each point assumes one and only one of the Neugebauer primaries. When viewed from a distance, the visual system will integrate over the small areas, resulting in the impression of a blending of the primaries.*

work of Pearson, [10] Schläpfer, [11] Mahy, [12] and other researchers, who looked into the same question. In his 1937 paper, Neugebauer lucidly pointed out that one of the consequences of his model was that the chromaticities attainable with a set of 3 process inks were restricted to the hexagon defined by the chromaticities of the single inks and their two-ink overprints. He also described the gamut as a solid in terms of the tristimulus values.

An important application of the Neugebauer equations (and their derivatives) is color management. Hardy, of Massachusetts Institute of Technology, and Wurzburg, of Interchemical Corporation, described an early effort to produce a color separation system based on the Neugebauer equations. [13] This system was quite ahead of its time on a number of fronts; it included electronic dot generation, [14] as well as analog solution of the simultaneous Neugebauer equations. [15] The Radio Corporation of America also had a scanning system research program based on the Neugebauer equations. [16, 17, 18]

Enhancements to the Neugebauer Equations

There have been numerous modifications to the Neugebauer equations suggested over the years. In this section, only a selected subset of these are described.

Yule and Colt [19] suggested that the Yule-Nielsen modification [20] be applied to the wideband Neugebauer equations. This entailed raising all wideband reflectances to the power of $1/n$, the reciprocal of the Yule-Nielsen n-value. This was a suggestion, unsupported by experimental data. In 1966, Pobboravsky compared the accuracy of the Neugebauer equations, the Yule-Nielsen modified Neugebauer equations, and a second-order polynomial in Red, Green, and Blue density for neutral and near-neutral patches, and concluded that the Yule-Nielsen modification "produced no significant increase in agreement [between model predictions and measurements] over the unmodified equations." [21]

Viggiano [22, 6, 23] pointed out that Yule-Nielsen modification tacitly assumes that the spectra of the primaries do not vary in any band to which the modification is applied. This implied that the modification would not perform properly on the wide band measurements used in all published work up to that point. Once the Yule-Nielsen modification was applied to reflectance spectra, rather than tristimulus values or wide band reflectances, the accuracy improved markedly.

Fluorescent inks were ably handled by Emmel and Hersch [24, 25] through the ingenious use of the matrix exponential, permitting inclusion of the absorption and emission characteristics of the inks in a straightforward manner.

Other developments have involved the use of the Clapper-Yule model as an alternative to the Yule-Nielsen correction by several investigators, including Rogers [26] and Hersch, Collaud, Crete, and Emmel, [27] while Gustavson [28, 29] made use of convolution to model the Yule-Nielsen effect.

A refinement with intriguing possibilities and great promise has been advanced by Azuma, Uomoto, Takahashi, and Inui. [30] Their "core-fringe" model relaxes the assumption that each ink is distributed in a binary manner on the substrate; their inventive model admits also an intermediate level of inking. This intermediate level, which produces what they refer to as the "fringe," can account for phenomena such as lateral ink spreading that cause softening of the dot's edges.

Heuberger, Jing, and Persiev [31] suggested what they termed the "Cellular" approach. The continuum of colorant levels is split into two (or more) intervals for each colorant, resulting in a number of subdivisions of colorant space termed "cells." The Neugebauer formulae are applied within each cell after scaling the colorant amounts based on the interval endpoints. Heuberger and his associates found a significant increase in accuracy over that of the unmodified Neugebauer model. Hua and Huang [32] reported a similar increase in accuracy for a celluarized version of the Viggiano model.

The accuracy of some of these modifications has been investigated by Rolleston and Balasubramanian; [33] in contrast with Pobboravsky's conclusion mentioned earlier, they found a significant improvement (mean $\Delta E^*_{ab} = 4.5$ vs. 7.4) when the Yule-Nielsen correction was applied as suggested by Yule and Colt. The accuracy exhibited a further significant improvement (mean $\Delta E^*_{ab} = 2.7$) when the spectral model of Viggiano was applied. Significant improvement was noted when the cellular model of Heuberger, *et al.,* was employed (with 5 knots, mean $\Delta E^*_{ab} = 2.8$); application of the Yule-Nielsen correction to the wide band measurement produced a nearly identical level of accuracy (mean $\Delta E^*_{ab} = 2.6$) with five knots. This was also the level of accuracy attained by the cellular version of the Viggiano model. In other words, the Viggiano model with or without the cellular modification performed significantly better than the other models considered unless they were used in conjunction with the cellular approach.

The enhancements mentioned above have focused on the additive aspect of the Neugebauer equations. The assumption is that the 8, 16, or, in general, 2^k Neugebauer primaries for k-ink printing are measurable. This is not to say that there has not been effort directed at the subtractive aspect of Neugebauer's model, so that, rather than having to measure 2^k primaries, one need only measure the k inks and the paper. There is ample motivation to do this. As the number of inks increases, the number of Neugebauer primaries increases literally exponentially: 8 primaries for 3 inks, 16 primaries for 4 inks, 128 primaries for the 7 ink process espoused by Küppers, [34] Boll, [35] and others. As the number of inks increases, it becomes increasingly intractable to measure all primaries and increasingly desirable to estimate them from, say, the spectra of the unprinted substrate and the spectra of the inks. Researchers including Stollnitz [36] have developed models for prediction of the overprints from measurements of the individual inks. Similarly, van de Capelle and Meireson [37] suggested a method based on prints of solids and tints on paper (to obtain absorption information), on a black background (to obtain scattering information), and on a gray background (to obtain information on trapping).

One important thing all of these investigations have had in common is Neugebauer's notion that color halftone printing is subtractive in the formation of the Neugebauer primaries, and additive (in some sense) in the manner in which these primaries contribute to the overall color produced. The "additivity" may be in a power-law space, or in terms of ink transmittance, but Neugebauer's basic idea that in color halftone printing "... benutzt man sowohl die additive als auch die subtraktive Farbmischung" [3] *(translation appears on the first page, at the beginning of this section)* is the common theme.

Inversion of the Neugebauer Equations

Archer [38] solved a special case of the Neugebauer equations, when the three reflectances were equal. If the tristimulus values are normalized to those of the substrate, Archer's solution provides the neutral locus. Mahy and Delabastita [39] tackled the more complicated general case, and found that as many as six solutions satisfied a given set of conditions, though several were complex and others were physically unrealizable though real. While these techniques are easily extendible to the Yule-Nielsen correction, and Mahy and Delabastita mention local linearization, these direct inversion techniques seem less adaptable to the spectral case.

Accordingly, numerical techniques seem most popular for inversion *in praxis.* Pobboravsky and Pearson [40] describe an approach for the wide band Neugebauer equations with the Yule-Nielsen modification; their approach is reasonable for the spectral extension of Viggiano.

More daunting is the inclusion of a fourth ink. In traditional color management, one is given a color specification as a set of three tristimulus values (or some derivative thereof) and asked to determine the colorant amounts needed to produce that color specification. The color specification takes the form of three equations, but there will be four (in general, the number of inks) unknowns. An additional constraint must be provided to obtain a unique solution. This is often in the form of a black generation algorithm.

Perhaps the most impressive from a historic perspective, however, was the development of analog circuitry to invert the Neugebauer equations for the Interchemical scanner mentioned above. [15] The Cyan, Magenta, and Yellow signals were used to control the duty cycles of three rectangular wave generators having irrationally-related frequencies. By multiplying, for example, the output of the Cyan generator with that of the Magenta generator and the complement of the Yellow generator, a new waveform would be generated whose duty cycle was $c \cdot m \cdot (1-y)$, or the fractional area of the Blue (Cyan-Magenta) overprint. This signal would be replicated three times, once for each of the reflectance channels R, G, and B. One replicate would be modulated by the R reflectance of the Blue overprint, another by the Blue's G reflectance, and the third by the Blue's B reflectance. The R reflectances would be summed up and subtracted from the R reflectance to be printed. Residual signals were also computed for the G and B channels. These were used in a feedback system to modify the Cyan, Magenta, and Yellow levels. Black was computed as the maximum of functions of Cyan, Magenta, and Yellow. [15] This technique is a form of what became known three and a half decades later as "Gray Component Replacement" (GCR). [41]

An Alternative to the Neugebauer Equations

During discussion of a paper at the 1955 TAGA conference, Neugebauer himself declared that the equations that bore his name were "not always an excellent tool for solving the problems of color reproduction." [42] Neugebauer then described a system in which a large number of color patches were printed then scanned, resulting in a lookup table which described not only the printing, but the scanning, as well. This approach was later improved upon by Korman [43, 44], and became known as the "scan the gamut chart" approach. It seems remarkable that Neugebauer himself sowed the seed of what had been for a while a very promising alternative to the eponymous equations.

Filter Colorimetric Quality Factor

Neugebauer's work may be characterized as being both theoretical and practical at the same time. One of his abiding interests was optimal color reproduction through photomechanical means; the equations which bear his name describe our best understanding, at the time, of the press's output. But how to prepare films which would produce the best plates for the press? Neugebauer turned his attention to the question of optimal color filters question in the mid-1950s: [45, 46] Given a number of color filters, which red one, which green one, and which blue one will produce the greatest color fidelity in separations produced from them? Characteristically, Neugebauer arrived at another elegant solution: Select the red filter whose transmission spectrum is best resolvable into a linear combination of the CIE color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$, and do likewise for the green and blue filters. Neugebauer took as his criterion the average of the squared multiple correlation coefficient, R^2, and, in order to simplify the computations, provided an orthonormalized set of color matching functions. This meant that the value of R^2 for each filter could be computed most efficiently, an important consideration at the time considering the computations would need to be carried out using a desk calculator. The calculations were simplest when one made a number of assumptions, the most significant of which was that the illuminant under which the original and reproduction were to be compared had its spectral power distribution defined by the product of sensitivity spectrum of the film and the spectral power distribution under which the separations were to be made.

The Colorimetric Quality Factor as a Departure Point

In more recent years, researchers have faced problems similar enough to use Neugebauer's Q-factor concept as a starting point, but different enough to need a departure. One intriguing case is the question of "Which 4 (or more) filters are optimal?" This was one of the questions tackled by Vora and Trussell at North Carolina State University in the early 90s. [47, 48]

In designing a practical system, its architects must be concerned with not only colorimetric accuracy, but also with sensitivity and noise. There exists a tradeoff among these three factors. A capture system with very wide bandwidth sensors will have greater sensitivity than one with narrower bandwidth sensors, and it will tend to have greater colorimetric accuracy, but as the bandwidth increases the mathematical processing necessary to attain colorimetric accuracy increases the noise. Vrhel and Trussell [49] recognized this, and incorporated the effects of noise in their metric. Sharma and Trussell, [50, 51] also taking noise into account, developed a perceptual figure of merit using a linearized version of the CIELAB color space. Quan, *et al.,* [52, 53] also investigated this tradeoff, and arrived at what they termed the "Unified Measure of Goodness."

There are other reasons why the very practical solution proffered by Neugebauer in 1956 benefits from adjustment to solve today's problems. One prominent among these arises in unconstrained filter set optimization: If no constraints are placed on a computerized optimization process for filter specification of hypothetical filters (in terms of parameters like transition wavelengths and steepness) the optimizer will select the same set of parameters for all three filters, as one set of parameters will be more easily resolvable into a linear combination of the color matching functions than any other.

Another aspect of Neugebauer's formulation of filter set quality is its inability to handle more than three channels. As mentioned earlier, this came to the fore in the late 1980s, when compact photometric equipment and compact embedded computer controllers came together; people wanted colorimeters whose spectral products were more exact replicas of the spectral tristimulus values for a particular illuminant than those obtained from the best three-filter instruments. Colorimetric accuracy can be greatly improved through the addition of additional channels, and the Neugebauer technique was designed for three and only three channels.

Also, it is not necessary to have a set of filters that closely match linear combinations of the color matching functions in order to attain a high degree of colorimetric accuracy. Viggiano and Wang demonstrated that, in theory, high colorimetric accuracy is possible for dye-based imagery if the capture system has extremely narrow bandwidths; [54] this was demonstrated in practice by Shyu. [55] An interesting and potentially useful modification of this work would be to examine whether input, such as color halftone prints, whose spectra require more than the three dimensions used by Viggiano and Wang, could also be analyzed using their approach by retaining more than three eigenvectors. At first blush, this should be possible.

Another aspect of the calculation which should be taken into account is that the integrations are unweighted by the reflectance of an object. Finlayson and Drew [56] have discussed the pitfalls of such calculations: they assume that all reflectances between -1 and +1 are equally likely, not between 0 and +1, as had been initially believed. They demonstrated an increase in accuracy when optimizing for only physically realizable spectra. It seems logical that this type of refinement should be applied to the figure of merit for such an optimization.

However, discussion of these issues must be tempered with knowledge of the problem Neugebauer was attempting to solve: selection of the most "colorimetric" red filter from a small set of possibilities, selection of the most colorimetric green filter from a small set of possibilities, and selection of the most colorimetric blue filter from an even smaller set of possibilities. He indeed solved it admirably; color separation literature which predates his work mentions using a Wratten A (or 25) filter for the Red channel; guidelines which comes after Neugebauer's investigation frequently mention other filters, such as the 23A, which has greater color fidelity. [57]

Concluding Remarks

Certainly, digital photography is responsible for much of the recent interest in the colorimetric quality of color image capture systems. Computers have not killed print; they have caused it to expand and become more distributed in its exercise. Much of the effort which has gone into the scanners and color correction systems and the models and the optimization criteria which have been mentioned here has been aimed at making the color reproduction process more automated, more objective, more robust, more technically rigorous. This author is awed, not only by the way these two works have permeated much of the work in digital color imaging, but also by the notion that people today, not technicians skilled in the art, but, essentially everybody, can take a picture with a digital camera, then print it out to share, expending a minimal amount of bother, not having to worry about "wanted and unwanted absorptions," "proportionality and additivity failure," and other concerns. The consumer photographic paradigm of today is fruit from the seeds sown so long ago by people like Neugebauer. Whenever we avail ourselves of today's popular technology, we pay silent tribute to them.

Acknowledgments

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References

[1] Henry E Neugebauer. Memories of my father. In *SPIE vol. 1184 Neugebauer Memorial Seminar on Color Reproduction*, p. xi – xv. International Society for Optical Engineering, 1989.

[2] John C Urbach. The life and work of H E J Neugebauer. In *SPIE vol. 1184 Neugebauer Memorial Seminar on Color Reproduction*, p. 2 – 6. International Society for Optical Engineering, 1989.

[3] Hans E J Neugebauer. Die theoretischen Grundlagen des Mehrfarbenbuchdrucks. *Zeitschrift für wissenschaftliche Photographie Photophysik und Photochemie*, **36** (4) : 73 – 89, April 1937.

[4] *Procèdè*, **26** (3) : 17 – 21, 1924.

[5] *Procèdè*, **26** (4) : 26 – 27, 1924.

[6] J A Stephen Viggiano. Models for the prediction of color in graphic reproduction technology. MSc thesis, Rochester, NY: Rochester Institute of Technology, 1987.

[7] Paul A Delabastita. Screening techniques, moiré in four color printing. In *TAGA Proceedings*, p. 44 – 67. Technical Association of the Graphic Arts, 1992.

[8] Raja Balasubramanian. Printer model for dot-on-dot halftone screens. In *Proceedings of SPIE Volume 2413 Color Hard Copy and Graphic Arts IV*, p. 356 – 364. International Society for Optical Engineering, 1995.

[9] Alexander Murray. The masking method of color correction applied to three- and four-color reproduction. *Photoengravers Bulletin*, **6** : 13 – 21, 1934.

[10] Milton L Pearson. The use of the color gamut of an ink set in the selection of process inks. In *TAGA Proceedings*, p. 59 – 74. Technical Association of the Graphic Arts, 1964.

[11] Kurt Schläpfer and Erwin Widmer. Which color gamut can be achieved in multicolor printing and in television? In *TAGA Proceedings*, p. 41 – 65. Technical Association of the Graphic Arts, 1993.

[12] Marc Mahy. Calculation of color gamuts based on the Neugebauer model. *Color Research and Application*, **22** (6) : 365 – 374, December 1997.

[13] Arthur C Hardy and F L Wurzburg. Color correction in color printing. *Journal of the Optical Society of America*, **38** (4) : 300 – 307, April 1948.

[14] Arthur C Hardy and F L Wurzburg. A photoelectric method for preparing printing plates. *Journal of the Optical Society of America*, **38** (4) : 295 – 300, April 1948.

[15] Arthur C Hardy and Edward C Dench. An electronic method for solving simultaneous equations. *Journal of the Optical Society of America*, **38** (4) : 308 – 312, April 1948.

[16] John S Odell. All electronic electronic color correction - a progress report. In *TAGA Proceedings*, p. 131 – 137. Technical Association of the Graphic Arts, 1952.

[17] V L Marquart and J S Rydz. The application of the Neugebauer equations to electronic color correction. In *TAGA Proceedings*, p. 15 – 27. Technical Association of the Graphic Arts, 1955.

[18] H E Rose. Adaptation of electronic color correction to the printing process. In *TAGA Proceedings*, p. 28 – 37. Technical Association of the Graphic Arts, 1955.

[19] J A C Yule and R Colt. Colorimetric investigations in multicolor printing. In *TAGA Proceedings*, p. 77 – 82. Technical Association of the Graphic Arts, 1951.

[20] J A C Yule and W J Neilsen [sic]. The penetration of light into paper and its effect on halftone reproduction. In *TAGA Proceedings*, p. 65 – 76. Technical Association of the Graphic Arts, 1951.

[21] Irving Pobboravsky. Methods of computing ink amounts to produce a scale of neutrals for photomechanical reproduction. In *TAGA Proceedings*, p. 10 – 34. Technical Association of the Graphic Arts, 1966.

[22] J A Stephen Viggiano. The color of halftone tints. In *TAGA Proceedings*, p. 647 – 661. Technical Association of the Graphic Arts, 1985.

[23] J A Stephen Viggiano. Modeling the color of multi-color halftones. In *TAGA Proceedings*, p. 44 – 62. Technical Association of the Graphic Arts, 1990.

[24] Patrick Emmel and Roger David Hersch. A "one-channel" spectral colour prediction model for transparent fluorescent inks on a transparent support. In *Proceedings of the Fifth IS&T/SID Color Imaging Conference*, p. 70 – 77. IS&T: the Society for Imaging Science and Technology, 1997.

[25] Patrick Emmel and Roger David Hersch. Spectral colour prediction model for transparent fluorescent ink on paper. In *Proceedings of the Sixth IS&T/SID Color Imaging Conference*, p. 116 – 122. IS&T: the Society for Imaging Science and Technology, 1998.

[26] Geoffrey Rogers. A generalized Clapper-Yule model of halftone reflectance. *Color Research and Application*, **25** (6) : 402 – 407, December 2000.

[27] Roger D Hersch, Fabien Collaud, Frederique Crete, and Patrick Emmel. Spectral prediction and dot surface estimation models for halftone prints. In *SPIE vol. 5293 Color Imaging IX*, p. 356 – 369. International Society for Optical Engineering, 2004.

[28] Stefan Gustavson and Björn Kruse. Evaluation of a light diffusion model for dot gain. In *TAGA Proceedings*, p. 58 – 68. Technical Association of the Graphic Arts, 1996.

[29] Stefan Gustavson. *Dot Gain in Colour Halftones*. PhD dissertation, Linköping, SE: Linköping Institute of Technology, 1999.

[30] Yoshihiko Azuma, Hiromi Uomoto, Shunsuke Takahashi, and Masao Inui. Prediction of color in halftone prints using core-fringe model. In *The First European Conference on Color in Graphics, Imaging, and Vision (CGIV)*, p. 594 – 597. IS&T: the Society for Imaging Science and Technology, April 2002.

[31] Karl J Heuberger, Zhou Mo Jing and Serdar Persiev. Color transformations and lookup tables. In *TAGA/ISCC Proceedings*, p. 863 – 881. Technical Association of the Graphic Arts, 1992.

[32] Ching-Chen Hua and King-Lung Huang. Advanced cellular ynsn printer model. In *Proceedings of the Fifth IS&T/SID Color Imaging Conference*, p. 231 – 234. IS&T: the Society for Imaging Science and Technology, 1997.

[33] Robert Rolleston and Raja Balasubramanian. Accuracy of varios types of Neugebauer model. In *Proceedings of the First IS&T/SID Color Imaging Conference*, p. 32 – 36. IS&T: the Society for Imaging Science and Technology, 1993.

[34] HARALD KUEPPERS. Printing process where each incremental area is divided into a chromatic area and an achromatic area and wherein the achromatic areas are printed in black and white and the chromatic areas are printed in color sub-sections. United States Patent 4812899, 1989.

[35] HAROLD BOLL. Color-to-colorant transformation for a seven ink process. In *SPIE vol. 2170 Device-Independent Color Imaging*, p. 108 – 118. International Society for Optical Engineering, April 1994.

[36] ERIC J STOLLNITZ. *Reproducing Color Images with Custom Inks*. Phd dissertation, Seattle, WA: University of Washington, 1998.

[37] JEAN PIERRE VAN DE CAPELLE AND BALDEWIN MEIRESON. A new method for characterizing output devices and its fit into ICC and hifi color workflows. In *Proceedings of the Fifth IS&T/SID Color Imaging Conference*, p. 66 – 69. IS&T: the Society for Imaging Science and Technology, 1997.

[38] H BRENT ARCHER. An inverse solution of the Neugebauer equations for the calculation of gray balance requirements. In *Advances in Printing Science and Technology: Proceedings of the 16th International Conference of Printing Research Institutes*, p. 154 – 168. International Association of Research Institutes of the Graphic Arts Industry, London: Pentech Press, 1981.

[39] MARC MAHY AND PAUL DELABASTITA. Inversion of the Neugebauer equations. *Color Research and Application*, **21** (6) : 404 – 411, December 1996.

[40] IRVING POBBORAVSKY AND MILTON PEARSON. Computation of dot areas required to match a colorimetrically specified color using the modified Neugebauer equations. In *TAGA Proceedings*, p. 65 – 77. Technical Association of the Graphic Arts, 1972.

[41] FRANZ SIGG AND PATTY COST. On second thought, let's call it GCR. *Technical and Education Center Newsletter*, **12** (6) : 5 – 6, 1984.

[42] H E J NEUGEBAUER. Discussion following presentation by H E Rose. In *TAGA Proceedings*, p. 37. Technical Association of the Graphic Arts, 1955.

[43] N L KORMAN. Operator-machine relationships with the digital computer-scanner for color separation. In *TAGA Proceedings*, p. 323 – 329. Technical Association of the Graphic Arts, 1973.

[44] N L KORMAN. Instrumentation of a digital computer-scanner for color separation. In *TAGA Proceedings*, p. 324 – 333. Technical Association of the Graphic Arts, 1975.

[45] H E J NEUGEBAUER. The colorimetric effect of the selection of printing inks and photographic filters on the quality of multicolor reproductions. In *TAGA Proceedings*, p. 15 – 27. Technical Association of the Graphic Arts, 1956.

[46] H E J NEUGEBAUER. Quality factor for filters whose spectral transmittances are different from color mixture curves, and its application to color photography. *Journal of the Optical Society of America*, **46** (10) : 821 – 824, October 1956.

[47] POORVI L VORA AND H JOEL TRUSSEL. Measures of goodness of a set of color scanning filters. In *SPIE volume 1670: Color Hard Copy and Graphic Arts*, p. 344 – 352. International Society for Optical Engineering, 1992.

[48] POORVI L VORA. *Optimization Criteria and Numerical Analysis in the Design of Color Scanning Filters*. PhD dissertation, North Carolina State University, 1993.

[49] M J VRHEL AND H J TRUSSELL. Optimal color filters in the presence of noise. *IEEE Transactions on Image Processing*, **4** (6) : 814 – 823, June 1995.

[50] GAURAV SHARMA. *Color Scanner Characterization, Performance, Evaluation, and Design*. PhD dissertation, North Carolina State University, 1996.

[51] GAURAV SHARMA AND H JOEL TRUSSELL. Measures of goodness for color scanners. In *Proceedings of the Fourth IS&T/SID Color Imaging Conference*, p. 28 – 32. IS&T: the Society for Imaging Science and Technology, 1996.

[52] SHUXUE QUAN, NOBORU OHTA, ROY S BERNS AND NAYOYA KATOH. Optimal design of camera spectral sensitivity functions based on practical filter components. In *Proceedings of the Ninth IS&T/SID Color Imaging Conference*, p. 326 – 331. IS&T: the Society for Imaging Science and Technology, 2001.

[53] SHUXUE QUAN. *Evaluation and Optimal Design of Spectral Sensitivities for Digital Color Imaging*. PhD dissertation, Rochester, NY: Rochester Institute of Technology, 2002.

[54] J A STEPHEN VIGGIANO AND C JEFFREY WANG. A novel method for colorimetric calibration of color digitizing scanners. In *TAGA Proceedings*, p. 143 – 160. Technical Association of the Graphic Arts, 1993.

[55] MING-CHING JAMES SHYU. Colorimetric characterization of a desktop drum scanner using a spectral model. Master's thesis, Rochester, NY: Rochester Institute of Technology, 1994.

[56] GRAHAM D FINLAYSON AND MARK S DREW. The maximum ignorance assumption with positivity. In *Proceedings of the Sixth IS&T/SID Color Imaging Conference*, p. 202 – 205. IS&T: the Society for Imaging Science and Technology, 1996.

[57] MILES F SOUTHWORTH. *Color Separation Techniques*. North American Publishing, Philadelphia, PA, first edition, 1974.

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Steve holds an AB degree from Thomas Edison College in Mathematics and Natural Sciences, and Master's degrees in Mathematical and Applied Statistics and Printing Technology from RIT. He is a member of IS&T, and has served on the Color Imaging Conference technical committee for several years. Steve is also a member of CIE TC8-02 (Colour Differences in Images, for which he authored the section on statistics) and TC8-03 (Gamut Mapping).