be surprised how some of the illusions really "work": even if you know exactly what the "correct" answer should be, you'll find yourself fooled by most illusions most of the time. I found this program extremely useful to demonstrate various phenomena during my tutorial. It broke the routine for the students, they participated in some of the experiments, and even were able to get surprisingly good results. You should, however, download the patch after you have installed the program from the CD. While I have not encountered the effect of the reported bug in the original version, the author recommends the patch (http://www.oup.co.uk/best.textbooks/psychology/levine/errata/ sensperc.exe).

The "glossdex" — a combination glossary and index — is a nice touch; instead of having to look up a word in the glossary and then in the index, you get the pointer right there and then.

Another "first" for this edition: Jeremy Shefner's interests have changed, and he is no longer a coauthor.

All in all, I recommend this as both a reference and a textbook for any general perception professional or student.

HAIM LEVKOWITZ

Printing Materials: Science and Technology by Bob Thompson, PIRA, 1998. $90, 590 pp.

People interested in printing would presumably benefit from at least a passing acquaintance with the underlying scientific structure of the craft — the physics of light and optics, the chemistry of organic compounds, and the theory of quantum energy. A diligent student with this book could learn more than enough about these subjects to reinvent most of the printing technology and paper making in use today. *Printing Materials: Science and Technology* reviews fundamental principles of printing materials and technologies, and the economic and ecological constraints that have enabled them. In short, it is a fully authoritative reference work. In this field, however, reference works of this depth may rarely be needed. To be sure, the book is not labeled a reference work. It is intended as a textbook for students of printing technology. As such a textbook, it could work well, but only with a good teacher who could help students distinguish the significant details from the inessential. The tone is set with the book's first words: "Whether the chicken came first or the egg, one thing of which we can be certain is that the atom was there before either of them." At a micro level, it is highly readable, from paragraph to paragraph. The author's language, for all its density, is straightforward and to the point. The illustrations are placed nicely, clearly labeled, and support the text well. The chapters are organized so that it is easy to find information. The book is well organized as a whole.

The book starts by reviewing basic applications of scientific concepts to printing, including in its scope topics such as atoms, molecules, organic chemistry, and optics. It then covers in more detail the substrates of printing — paper manufacturing, processing of fibers, paper properties and strengths, adhesion, printing problems, among other things. Basics of inks and coatings are also well covered, including the chemistry and physics of color, as are imaging systems. In short, it is a thorough primer of printing materials, complete with a periodic table of elements.

Unfortunately, some of the critical sections of the book seem outdated. For example, in talking about digital photography, the author states that digital cameras are priced at about 20,000 pounds sterling. Furthermore, sometimes the author's knowledge may get in the way of explaining concepts clearly. When talking about waveforms, the author makes a diversion to talk about the media through which sound waves travel. Why is this necessary in a book in which light is of fundamental interest? Furthermore, despite all its depth about physics and chemistry, there is very little attention paid to perception — the process that defines the effectiveness of printed media. There is no mention of psychophysics, vision, or perception, in the index. There is about a page on color perception. That page talks about the chemical and molecular mechanics of photoreceptors, and leaves it at that. As with much of the rest of the book, the reader is required to put the information in a larger context. A significant proportion of the book is devoted to color considerations in printing. Topics include organic printing technology, measurement of chemistry and physics of color, as well as the measurement of color inks and film.

This would be an excellent book for students or beginning professionals joining the printing or publishing industry, who also want a primer on basic scientific concepts. In particular, for someone who never had to take a science course but needed knowledge on the scientific underpinnings, particularly from the point of view of physics or chemistry, this would be the book to buy. It would provide refresher knowledge for those who have been in the industry some time, as well as introduce some new technologies for those who would like to keep current with how the new advances are implemented. However, the desire of the author to communicate the scientific principles leads him to include sections on physics that most people in the field would already know.

FAITH FLORER

Is There a Perceptual Color Space?

Geometric Representations of Perceptual Phenomena. R. D. Luce, M. D'Zmura, D. Hoffman, G. J. Iverson, A. K. Romney, editors. Earlbaum 1995. 356 pp, $79.95.

". . . a law of inherent opposites,
Of essential unity, is as pleasant as port,
. . . We cannot go back to that.
The squirming facts exceed the squamous mind,"

Wallace Stevens,
Connoisseur of Chaos[1]

The possible geometric representations of perceived colors and perceived space were the issues that most engaged **Tarow Indow**, whose 70th birthday was celebrated by the book under review. Modern science evolved from a scholastic tradition that tried to understand the world in terms of universal harmonies and Pythagorean geometries. Color science too has long attempted to encapsulate the relations between color percepts in low-dimensional geometrical spaces.[2] However, the first color space based on empirical measurements was presented by Maxwell.[3] As is well known, the measurement procedure was color matching in aperture mode, which reduced the infinite-dimensional wavelength space of visible lights to a three-dimensional space of metamers. Maxwellian spaces and their linear transformations have proven invaluable in psychophysical and neurophysiological studies of color vision. However, these spaces predict only which physically distinct mixtures of lights will appear the same when presented in aperture mode, and do not attempt to represent the relations between color percepts.

A landmark relational theory was put forward by Hering,[4] and Schrodinger cast it geometrically into a transformation of metamer space.[5] Hering, as is well known, conceived of three perceptual axes anchored by pairs of opponent-colors: red/green, yellow/blue, and white/black. The genesis of ideas is almost impossible to reconstruct after a century has passed, but I have sometimes wondered whether Hering was using an analogy to the geometry of space. A pair of oppositions, North/South and East/West, work well for describing all directions on maps; and two axes, up/down and right/left, suffice for describing all orientations in the frontal plane. As Runge responded to Goethe: "If we were to think of a bluish orange, a reddish green or a yellowish violet, we would have the same feeling as in the case of a southwesterly northwind."

Since, in some quarters, there still exists a vestigial notion that cortical neurophysiology should correspond to Hering's scheme, orientation in space is an analogy worth pursuing a little further. Despite the sufficiency of one pair of orthogonal axes for representing orientation in the frontal plane, the orientation tuning of neurons in primary visual cortex provides a finer grained sampling of orientations. The preferred orientations of successive neurons in a cortical column can differ by less than 10°, and during visual activity the difference may be further refined by renormalization between adjacent neurons.[6] This diversity of mechanisms presumably underlies the fast and reliable computation of oriented energy over the visual field that is required for a number of visual tasks, for example, the perception of 3D shape from texture cues.[7] In a similar fashion, psychophysical and physiological studies have converged on a picture of the visual cortex as containing a large variety of color-sensitive neurons, each neuron tuned to a different direction in color space. This picture is supported by evidence from a large number of psychophysical tasks including adaptation to prolonged temporal modulation,[8,9] induced color appearance,[10] color search,[11] discrimination of color changes,[12] separation of plaid motion into component motions,[13] and texture segmentation.[14] In addition, there is evidence for rectified color mechanisms subserving detection[15] and induction.[16,17] Electrophysiological evidence supports the existence of two tightly clustered classes of Parvo-neurons in the Lateral Geniculate Nucleus.[18] The preferred color directions of these classes, however, correspond to the cardinal directions[15] and not to Hering's pure hues. The same electrophysiological methods applied to areas V1, V2, and V3 of visual cortex revealed a much larger number of types of cells, each type preferentially tuned to a different color direction.[19–21] Given the above evidence, if there is a low-dimensional perceptual color space, it is unlikely to be based on a low-dimensional neurophysiological rationale.

The construction of a perceptual color space requires the conceptual leap that, not only can all visible lights be specified as points in a 3-D space, but that this is also true for all colors (see **Indow's** article). This assumption is almost certainly untrue for the complete gamut of colors that we perceive in the world. Wittgenstein[22] provided some of the clearest examples that the straightforward rules that seem to apply when names are assigned to isolated colors, break down when colors have to be described in spatio-temporal configurations of lights or surfaces, particularly those configurations that evoke percepts of metals, transparency, or luminosity. There are no metamers between colors perceived (or conceived) as belonging to different classes of physical entities such as substances, surfaces, illuminants, and transparent objects. Without a satisfactory operation of sameness across classes of perceived entities, there is no possibility of embedding all perceived colors into one space, geometric or linguistic.

Indow's article presents a thoughtful summary of his and other's attempts to construct uniform color spaces for lights seen mostly in aperture mode but sometimes with simple surrounds. (**Indow** explicitly excludes only colors attributed to the gloss of the surface.) These attempts have used (i) psychophysics, which does not involve scaling, e.g., just noticeable differences, and points of subjective equality; and (ii) direct scaling measurements that represent some aspect of perception caused by the stimuli. Maxwellian spaces are converted to uniform color spaces on the basis of either (i) a global criterion: whether the space represents the Munsell system without distortion; or (ii) a local criterion: whether JNDs are represented by segments of equal length in all directions and at all points. **Indow's** steadfast and careful work illuminates many complexities in using multidimensional scaling (MDS) methods and should be required reading for researchers investigating similar procedures. It does seem to me that this enterprise needs to be supplemented by investigations of processes and tasks. It seems entirely circular to try to infer from MDS results what observers were doing when they provided the scaling data or perceptual differences, therefore, independent experimental manipulations of strategy may be of use in making such inferences. In addition, scaling tasks usually involve pairs of steady stimuli presented for prolonged periods on uniform backgrounds. It is unlikely that the results would be similar in more spatio-temporally complex situations. For example, discrimination ellipses measured under steady adaptation do not predict ellipses measured in conditions that include transitions[23,24] as would be the case in most naturalistic conditions. In addition, in both **Indow** and **Izmailov's** articles, MDS methods have been restricted to embedding perceived colors in low-dimension Euclidean spaces. This is a strong and probably untenable assumption.

The geometric properties of the neural representation of color should be an issue of general interest, because many questions of complex color perception can be formally translated into geometric terms. **Drosler's** article provides one such direction by considering Helmholtz's line element as a generalization of Weber's Law. The line element is actually one example of what are called Minkowski Geometries.[25] As discussed below, the larger class of such geometries is worth exploring for perceptual color spaces.

In one of the very few direct explorations of geometric operations in color space, Wyszecki and Fielder[26] being the other, **Maloney**, **Wuerger**, and **Krauskopf** used original and clever combinations of proximity measurements to test the Euclidean assumptions underlying MDS. Their results rejected these assumptions, and it would be interesting to supplement their geometrical operations to test whether any Minkowski geometry would be an adequate space for perceived colors. In such geometries, space does not have to be uniform and isotropic. From outside it appears that the unit for measuring length is different in different directions, hence circles and spheres are not round objects but some other convex shape. From inside, distance measurements would adjust to rotation, making it harder to judge the anisotropy. However, some interval measurements can show that the space is non-Enclidean. For example, the ratio of circumference to radius of a circle varies with the plane in the space, and is generally not 2π. A fundamental concordance with color percepts is the lack of a satisfactory concept of "orthogonal." There are shortest distances from a point to a line or plane, but the orthogonal relationship is not symmetric. Therefore, Pythagoras' Theorem does not even exist. Minkowski geometries, like metamer spaces, are "affine" in the sense that their properties are independent of the choice of basis vectors, which is equivalent to being invariant under invertible linear transformations.

The article by **Iverson** and **D'Zmura** is a readable summary of their extensive work on recovery of spectral properties of light and surfaces, given different numbers of photopigments, lights and surfaces. Those readers inspired by this article to read the more detailed original articles, will be rewarded not only by more mathematically complete results, but also by sophisticated examples of matrix manipulations applied to the color domain. Spectral recovery methods are possibly of greatest utility in machine-vision applications requiring analyses of remote materials. Any biological system that extracted infinite-dimensional or even 31-dimensional spectra in the cortex, would either have to be adept at reasoning in high-dimension spaces, or would have to make a neural scheme that converts this information back into a manageable few dimensions.

The article by **D'Zmura**, **Iverson**, and **Singer**, similar to Brainard and Freeman,[27] reformulates the spectral recovery problem in terms of Bayesian decision theory. This approach is akin to bringing into the problem, accumulated knowledge in the guise of prior probabilities of occurrence of lights and surfaces. As is generally true of Bayesian procedures, success depends on appropriateness of priors and of independence assumptions. The article is open to criticisms on both these grounds. Besides collection of more extensive marginal frequency of occurrence data, it would be worth collecting data on joint occurrences of surfaces and illuminants, and applying Lindley's[28] concept of coherence to obtain useful prior conditional probability distributions.

I have tried to point out some of the "squirming facts" that complicate the search for a unified perceptual color space with a small number of opponent axes as basis vectors. For the readers of *Color Research and Application*, this review has been limited to the six articles that discuss color-related issues. If reviews of individual articles appear contentious, it is only because these articles are engaging and thought provoking. I have enjoyed and profited from reading this book, and so will any student of color perception who works through the articles.

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QASIM ZAIDI

Comment on Review of Color and Its Reproduction

The review by Dr. Chris Hawkyard of my book *Color and Its Reproduction,* published in the October 2000 issue, contains some obvious errors and some rather ill-informed comments.

The reviewer incorrectly claims that I do not mention the use of diffraction gratings within spectrophotometers (I do, on p. 97) and that I make no mention of the Pantone color specification system (in fact, most of p. 110 covers this and similar systems).

The reviewer finds it a “surprising omission” that I do not illustrate a cross-screen grid (a crossline screen) or the process by which halftone images are produced from continuous tone negatives. He is apparently unaware that the industry ceased using crossline screens in the 1960s and did not make significant use of continuous tone negatives after the 1970s. Grid-based laser screening from digital data became the preferred method of halftoning during the mid 1970s. This method, which is described on pp. 305–311 of the text, has long been the exclusive method for graphic arts color halftoning.

The reviewer cites two “errors” in the text:

a. No signal from the red sensitive cones (p. 52). The color sensation chosen to explain the color vision mechanism is cyan, which, theoretically, does not reflect any red light to activate the red sensitive cone. The diagram is illustrative of a simplified ideal system and, as such, is not in error.
b. CIE chromaticity chart used to represent ink set gamut with white at the center (p. 135 and cover). In using the diagram in this way, I am simply following the long-established lead of such authorities as David MacAdam.[1] In fact, my diagram is a modified version of one that MacAdam (and Eastman Kodak) used for many years. There is nothing wrong with using this diagram to display the gamut of subtractive colors.

My final remarks concern the reviewer’s bizzare comparison of my book with Dr. R. W. G. Hunt’s *The Reproduction of Colour.* Most reviewers who were familiar with the color reproduction literature would know that if a comparison of my book with another text were to be made, it would be made relative to Dr. J. A. C. Yule’s *Principles of Color Reproduction.* Dr. Yule’s classic 1967 text, which has recently been republished in an updated reprint edition, focuses exclusively upon the graphic arts and related industries.

The astonishing point about the reviewer’s comparison of my book with Dr. Hunt’s text is that he readily acknowledges that I clearly define the fundamentally different scope and audience for *Color and Its Reproduction* in my preface. This fails to stop him from making a detailed comparison of the differences between the two texts. Perhaps this irrelevant comparison would have been avoided if I had titled my book *Color and Its Reproduction for the Graphic Arts,* but the fact that the book is published by the Graphic Arts Technical Foundation (GATF) should provide a clear clue about the book’s emphasis. The first edition of the book was published in 1988 and has been one of GATF’s best sellers. I am not aware of anybody being deceived by the title during these past twelve years.

The reviewers insistence on comparing Dr. Hunt’s book (written mainly for color scientists and engineers) with mine (written mainly for graphic arts practioners) traps him into the further “surprising” observation that the main text does not contain a single mathematical equation. In fact, there are numerous equations throughout the text, but the real point here is that the reviewer’s surprise seems to stem from a belief that the printing industry’s scanners and presses are being operated by scientists and engineers who would make use of a greater emphasis on mathematics. In practice, the industry’s scanners and presses are being operated by designers and craftsmen who would find the equations I have placed in the Appendix to be quite irrelevant to the kind of understanding of the subject that they are seeking from the book.

The reviewer closes his review by candidly admitting his lack of knowledge of the book’s graphics content. It is a pity that he did not learn more about this most important branch of color reproduction before making such confident judgments about the subject.

1. MacAdam, David L. Color difference evaluation. In: Industrial color technology, Gould RF, Editor. Washington, D.C.: American Chemical Society; 1972, p 69–86. (See, in particular, the diagram on p. 71, and the color illustration on the dust jacket—my cover and p. 135 diagrams are adapted from this.)

GARY G. FIELD