Association for PRINT Technologies

Discovering a **New World** of **Color** and Appearance Management Solutions

Introduction

While current color management solutions based on ICC Version 4 (ICC V4) are practical for colorimetric management of color, the ICC V4 architecture was not designed to support the data types and data transformations required for the management of color appearance. Managing color appearance is more demanding than colorimetric color management because it entails understanding and processing data about:

1) spectral properties of near infrared, visible, and ultraviolet light
2) characteristics of the materials that absorb, transmit, refract, diffract and reflect the light
3) geometry of the various light sources and observer viewing conditions involved
4) signal processing functions of the visual system that detect the light inputs to the eyes
5) cognitive processes which synthesize these inputs into perceived color appearance

This study addresses trends, issues, challenges, and opportunities likely to be of importance to APTech vendors and print service providers related to fundamentally new color appearance management solutions based on iccMAX and related standards. An extensive compilation of information resources about iccMAX can be found on the ICC website.[1]

Colorimetric Color vs. Hyperspectral Color & Appearance

Color appearance is a perceived property of the spectral energy (spectrophotometry) and specular attributes (goniometry) of light that enters the eye. New appearance management solutions based on iccMAX will differ from current colorimetric ICC V4 color management solutions in the ways both spectral and specular measurements are employed, as well as in the ways that color profiles are created, and perceptual transformations are carried out. They will also differ from existing proprietary solutions that address various aspects of color appearance management such as the management of fluorescent color or gonio-apparent effects such as pearlescent or metallic appearance.

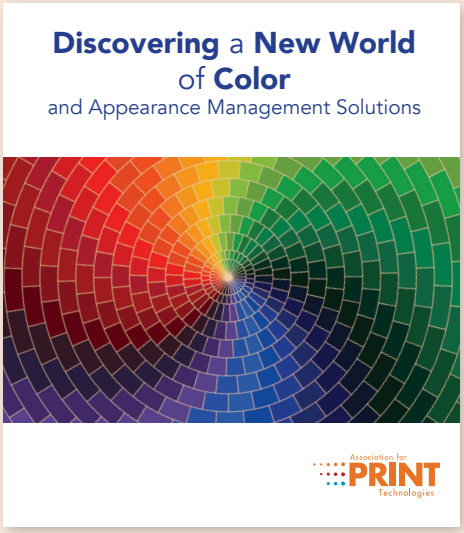
The field of Hyperspectral Imaging, which encompasses both spectral and specular measurement, is expected to undergo dramatic change and growth over the next five years. It is likely that billions of dollars in economic activity other than print-related activity will also depend on the availability of cost-effective hyperspectral sensors and hyperspectral imaging solutions. A recent Zion Market Research report estimates the market for hyperspectral imaging across all industries will be worth $11.34 billion by 2022, growing at a Compound Annual Growth Rate (CAGR) of ~10.9% between 2017 and 2022.

Developments in this expanding field of hyperspectral imaging will have significant implications for graphic arts color measurement device manufacturers and print service providers. Until now, graphic arts color management has relied on a relatively small field of color measurement device manufacturers, but going forward, it is likely that startups or established vendors of spectral and specular measurement devices will test the waters for their devices in the future color appearance management solutions for print.

The Best of Times and the Worst of Times for Color Management

To paraphrase Dickens, this is the best of times and the worst of times for color management. It is the best of times because awareness, knowledge, and adoption of ICC standards-based color management solutions have risen dramatically since the founding of the ICC in 1993. ICC color management is now commonly used across most CMYK supply chains and color management is a commonly used term. According to the 2015 PRIMIR study "Wide Format Inkjet Printing Trends & Opportunities" nearly half (46%) of respondents indicated that they had a dedicated color-management software package.

The bad news for current ICC color management solutions is that lighting and displays are changing, printing processes are going digital, and color measurement is going hyperspectral. Even human visual cognition may change due to advances in Augmented Reality (AR), Extended Reality (XR), and by means of gene editing therapies that promise to cure color blindness and potentially enhance human color vision. These market and technology factors are likely to limit increased adoption of 4 color printing processes and colorimetric color management solutions that are inherently metameric.



About This Study

The Association for PRINT Technology's market research unit, PRIMIR, commissioned this study by Nima Hunter, Inc. to provide its members with credible baseline metrics and projectable consensus forecasts of vendor product manager opinions, expert opinions, prepress customer opinions and end-user opinions related to the adoption and use of new color and appearance management software and color measurement hardware over the 2017-2022 forecast period. The scope is limited to markets in the U.S. commercial, in-plant, packaging, and wide-format inkjet for color management solutions, ICC profiling, and the preparation of prepress files.

Specifically, this study was commissioned to address the following topics:

- Companies focusing on color management solutions
- Color measurement hardware and color management software available
- Who is managing software and hardware system integrations?
- Industry accepted color management best practices
- Changes in color and appearance measurement technology
- Expected roles that iccMAX is likely to play

The study also identified and probed key stakeholders regarding additional color and appearance management technologies, trends, and topics likely to be pertinent to APTech members for potential future research.

1. http://www.color.org/iccmax/index.xalter

Educating the Market about Appearance Management

One of the challenges faced by APTech vendors developing new color appearance management solutions will be to work together to define the category and educate the market about how features of new iccMAX color appearance management solutions differ from proprietary alternatives and ICC V4 color management solutions. APTech vendors will also need to demonstrate why the benefits associated with the new iccMAX solutions category will matter to brand owners, creative professionals, print buyers, print service providers, and consumers.

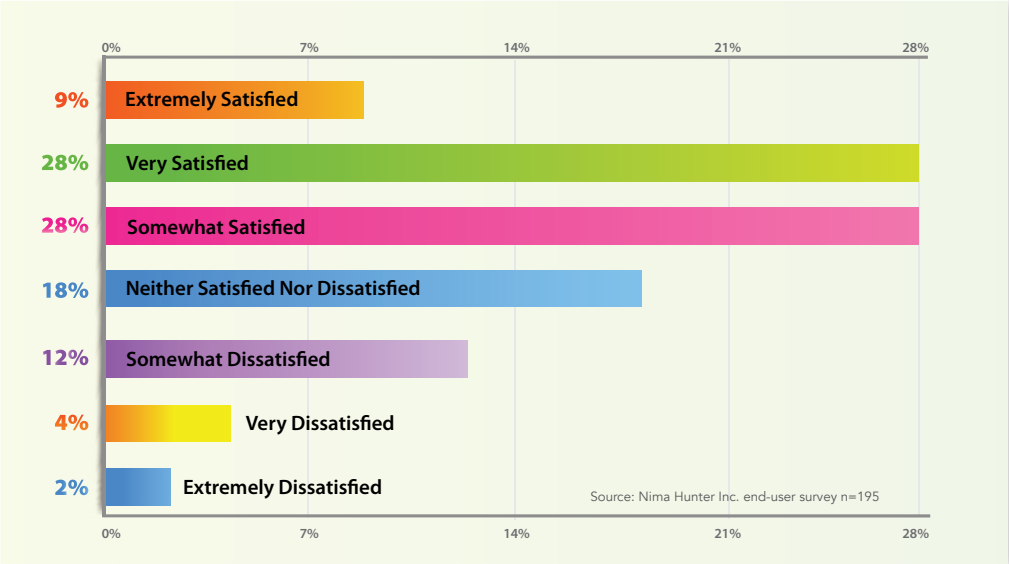
After many years of being oversold, hyped, and harpooned for promising the moon and falling short, color management is now being adopted. ICC V4 color management works and delivers substantial benefits to a growing user base. In part, this is due to user education undertaken by ICC, the vendor community, APTech, and a growing contingent of G7 certified color management consultants.

Over 65% of the respondents to the quantitative survey for this study believe that current color management solutions satisfy some or all of their needs, compared to 18% of respondents who indicated some degree of dissatisfaction. Only 6% of respondents were either very or extremely dissatisfied.

Typically, these conditions would indicate that vendors should double down on what they are doing to increase adoption and satisfaction with the solutions which they currently offer. To the extent there are users printing with CMYK colorants who are satisfied with evaluating color under D50 illumination, there are still significant opportunities to increase market adoption of colorimetric ICC v4 color management. However, changes in the way we light our world are likely to increase levels of dissatisfaction with current color management solutions because they are inherently metameric. Variation in ambient lighting and viewing conditions exacerbates metamerism due to the structural limitations of colorimetric color management. Changes in lighting technology are being driven by policy, cost, and energy efficiency, however, over the next five years, smart solid-state lighting is likely to become the gateway to new "smart" IoT applications and business models for lighting as a service.

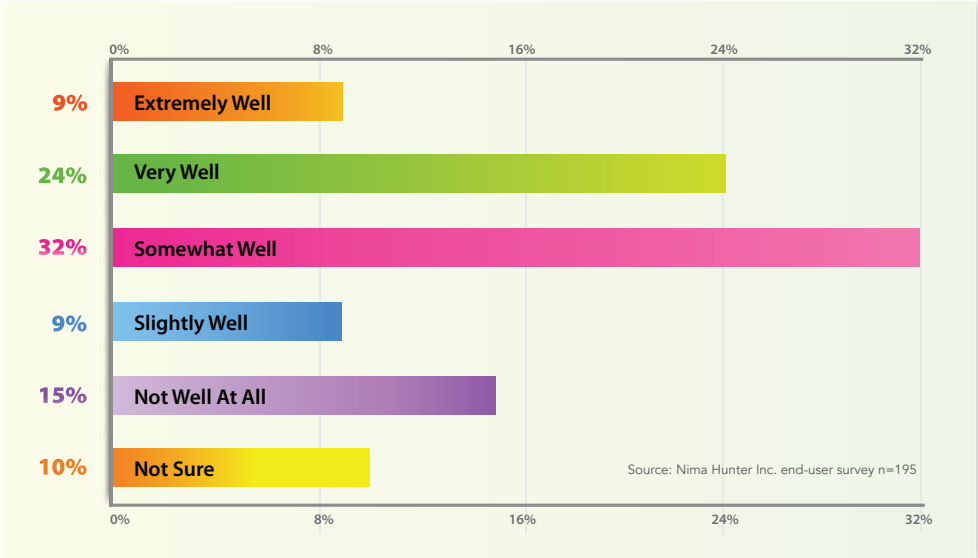
The exponential increase in silicon processing power means that soon every LED light source will also be a communication and computing node, and a growing number of solid-state light sources will be capable of dynamically changing their color. The research conducted for this study indicates that frustration with metamerism is one of the primary factors likely to drive demand for new iccMAX color appearance management solutions going forward. When asked to reflect on how current color management will meet their expectations in three to five years, only 35% of respondents to the end-user survey conducted for this study indicated that they expect current color management solutions to address their needs extremely or very well.

***Figure 1:* Satisfaction with color management solutions today**



***Q.** Overall, how satisfied are you with the color management solutions available to your organization today?*

***Figure 2:* Satisfaction with current color management solutions in 3-5 years**



***Q.** How well do you think the color management solutions currently employed by your organization will meet your needs in 3 to 5 years?*

Two of the primary drivers of dissatisfaction with current standards-based color management solutions identified by a consensus of the experts and end-users interviewed for this study are metameric color matching problems: 1) matching color under different lighting or viewing conditions, and 2) matching the appearance of fluorescent, metallic, pearlescent, gloss, or textural effects. Neither of these challenges can be addressed with approaches to color management based on ICC V4.

Today's color management systems employ colorimetry in combination with a highly constrained set of colorants, lighting, viewing, and observer parameters to manage color. In so doing, their ability to match the color of two objects under varying conditions is inherently limited and subject to metamerism. ICC V4 based color management solutions can be extremely effective as long as one is satisfied with working within its constrained parameters. However, if one's objective is to manage, reduce, or eliminate metamerism outside of those constraints, then solutions that manage color and other aspects of appearance will be necessary.

Metameric Color Appearance

Metamerism is used to describe situations in which the color of two objects match under one set of conditions, but do not match under a different

set of conditions. Appearance consists of the color that we perceive when we see light, as well as other factors that influence our cognitive response to the visual stimulation of the rods and cones in our eyes. The perception of color appearance by the brain is affected by the intensity and spectral characteristics of illumination, the geometry of the lighting and viewing conditions, the spectral absorption attributes of the objects in our visual field, the fluorescence of any of the objects within our field of view, the surface quality of the objects, and what surrounds the objects that reflect, refract, diffract, diffuse, or transmit light to our eyes.
iccMAX was designed to overcome the limitations inherent in the architecture of ICC V4, and serve as the basis for a new generation of open, extensible, standards-based appearance management solutions that can address the four sources of metamerism:

- **Observer metamerism** – which occurs when two objects, which match under a set of conditions for one observer, do not appear to match to another observer under the same set of conditions.
- **Illuminant metamerism** – which occurs when two objects, which match under one set of conditions, no longer match when the illuminant is changed.
- **Geometric (goniometric) metamerism** - which occurs when two objects, which match under one set of illumination, or viewing conditions, no longer match when the geometry of illumination or viewing geometry or both are changed.
- **Instrument metamerism** – which occurs when two objects, which yield the same, specular spectral curve, or color coordinate data with one measurement instrument, yield different, specular, spectral curve, or color coordinate data when measured with another instrument.

Changes in Lighting on the Horizon

The growing adoption of new solid-state lighting can also be expected to increase the need for iccMAX color appearance management solutions. Dramatic changes are underway in the technologies being employed to light our homes, our workplaces, and our brick and mortar retail environments that are increasing the incidence of metamerism. Significant changes are also taking place in the light sources behind the mobile, desktop, and large format out of home displays that e-commerce relies on.

A world formerly lit primarily by daylight, incandescent, and fluorescent light is now being illuminated by a growing number of LEDs and other solid-state lighting solutions with spectra that differ from the D50 illuminant description which current standards-based color management solutions such as ISO 3664:2009 are based on. An important related standard has been developed by the Illuminating Engineering Society of North America (IES). IES TM-30-15 is a new standard for the evaluation and communication of a light source's color rendering properties that addresses flaws and limitations of the widely used Color Rendering Index (CRI) method.

Continuous pressure for energy efficiency savings has been a primary driver of technology advances in solid state lighting and the replacement of incandescent and fluorescent lighting that is not likely to abate. In the U.S. Department of Energy forecast scenario for solid-state general illumination applications prepared by Navigant Consulting in 2016, LED lighting is projected to achieve a market share of 84% of lumen-hour sales in the general illumination market by 2030. Reduced lighting energy consumption in that year alone would be reduced by 40%, for a savings of 261 terawatt-hours of electricity. This would be worth over $26 billion at today's energy prices and would be equivalent to the total energy consumed by nearly 24 million U.S. homes.

Changes in Colorants & Surface Patterning Technology

Another important factor that APTech vendors, print service providers, color management consultants, brand owners, creative professionals and print buyers need to become knowledgeable about are changes in colorant and surface patterning technologies. Special effect colorant innovations are likely to play an increasingly important role in print over the next five years. In addition to changes in the lighting environments where print is viewed, innovations in pigment technologies will challenge the limitations of colorimetric color management. A new generation of colorant technologies are being actively pursued by the automotive industry, as well as by the printing and packaging industries for decorative and security applications. According to a 2017 study conducted by the research firm Markets and Markets, the global special effect pigments market is projected to grow at a CAGR of 5.3% to $969.2 million by 2022.[2] Many of these special "physical effect" structural colorants derive their spectral and specular characteristics from physical optics processes, such as interference, diffraction, and plasmonic resonant light scattering. Two advantages of such physical effect or structural colorants are that they do not fade and that they can be made to show color in any part of the infrared or visible spectral regions with variations in color appearance that can change with lighting or viewing angles in spite of the fact that the pigment material itself may be completely colorless.

Opportunities for Standards-Based "Hyperspectral" Appearance Management Solutions

Even among experts surveyed for this study, awareness and knowledge about game-changing technologies such as chip-scale hyperspectral sensors is low. Also, most of the color management experts and end-users interviewed for this study were unaware of the more than 200 vendors of hyperspectral imaging systems -- including smartphones capable of hyperspectral imaging – that are solving color appearance management challenges in markets beyond the printing industry and that could be used in conjunction with iccMAX solutions.

Opportunities for new standards-based "hyperspectral" color appearance management solutions are arising from a confluence of market and technology factors that challenge the limitations of the current ICC Version 4 color management architecture and the current solutions based on it. Some of these disruptive factors include:

- A growing number of substrates, colorants, coatings, and digital print processes
- Innovations in 2D and 3D design tools, Augmented Reality (AR) and Extended Reality (XR)
- New hyperspectral imaging, color/appearance measurement, and machine vision technology
- Development of the ISO 20677 standard for color management based on iccMAX
- The growing power and ubiquity of smartphones, broadband access, AI, and cloud services
- Innovation and growth in MEMS, plasmonics, solid-state lighting, and quantum dot displays
- Pressure for product consistency and faster time-to-market across global supply chains
- Demand for more effective product security, anti-counterfeiting, and track & trace solutions
- Changing workforce demographics, e-commerce dynamics, and consumer expectations
- Rapidly expanding markets for hyperspectral imaging applications beyond the graphic arts

Opportunities for Developers and Users of Color Appearance Management

This confluence of market and technology forces is creating opportunities for the developers, marketers, and future users of new color appearance management solutions. In particular, opportunities will exist for solutions that overcome the inherent structural limitations of current colorimetric solutions to address the unmet and underserved needs of brand owners, creative professionals, print buyers, and consumers. One of the most commonly cited challenges that brand owners, designers and print buyers face is achieving consistent color appearance for their products, packaging and brand experiences in the growing variety of ambient lighting and viewing conditions in which customers around the world can encounter their zeroth, first, second, and third moments of truth.

For centuries, managing the color of printed matter was predominately a combination of art, craft, and trade secrets until the formation of the International Color Consortium (ICC) in 1993. The goal of the ICC was to create, promote, and encourage the evolution of an open, vendor-neutral, cross-platform, device-independent, color management system architecture and components. Twenty-six years later, the ICC's membership has swelled to over 70 vendors. Many ICC specifications have become ISO standards.

2. https://www.researchandmarkets.com/reports/4300559/special-effect-pigments-market-by-type-metallic

Supporting process certifications programs such as G7 have flourished and solutions for CMYK printing have become mainstream. During that same period, digital imaging and computational technologies have advanced exponentially.

At the time of the ICC's founding, printing was primarily a long-run analog CMYK business viewed under daylight, fluorescent and incandescent light.

The way we light our world is expected to change dramatically over the next five years.

In addition, a growing volume of print is migrating to digital print engines capable of CMYK+ color and appearance embellishments that have primarily been managed with proprietary color management solutions despite limitations they may present to brands with complex supply chains and multiple vendors.

In anticipation of these changing needs over four years ago the ICC initiated the development of an extensible new specification called iccMAX. It was designed to address many of these new requirements for the graphic arts and beyond. New features introduced in iccMAX include spectral profiles and spectral processing, material identification and visualization, characterization of Bidirectional Reflectance Distribution Function (BRDF) and other new data types, as well as an improved gamut boundary descriptor, and support for arbitrary or programmable color transforms. iccMAX was also designed to address a rapidly expanding market for new hyperspectral imaging and gonio-spectral color and appearance management applications outside of the graphic arts.

The importance of investment and developments in the field of hyperspectral imaging extrinsic to the graphic arts industry needs to be emphasized. Hyperspectral imaging makes it possible to identify how well two objects that are a color match under one lighting condition will match under a different condition. A recent Zion Market Research report estimates that the market for Hyperspectral Imaging across all industries will be worth $11.34 billion by 2022, growing at a CAGR of ~10.9% between 2017 and 2022. Every object or material—whether solid, liquid, or gas—reflects or emits electromagnetic energy in a distinctive way that hyperspectral imagers can measure.

Overall Recommendations

Implications and recommendations arising from this research project that is specific to the various APTech stakeholder groups is provided in section 5 of the full report, but there are several recommendations presented here, which are applicable to all APTech members:

1) Educate and inform yourself, current customers, and prospective customers about metamerism, appearance, and the potential benefits of iccMAX appearance management solutions.
2) Conduct marketing outreach efforts to identify potential early adopters and developers of iccMAX appearance management solutions. It is recommended that APTech vendors and print service providers focus efforts to identify early adopters of iccMAX among the ranks of brand owners, creative professionals, and print service provider users of ICC v4 solutions. In particular focus on those who expect increased demand for special effect embellishments and CMYK+ color.
3) Stimulate development of iccMAX appearance management solutions via iccMAX Devcons, hackathons, open innovation initiatives, incubators, and accelerators.
4) Collaborate to develop and disseminate explainer videos, infographics, webinars, podcasts, white papers, case studies, etc. that bring the business, environmental, social, and aesthetic benefits of standards-based iccMAX color appearance management to light.
5) Develop end-to-end iccMAX appearance management solutions. Mainstream adoption of iccMAX will be fostered by the availability of exemplary use cases and a full array of tools for appearance measurement, visualization/proofing, device profiling and calibration, process control & automation, job estimating, job-queue management, costing, and web-to-print.
6) Encourage open-source development and the cross-licensing of enabling intellectual property to discourage patent trolls and foster rapid widespread adoption of affordable iccMAX appearance management solutions.
7) Develop strategies for leveraging the adoption of new hyperspectral sensing, measurement, and imaging solutions exogenous to the graphic arts to reduce time-to-market and R&D costs.
8) Support development of de-jure standards pertaining to printing colorants, light sources, displays, and appearance management hardware and software, as well as new professional certifications for appearance management practitioners.
9) Actively support engagement with product managers, color scientists, engineers, and marketers of hyperspectral imaging solutions to identify opportunities for pre-competitive collaboration on core R&D, shared market research, education, and alignment of standards development efforts.
10) Support development and adoption of primary, secondary, and college level curricula about light, color science, human cognition, metamerism, and color appearance management.
11) Track technology trends and market dynamics for new CMYK+ digital and 3D printing solutions, displays, solid state lighting, lighting measurement, gonio-apparent colorants, hyperspectral sensors, machine vision, and consumer devices with hyperspectral imaging capabilities.
12) Evaluate the projected size and dynamics of high potential markets for applications to target (such as digital textile printing) when determining product development and marketing priorities.
13) Fund and support collective market research and education initiatives (especially among brand owners, designers, and print buyers) that quantify category awareness, knowledge, consideration, and purchase decision factors for standards-based iccMAX color management solutions, which address underserved and unmet needs in packaging, labels, textiles, industrial printing, large format output and other high-value applications of iccMAX that are intrinsic to and extrinsic to printing.