E-paper: Paper-like or Paper Envy?

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Abstract

The term "paper-like" is regularly used to describe the appearance of many emerging reflective technologies. What are the display properties and associated metrics possessed by these purported paper-like devices? Do reflective displays need to be paper-like to be useful? This presentation will review reflective display characteristics meriting consideration, the challenges with their quantification, and the importance of benchmarking against relevant paper examples. We will also examine how this information can be useful for the modeling and simulation of new display concepts.

Introduction

Many reflective displays are described as paper-like. White reflectivities as high as 60% and contrasts from 5:1 to 20:1 are typically quoted for such materials. But what do these numbers really mean? Often the measurement and analysis details associated with these numbers are absent. Consequently, it is virtually impossible to accurately predict the relative appearance of said displays and papers.

Are the display attributes of bright state and contrast alone sufficient to determine whether or not a device is paper-like? Depending upon the targeted application, other visual attributes such as resolution, bit depth (grayscale), color capability, and addressability (segments vs. pixelation) might be equally important. There are also physical attributes to consider, such as thickness, flexibility, durability, and conformability. What qualities would a reflective display need in order to be considered paper-like?

Front-of-Surface (FOS) Metrology Challenges

Several publications from metrology experts aim to educate technologists about the complexities of reflection measurements. Unfortunately, the warnings have gone unheeded by many and ambiguous data continues to be reported.

Kelley et al. have written extensively about the Bidirectional Reflection Distribution Function (BRDF) as a means of classifying and quantifying the reflection properties of flat panel displays [1]. The three basic reflection components—specular, haze, and diffuse (Lambertian)—can be most readily observed by placing a point source proximate to the darkened display surface. Displays may exhibit any or all components, depending upon the technology and the properties of any auxiliary components present such as anti-glare or anti-reflective layers. Like display devices, the BRDF of paper samples can be qualitatively assessed and as complex, depending on the paper stock, surface properties, and colorant present. The haze reflection component has been identified as being particularly problematic to quantify. Papers and displays that are dominated by specular and Lambertian-type reflections are less challenging to characterize.

The fact that both papers and reflective displays might have BRDFs that range from simple to complex gives one pause to consider: is a simple reflective measurement sufficient to assess whether a reflective display truly emulates paper in appearance? If so, what kind of paper does the reflective display resemble? Depending upon the application, printed-paper can be glossy, semi-glossy, matte, or a very diffuse reflector of light.

Instead of comparing simple reflectance numbers, one might compare material BRDFs. The problem with this approach is that interpretation of BRDF differences is not obvious. In addition, the BRDF is rather laborious to obtain and, therefore, would not be considered a pragmatic approach for researchers to adopt. A workable solution might be to report the material BRDF qualitatively, in addition to reflection measurements. This would indicate whether the reported measurements are capable of an accurate description of the reflection phenomena.

There are three measurement geometries that probe the nature of material surface properties [2]. The first, 45/0, consists of illuminating the sample with collimated light at 45° and detecting the reflected light normal to the surface. This estimates diffuse reflection characteristics, but can lead to ambiguous results for samples exhibiting haze. The second and third geometries use diffuse illumination and detection 8° from the sample normal, either including (d/8:i) or excluding (d/8:e) specular reflections. As with 45/0 measurements, d/8:e leads to ambiguous results when haze is present. Only Lambertian materials are invariant to measurement geometry; unfortunately, many materials of interest are otherwise.

Two additional phenomena that result in metrology challenges are fluorescence and angle-dependent viewing. Materials containing fluorescent agents, such as optical brighteners or fluorescent colorants, will give illuminant-dependent "reflectance" spectra because they consist of a combination of an inherent reflection and an emissive component. Cholesteric liquid crystal devices have colors that may change hue substantially as the observer/illuminant geometry is altered. Measurements that integrate reflected light do not account for these.

In order to estimate reflective display appearance from measurements, some knowledge of the viewing condition is necessary. The reflective properties of the display will determine to what level of detail the illumination conditions must be known.

The challenge and complexities associated with reflective display front-of-screen assessment are not limited to metrology issues. Data reduction to yield parameters and performance metrics provide additional opportunities for confusion.

Display Parameters

White Point

The bright state of a reflective display and paper whiteness are important quality attributes. Apart from the metrology challenges, what is the most appropriate way to analyze these data?

The three most common metrics reported are percent reflectivity (%R), luminance factor (Y), and CIE lightness (L*).

While most prevalent, %R is arguably the least useful to report, and those unfamiliar with human perception will visualize the associated appearance incorrectly. For color displays, %R is ambiguous as maximum reflectivity value is not a reliable predictor of relative intensity.

Luminance factor (Y), an estimate of visual intensity compared to an identically illuminated, perfectly diffuse white, is considered an improvement over %R, as it accounts for the influence of the visible spectrum on the perception of intensity. Unfortunately, luminance factor is not a perceptually uniform scale. For example, a mid-tone gray ("half-way" between white and black) would have a luminance factor of about 0.2, not 0.5, as a layperson might expect.

The lightness scale defined by CIE L*, a power function of luminance factor, mitigates this shortcoming. A perfectly diffuse white would have an L* of 100, absolute black an L* of 0, and a gray, intermediate in lightness to the other two, an L* of 50. Unlike the previous metrics, L* differences are uniformly perceived throughout the scale. Figure 1 illustrates how tones evenly spaced in L* are unequally distributed in luminance factor.

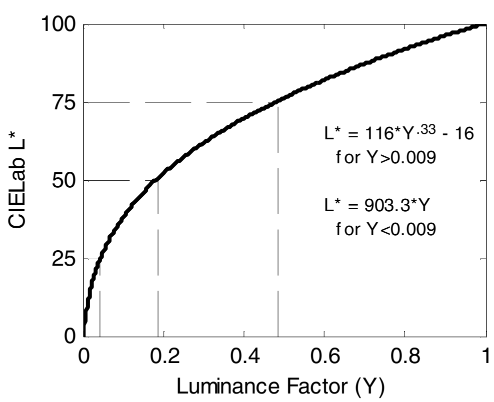

***Figure 1**. CIELab L* as a Function of Luminance Factor*

Table 1 lists the bright states for selected papers and reflective displays. The advantage of quoting L* is clear; one gets a much better perspective of the proximity of display white to a "perfect white." A luminance factor of 50% might be considered to be "half-way there" by some; however, the associated L* value of 76 indicates it is perceptually much closer.

Table 1: Bright States of Papers and Reflective Displays.

Device/ Material	d/8:i		d/8:e		45/0	
	Y	L*	Y	L*	Y	L*
Newsprint	0.61	82	0.61	82	0.58	81
Ad Circular	0.71	87	0.71	87	0.68	86
Glossy Paper	0.88	95	0.78	91	0.60	82
Matte Paper	0.80	92	0.78	91	0.77	90
E-Book	0.43	72	0.37	67	0.38	68
E-Sign	0.26	58	0.22	54	0.19	51

L* computations assume that the materials of interest (and the diffuse white reference used) are being viewed under identical conditions (illuminant intensity, surround, etc.). The exponent value of 1/3 is strictly valid for stimuli surrounded by mid-tone (L* 50) gray field. If this is not so, another power function of luminance factor might be more appropriate to use [2].

Contrast

Like bright state, contrast is a regularly quoted attribute of reflective displays. Unfortunately, the only thing standard about its reporting is that a ratio of X:1 is presented. High contrast is intuitively a desirable property. Unfortunately, that desire has resulted in some rather confusing and convoluted practices aimed a getting "good numbers." As with metrology, details are often scarce as to how the paper and/or display device was measured and how the associated contrast was computed.

The current practices for computing contrast are summarized in Table 2. The subscripts *w* and *k* are used to denote bright state and dark state values, respectively.

Table 2: Current Practices for Computing Contrast

Name	Equation
(Reflection) Contrast	$\%R_w/\%R_k$
(Luminance) Contrast	Y_w/Y_k
Weber Contrast	$(Y_w - Y_k)/Y_k$
Michelson Contrast	$(Y_w - Y_k)/(Y_w + Y_k)$

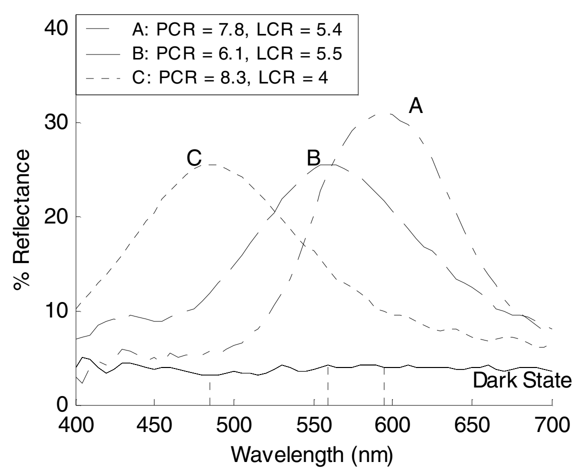

***Figure 2**. Spectral Reflectance of Light and Dark States of Various Devices*

When the term contrast alone is used, it may be based upon a %R measurement or a ratio of bright and dark state luminance factors. Color reflective display researchers often use %R based contrast as an opportunity to produce inflated contrast numbers. For example, it is possible to take the maximum reflectivity of a colored bright state, and the minimum reflectivity value of a colored dark state, to get the highest contrast ratio. It is arguably more appropriate to compute luminance contrast for these situations, despite the fact that much lower contrast numbers might result.

Consider the reflectance spectra of three devices shown in Figure 2. All three devices share the same dark state reflectance, but have very dissimilar bright state spectra. PCR and LCR represent %R and luminance contrast ratios, respectively. While Device A clearly has an advantage over Device B in terms of peak reflectance and PCR, they have equivalent LCR. Comparison of Devices B and C, which have identical peak reflectance, not only illustrates different LCR, but also highlights another "beneficial" aspect of using PCR to inflate numbers: small fluctuations in the spectra of the dark state at the wavelength of interest can boost contrast ratios.

Contrast numbers are also affected by the metrology chosen to compute them. For example, as shown in Table 3, 45/0 reflection measurements that exclude specular and portions of any haze components present yield better (higher) contrast numbers than those associated with d/8 measurements. For this reason, 45/0 LCR is often reported in spite of the fact that d/8:e data might be better correlated to common viewing conditions [2].

Table 3: Luminance Contrast (LCR) of Papers and Reflective Displays. Qualitative appearance of the dark state of each material is parenthetically described with dominant features in uppercase (L = Lambertian, S = Specular, H = Haze)

Device/Material	d/8:i	d/8:e	45/0
Spectralon (L)	57	57	66
Newsprint (hL)	5.7	5.7	6.6
Ad Circular (sHL)	9.1	10	20
Glossy Paper (ShL)	14	45	60
Matte Paper (sHL)	14	18	81
E-Book (sHL)	2.9	4.0	5.8
E-Sign (SHL)	2.0	2.6	3.3
Opal/Glass (Sl)	23	292	1.2e+05

Vision scientists commonly use contrast metrics that relate luminance differences to levels of viewer adaptation [3]. For small stimuli in large uniform fields, Weber contrast is the most relevant metric. The large background predominantly influences the adaptation level.

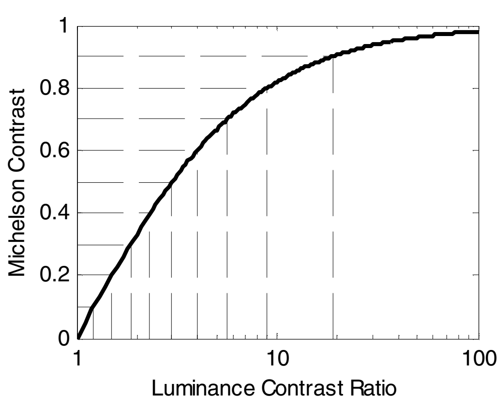

***Figure 3**. Michelson Contrast as a Function of Luminance Contrast Ratio*

Michelson contrast, alternatively called Modulation Contrast, has its origins in signal processing. There are many published papers that argue Michelson contrast is the most relevant metric for textual content, as both stimuli and field contribute to the adaptation level [4]. Performance metrics, based upon tasks sensitive to text legibility and readability, correlate well with Michelson contrast. A Michelson contrast of 0.5 is considered the minimum for text legibility [5]. Note that the first 4/5 of the Michelson scale is encompassed in the first decade of luminance contrast. Much of the remaining fifth is covered by the next decade of luminance contrast. Michelson Contrast is insensitive to LCRs higher that 100:1.

There have been alternative expressions proposed for contrast. The appropriate contrast metric is likely application-dependent. Independent of the metric used, one should be aware that many contrast numbers reported are fundamentally flawed as a result of artifacts present in the raw data. For example, Kelley [6] reports display dark states might be darker than measurements indicate, because of stray light entry into measurement apparatus.

Resolution

While bright state and contrast are predominantly associated with the term paper-like, it is hard to envision applying the descriptor without some consideration of resolution. Reflective displays exist in either segmented or pixilated formats. Unlike whiteness or contrast, resolution is not an inherent paper attribute. It is a system issue, the net result of physical and optical spread of colorants and the properties of the marking engine used.

Emerging reflective display technology appears to be focused on informational applications that require text and glyph rendering. For these applications, one might argue that being paper-like requires consideration of a reflective display's text capabilities.

In this context, are reflective displays that use segments to depict text and numerals paper-like? Many LCD displays use image segments to create numerals and crude characters. Text is very difficult to render with segments, and designing for anticipated segment failures is problematic [7]. Segmented text is confined to fixed sizes, styles, spatial locations, and spacing. These constraints seem rather severe when one considers what is achievable with low-cost home printers and economical paper.

If only pixilated devices can be considered paper-like, then what resolution is sufficient? This is likely to be application specific but also would be expected to be a function of display size, intended viewing distance, and, from a creative standpoint, desired character font.

A commercially available reflective display E-book has a resolution of 170 dpi; approximately double that of CRT computer monitors. This is not surprising given that the E-book is viewed about two times closer than a monitor. Even so, 170 dpi falls short of the 300 dpi and higher resolutions of printed papers. As with CRT monitors, anti-aliasing is used to improve the loss of text quality at low resolution.

For devices that are pixilated, there is the additional issue of pixel aperture or fill factor. The FOS properties of both the active and inactive areas of the pixel contribute to the display appearance [4]. Reporting the reflection properties of only the active area leads to misleading predictions of pixilated display appearance.

Color Gamut and Bit Depth (Grayscale)

Not all reflective displays are capable of color. Given the dominance of black and white printed materials in the world, reflective displays devoid of color should be eligible for the paper-like designation. If an application requires a reflective display to be capable of color, what is the best way to delineate this attribute?

"Full color" is often touted as a desirable feature. What does this term actually mean? The quantification of color gamut or palette is a topic of research in its own right. Color, like bright state and contrast, is an incredible source of confusion. Chromaticity plots are often used to communicate color capabilities of displays but are misleading representations of appearance. These plots lack luminance information needed to fully describe a color stimulus. Two devices might claim the same capability to generate a particular chromaticity coordinate. At low luminance levels an observer would perceive the stimulus as dark and devoid of color. Color created by spectral subtraction from a continuous source results in primary colors that change hue (and hence chromaticity coordinates) as colorant level is modulated (unstable primaries). Therefore, unlike some emissive displays, one cannot represent the achievable chromaticity coordinates using the triangle formed by the three color primaries.

It is also clear from research on color naming that hue alone, loosely associated with chromaticity plots, is insufficient to describe color stimuli perceived by observers [8]. For example, the colors pink, yellow, orange, and brown have relative intensities associated with them, as do the tones black, gray, and white. It follows directly from this that reflective display color capability will be dependent upon the ability to get good bright and dark states. Elevated bright states are required to generate color stimuli an observer would consider pink or yellow, while the colors blue and green are achievable on less capable displays.

Comparatively little is published concerning the bit depth or available gray levels that a reflective display must possess to be considered paper-like. Like resolution, papers in general have no inherent bit depth. The number of distinct levels obtainable is a system property, dependent upon paper, properties of the associated inks or colorants, and the marking engine.

Text on paper is typically one tonal value (black) to attain maximum contrast modulation associated with good legibility and readability. Style changes, such as italics, bold, underscore, size, and font are used to drawn attention or sort information. Thus one might consider paper-like for text-intensive applications to have no bit depth requirements. Grayscale text is intentionally limited to anti-aliasing techniques that improve visual quality compromised by insufficient resolution.

For non-text applications, higher bit depth is advantageous. In a monochrome system, it provides the necessary tonal values to render a pleasing image. Larger luminance ranges will require higher bit depths to a point where additional levels provide little value. For reflective displays having color capability, the palette resulting from one bit per channel would limit applications to simple glyph and icon renderings.

For color devices, bit depth directly relates to the number of different entries in the device color palette. Across most cultures, there are 11 uniquely identified color names [9]; a one-bit display, with three color primaries would be capable of 8 colors (typically black, white, cyan, magenta, yellow, red, green, blue). Therefore, one could hardly call a 1-bit system full color. Yellow, pink, brown, purple, and orange have hue and relative intensity requirements. To achieve them, an appropriate combination of bit depth, color primaries, and contrast would be required.

The definition of full color might lie anywhere on the continuum between a palette that has a single rendition of a color name to a palette comprised of millions of discernable colors. Low bit-depth systems with small color palettes might be suitable for spot color without rigid specification (highlight or representative hue). For complex imagery and rigidly specified spot color (trademark colors), many bits per channel might be required as a function of dynamic range to avoid color contouring and color errors.

Simulation of Display Concepts

It is often useful to preview display appearance prior to actual prototyping and manufacture. Accurate (i.e., not misleading) simulation of reflective devices requires consideration of the surface properties, metrology, and illumination factors previously described. Readily available materials and systems, such as inkjet, thermal, or photographic paper and printers, can be used for generating simulations. Softcopy monitor preview might also be an option. The surface properties of the simulation material (or monitor), in terms of BRDF, should be as close to the device aim as possible and well understood. The dynamic range and color gamut should encompass that of the device specifications. Color calibrations and transforms must be created to relate metrology of the simulation material to its appearance in controlled viewing environments. These viewing environments should have illumination geometries similar to the application space for the proposed device. Despite well-intentioned rigor in creating such controls and calibrations, actual visual verification between simulations and prototypical devices often yields new insights.

By way of example, the data in Tables 3 can be used to select the most appropriate materials for reflective display simulations. The qualitative BRDFs suggest that the matte paper might best emulate the look of the E-book, while the E-sign might prove difficult to emulate with a paper material.

Summary

The term e-paper or paper-like is used rather liberally in publications and press releases. Reflective materials, both displays and paper, pose quite a metrology challenge, and the practice of quoting one or two numbers as a means of communicating expected appearance trivializes these difficulties. When one considers the potential applications of reflective displays, it is clear that other attributes such as resolution, color capability, bit depth, and addressability, should be evaluated before applying the paper-like designation. This overview has not considered physical characteristics such as thickness, flexibility, portability, and durability. What is expected of reflective displays concerning these qualities? They might be as important for applications that are currently well served by conventional printed papers.

Reflective displays need not be paper-like to be useful, but saying that they are, when they are not, might set unobtainable performance expectations and lead to fatal application mismatches.

Some reflective displays might have more in common with their emissive cousins than with paper materials. Front-of-screen characteristics, resolution, and bit-depth constraints seem more "monitor or PDA-like" than paper-like. Further research is needed regarding the specific requirements of applications if reflective displays are to successfully displace printed paper.

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Scott O'Dell received a B.S. in Physics from Rensselaer Polytechnic Institute and is an alumnus of the Imaging Science & Technology Career Development (ISTCD) Program at Eastman Kodak Company. He is currently applying years of experience in imaging science, computer modeling and simulation, and image quality, as a Senior Research Scientist in the Display Science & Technology Group, Kodak Research and Development.