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Tablet Display Technology Shoot-Out

Smartphones and tablets represent a new class of displays with requirements different from that of TVs and monitors. Here is where manufacturers are – and are not – meeting the challenges of ambient light and other considerations.

by Raymond M. Soneira

SMARTPHONES AND TABLETS represent a major product revolution for consumers, but these mobile devices have had an even greater impact on the display industry. Up until recently, most display technology was dedicated to producing large AC-powered TVs and computer monitors that are used almost exclusively indoors under controlled and often subdued ambient lighting. Laptops are the original mobile displays, but they have hefty batteries, often run on AC power, and are also typically used indoors under controlled and subdued ambient lighting.

Enter smartphones and their bigger cousins, the tablets, as the first truly mobile displays. They are essentially handheld screens operating primarily on battery power that are designed for the convenient viewing of content and images virtually anywhere. More importantly, they are often used under relatively high ambient lighting and with screens that are typically oriented anywhere from 45° to entirely horizontal (as when resting on a table). These angles typically catch and reflect substantially more light than the vertically oriented screens of TVs, monitors, and laptops. Because they are carried around everywhere, these devices are also much more vulnerable to breakage, so they almost always come with a hefty cover glass, which further complicates reflections from ambient lighting.

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In addition to being mobile computers that produce high-resolution text and graphics, these devices are also mobile HDTVs and photo viewers. They are expected to deliver excellent picture quality and color accuracy over a wide range of ambient lighting. Their onboard digital cameras and their frequent use for photo sharing among family and friends make picture quality and color accuracy much more important than for HDTVs because the viewers often know what the photo subject matter actually looks like, especially when the photos are viewed on a large tablet screen moments after being taken.

Last, but definitely not least, the displays are used at relatively close viewing distances, typically less than 15 in. Given their small screen sizes and high pixel resolutions, they require very high pixel densities, starting from around 125 up to the latest 450+ pixels per inch (ppi) displays. Compare this to a 50-in. 1920 × 1080 HDTV, which has just 44 ppi. In terms of the more physically relevant area density, pixels per square inch, that is up by a factor of 100:1 – very impressive!

The above represents an incredibly tough and comprehensive set of requirements for any display to deliver. While much has been accomplished in just a few years, there is still much more that needs to be done. In this article, I will use an extensive set of lab tests and measurements on a number of cutting-edge displays and display technologies to see how they are meeting these challenges. I will also suggest areas and paths for improvement in future mobile displays.

Tablet Displays and Display Technologies

The line between smartphones and tablets has become increasingly blurred, which has given rise to an intermediate category called phablets. For this article, I am classifying any mobile display with a 5.5 in. or greater screen diagonal as a tablet. I picked a representative set of high-end displays and display technologies in this size class, with the additional requirement that they had to be tested on a production class device (rather than as a standalone display or prototype). Four tablet displays were tested and analyzed in-depth, plus many others are mentioned where appropriate. Here they are:

OLED Displays and Technology

While most mobile displays are still LCD based, OLEDs have been capturing a rapidly increasing share of the mobile-display market. The technology is still very new, with the Google Nexus One smartphone, launched in January 2010, as the first OLED display product that received widespread notoriety. In a span of just a few years, this new display technology has improved at a very impressive rate, now challenging the performance of the best LCDs. Virtually all of the OLED displays used in current mobile devices are being produced by Samsung Display. Here, I test the Samsung Galaxy Note II, a 5.5-in. 1280 × 720 RGB OLED tablet, which is the largest OLED tablet display currently available. Samsung had previously offered a Galaxy Tab 7.7-in. RGB OLED tablet – so larger screens are likely again in the near future. On the high-

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resolution side, the recently released Galaxy S4 smartphone has a 1920 × 1080 5-in. 441-ppi PenTile OLED display, which will undoubtedly be extrapolated into the next generation of OLED tablets.

LCDs and Technology

LCDs encompass a very broad range of display technologies. While some tablets have launched with lower-performance twisted-nematic (TN) LCDs, most successful tablets now use higher-performance LCDs, often with in plane switching (IPS), fringe field switching (FFS), or plane-to-line switching (PLS).

400+ ppi LCDs: Apple started a major revolution in display marketing by introducing its "Retina Display" in 2010, having 326 ppi on the iPhone 4. While the display is not actually equivalent to the resolution of the human retina, people with 20/20 vision cannot resolve the individual pixels when the Retina Display is held at normal viewing distances of 10.5 in. or more. The introduction of the Retina Display made it clear that displays were no longer commodities but rather an important sales and marketing feature for mobile devices. The iPhone 4 also started a ppi and megapixel war similar to what happened with smartphone digital cameras, which are still experiencing an ongoing wild goose chase heading into the stratosphere. Hopefully, the same sort of competition will not occur with mobile displays.

The real question is how high do we need to go before reaching a practical visual ppi limit? That is a topic that I will analyze in detail in a future article. However, a new generation of 400+ ppi displays is already here, driven by the desire of many manufacturers to produce a full-HD 1920 × 1080 display in a phablet screen size. In 2012, HTC introduced its Butterfly/Droid DNA smartphone with a 1920 × 1080 5.0-in. 440-ppi display manufactured by Sharp that uses continuous grain silicon (CGS) rather than amorphous silicon (a-Si), which becomes increasingly inefficient at high pixel densities. Similarly, LG introduced its Optimus G Pro phablet with a 1920 × 1080 5.5-in. 403-ppi display that uses low-temperature polysilicon (LTPS), which I test here.

7-in. LCDs: The now very popular 7-in. tablet format was pioneered by the Barnes & Noble Nook Color, Amazon Kindle Fire, and Google Nexus 7. The latter two tablets had 1280 × 800 displays in 2012. After dismissing the smaller 7-in. tablets, Apple subsequently introduced its own iPad mini, with a 7.9-in. 1024 × 768 display with a (surprisingly) lower performance and a much smaller color gamut and higher reflectance than both the Nexus 7 and Kindle Fire. The Google Nexus 7 was tested as a representative of the 7-in. tablets.

10-in. High-Resolution LCDs: Apple started the tablet revolution in 2010 with the iPad, a 9.7-in. 1024 × 768 132-ppi display. It had a high-quality IPS/FFS display. Following the revolutionary iPhone 4's 326-ppi Retina Display, Apple introduced a third-generation iPad in 2012 with a 2048 × 1536 264-ppi Retina Display. There have been lots of competing 10-in. tablets, first typically with 1280 × 800 displays and then later with 1920 × 1080 and above displays. The Google Nexus 10 is the iPad's current closest display competitor with a 10.1-in. 2560 × 1600 IPS/FFS display. For the large 10-in. high-resolution tablets, I will test the Apple Retina Display iPad.

Reflective Displays and Technology

A number of reflective tablet display technologies have been under long-term development, including E Ink's electrophoretic displays, Qualcomm's mirasol, Amazon's Liquavista, and Pixel Qi. The only one to reach a significant production stage so far has been E Ink, including its 6–10-in. Pearl monochrome and Triton color displays. Here, I will test E Ink's 8-in. 800 × 600 Triton II color tablet in the High Ambient Light section below.

Display Properties and Display Marketing

The tablets are compared in Table 1, which lists their product specifications and display properties. While this article provides objective technical data and analysis of the displays, it is important to understand that all of these products are configured by marketing requirements designed to get the attention of consumers by appealing to their interests, preferences, and biases, and in some cases to their lack of technical knowledge.

Color Gamut

The color gamut is the range of colors that a display can produce. In some cases, color management is used to adjust the display's native color gamut in order to better match an industry-standard gamut. I am bewildered that the display industry is still widely using as a reference the NTSC color gamut, which was defined in 1953 and has been obsolete for over 30 years. This confusion spills over from display manufacturers, to device manufacturers, to journalists and consumers, who frequently quote and evaluate the color gamut in terms of the totally irrelevant NTSC gamut.

Table 1: Four tablets representing different display technologies are compared in terms of their product specifications and display properties.

Categories	Samsung Galaxy Note II	LG Optimus G Pro	Google Nexus 7	Apple iPad Retina Display
Display Technology	OLED RGB Stripe	LCD IPS LTPS	LCD FFS aSi	LCD IPS/ FFS aSi
Display Manufacturer	Samsung Display	LG Display	Hydis	Multiple
Screen Diagonal (in.)	5.5	5.5	7.0	9.7
Screen Area (sq. in.)	12.9	12.9	22.0	45.2
Screen Aspect Ratio	16:9 = 1.78	16:9 = 1.78	16:10 = 1.60	4:3 = 1.33
Display Resolution	1280 × 720	1920 × 1080	1280 × 800	2048 × 1536
Pixels per Inch (ppi)	267	403	216	264
20/20 Vision Viewing Distance where Pixels are Not Resolved (in.)	12.9	8.5	15.9	13.0

What is the relevant color gamut? Essentially, all current consumer image content is created using the sRGB and ITU-R BT.709 (Rec.709) standards. This encompasses digital cameras, HDTVs, the Internet, and computer content, including virtually all photos and videos. Note that standard consumer content does not include colors outside of the standard sRGB/Rec.709 gamut, so a display with a wider color gamut cannot show colors that are not in the original and only produce inaccurate exaggerated on-screen colors. The color accuracy of the images produced by a tablet will depend on how closely the display reproduces the colors of the sRGB/Rec.709 color space in both hue and saturation.

Table 2 lists and Fig. 1 shows the measured color gamuts for the tested displays together with the sRGB/Rec.709 standard. Note that they are plotted on a CIE 1976 uniform chromaticity diagram [rather than the non-uniform 1931 CIE diagram that is still (surprisingly) being used]. The color gamuts were measured in a perfectly dark lab. In a later section, I

Table 2: Four tablets representing different display technologies are compared in terms of lab measurements in absolute darkness at 0 lux

Categories	Samsung Galaxy Note II	LG Optimus G Pro	Google Nexus 7	Apple iPad Retina Display
Brightness and Contrast				
Maximum Luminance (cd/m^2) Full Screen Peak White	225 (Standard) 216 (Movie)	440	374	421
Peak Luminance (cd/m^2) Small-Window Peak White	289 (Standard) 273 (Movie)	440	374	421
True Black Luminance at Maximum Brightness (cd/m^2)	0	0.43	0.38	0.48
Dynamic Black Luminance at Maximum Brightness (cd/m^2)	0	0.31	0.32	0.48
Contrast Ratio at 0 lux Relevant for Low Ambient Light	Infinite	1027 True 1419 Dynamic	984 True 1169 Dynamic	877 True
Colorimetry and Intensity Scales				
Color Gamut (%) Relative to sRGB / Rec.709	134 (Standard) 106 (Movie)	98	87	99
White Point (K) Correlated Color Temperature	7675 (Standard) 6597 (Movie)	8427	6714	7085
Intensity Scale Gamma	2.58	2.28–2.56	1.95–2.14	2.20
Screen Reflectance				
Average Screen Reflectance (%) Light From All Directions	4.9	7.7	5.9	7.7
Specular Mirror Reflectance (%) Percentage of Light Reflected	6.4	10.1	7.2	9.9
Contrast Rating for High Ambient Light	46–59 (Standard) 44–56 (Movie)	57	63	55
Variation with Vertical Viewing Angle				
White Luminance at 30° Compared to 0° (%)	78	41	44	43
True Black at 30° at Maximum Brightness (cd/m^2)	0	0.31	0.24	0.35
Dynamic Black at 30° at Maximum Brightness (cd/m^2)	0	0.22	0.20	0.35
Contrast Ratio at 30° Relevant for Low Ambient Light	Infinite	582 True 820 Dynamic	686 True 823 Dynamic	526 True

will examine how the color gamut changes with the ambient light level.

LCDs have had a difficult time reproducing the full sRGB/Rec.709 color gamut as a result of spectral light efficiency issues that decrease the luminance and power efficiency of the display when the color saturation is increased. Most mobile LCDs (including the iPad mini and Microsoft Surface RT) until recently delivered only 55–65% of the sRGB/Rec.709 color gamut, but many newer tablets are producing 80–100% of the standard gamut, including the Google Nexus 7, LG Optimus G Pro, and Apple Retina Display iPad tested here, the latter two with close to a perfect 100% gamut (in the dark). Quantum dots, which can efficiently increase the display color gamut, are beginning to appear on LCDs from smartphones up to HDTVs. A large color gamut also provides an important advantage when displays are viewed in high ambient lighting, which I will discuss below.

OLEDs currently have the opposite problem of traditional LCDs, too large a native color gamut, which requires color management in order to deliver accurate sRGB/Rec.709 colors. The resulting color mixtures require more display power and processing power to produce. The Samsung Galaxy Note II has four display modes with different color gamuts and white points – here I test the Standard and Movie modes; the latter provides a closer match to sRGB/Rec.709.

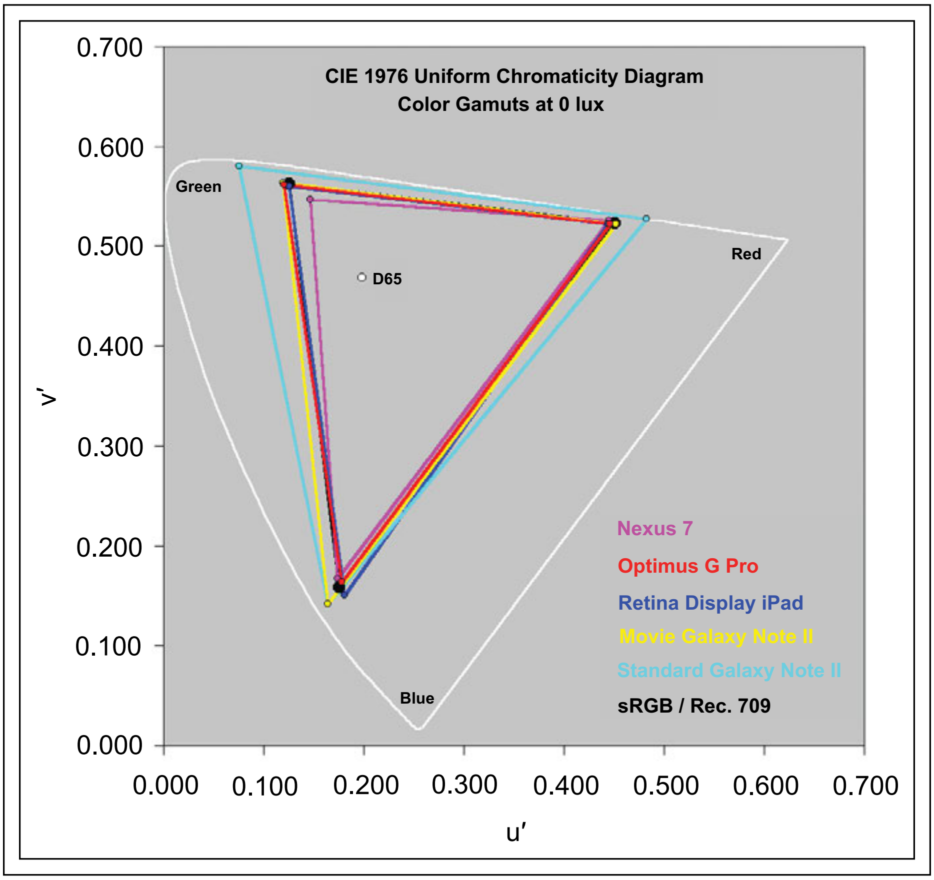

Fig. 1: *The color gamuts of the displays in absolute darkness 0 lux were measured using a spectroradiometer and plotted on a CIE 1976 Uniform Chromaticity Diagram. The outermost white curve represents the limit of human color vision. A given display can only reproduce the colors that lie inside of the triangle formed by its primary colors. The black circles identify the sRGB/Rec.709 Standard Color Gamut. Note that the black lines connecting the black circles are obscured by the individual display gamuts. The Galaxy Note II was measured both in its native Standard Mode and a color managed Movie Mode. D65 is the standard white point.*

Luminance and Intensity Scales

The intensity scale (sometimes called the gray scale) not only controls the image contrast within all displayed images, but also how the red, green, and blue primary colors mix to produce all of the on-screen colors. The steeper the intensity scale, the greater the image contrast and the higher the saturation for displayed color mixtures. So, if the intensity scale does not follow the standard then the colors and intensities will be wrong everywhere.

The intensity scales for many standards, including sRGB/Rec.709, follow a power law with a gamma exponent of 2.2. While many displays get sloppy or creative with their intensity scales, maintaining a power law (a straight line on a log–log graph) is extremely important because that preserves the red, green, and blue luminance ratios, and therefore the hues and saturation values for color mixtures regardless of signal level. Gamma values higher than 2.2 can be used to increase image contrast and color saturation, which is helpful when the color gamut is too small.

Table 2 includes measurements of the peak white luminance, white-point correlated color temperature, black luminance, and contrast ratio (in the dark). Some displays make some of these values variable (often called dynamic) in order to reduce power consumption or for an exaggerated visual effect. For LCDs, a dynamic black is implemented by dimming the backlight for low average picture levels (APLs). For OLEDs, the luminance is typically reduced for high APLs. LCDs are currently significantly brighter and OLEDs have perfect blacks. However, because the LCDs have contrast ratios of around 1000:1, their black luminance decreases proportionally with the screen brightness setting, so their non-perfect blacks will be satisfactory for most content under most ambient-light viewing conditions. Nonetheless, the OLED perfect blacks appear stunning for applications with significant black or dark content at low ambient light levels. In a later section, I will discuss what happens at higher ambient light levels.

Figure 2 shows the intensity scales, which were measured in a perfectly dark lab. The Retina Display iPad has a virtually perfect intensity scale. The Galaxy Note II (both Standard and Movie modes) has a fairly straight but much too steep intensity scale, while the Optimus G Pro and Nexus 7 have somewhat irregular intensity scales. In a later section, I will examine how the intensity scales change with the ambient light level.

Tablets (and smartphones) generally only provide one user adjustable parameter for the display – a brightness control. But differing user preferences and various applications would significantly benefit from providing additional display color and image contrast controls that would allow the user to better customize the display. One interesting technical development is that OLED displays use digital pulse width modulation to produce their intensity scales and the red, green, and blue luminance levels. This makes it possible for them to precisely vary and digitally control the intensity scales, gamma values, white points, color calibration, and management of the display in firmware or software. Many OLEDs, including the Samsung Galaxy Note II tested here, have started to take advantage of this functionality by providing several display modes with different color gamuts and white points. I hope to see this extended in future OLED products. LCDs, on the other hand, are non-linear analog devices, so accurately varying or changing their many calibration parameters is more difficult. It can be done, but requires different hardware configurations and additional factory calibration. However, the functional benefits together with its marketing features and advantages make this worthwhile.

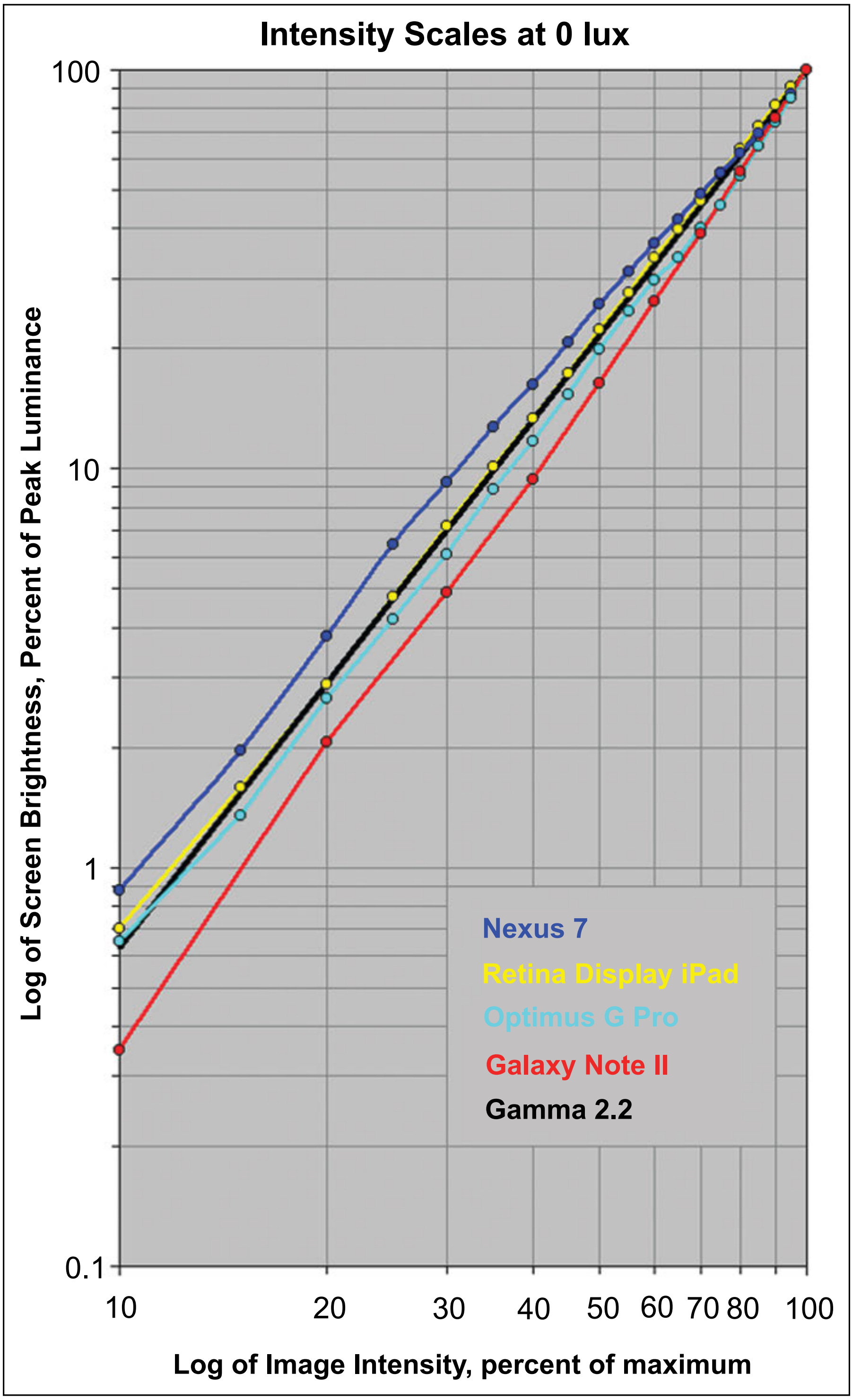

Fig. 2: The measured intensity scales of the displays in absolute darkness 0 lux are plotted as the log of screen brightness versus the log of the signal image intensity. The standard power-law gamma of 2.2 is the straight black line. The Retina Display iPad has a virtually perfect intensity scale; the other displays are either somewhat too steep or too shallow, which affects the image contrast in addition to the hue and saturation of color mixtures.

Viewing-Angle Performance

While tablets are used mostly as single-viewer devices, the variation in display performance with viewing angle is still very important because single viewers frequently hold a display at a variety of vertical viewing angles. When the display is lying on a table, the vertical viewing angle is typically 45° or more.

For LCDs, the typical 176+° advertised viewing-angle specification is misleading because it is defined for the angle where the (0-lux absolute darkness) contrast ratio falls to a miniscule 10, which is typically 1% of the contrast ratio for viewing at 0°. This highly exaggerated specification also makes it close to impossible for any new display technology (including LCD) that offers better viewing-angle performance to convey this to prospective investors, customers, and consumers.

Table 2 lists the variation in peak luminance, black luminance, and contrast ratio for a modest 30° vertical viewing angle. Note that the horizontal viewing-angle performance for multiple side-by-side viewers or for viewing at azimuth angles other than purely horizontal or vertical are often different. LCDs typically show a large 55% decrease in peak luminance at 30°. However, IPS/FFS LCDs show no visible color shifts with viewing angle, typically less than 2 JNCD (Just Noticeable Color Difference) at 30°. On the other hand, OLEDs show a much smaller 20% decrease in luminance, but a somewhat larger (but not objectionable) color shift that is due to anti-reflection and other optical elements.

Screen Reflectance

Virtually all smartphone and tablet screens can function as mirrors good enough to use for personal grooming – but that is a really bad feature, especially for tablets because their larger screens can not only reflect the viewer's face but also a wide range of objects that are behind the viewer. The reflections become obvious if you observe the tablet with the display turned off. When the display is on, those reflections are still there and wash out the image contrast and colors. In bright ambient lighting, the screen may be impossible to read without the user reorienting himself or the tablet. An additional problem with mirror (specular) reflections is that the eye automatically and involuntarily tries to focus on the more distant reflected objects instead of the screen, which is much closer. That continual refocusing can cause eye strain and fatigue.

While some HDTVs, computer monitors, and laptops have an anti-glare matte or haze finish that diffuses specular reflections, virtually all tablets and smartphones have a glossy mirror finish. One reason could be the manufacturing cost, another could be just to continue with traditional glossy cover glass designs, but it might also be that some consumers may shy away from the appearance of the hazy matte finish on such screens. In general, the matte and haze finishes improve overall screen visibility most of the time, but they will sometimes reflect ambient light that would not be seen with a specular mirror surface. I will explore this issue in detail in a future article. I hope that we will soon see more tablets and smartphones with an anti-glare cover glass rather than relying on after-market products that do not perform as well.

Lowering the screen reflectance is extremely important because reducing it by, for example, 10% allows the display to run with 10% less luminance and power at high ambient lighting, while still providing equivalent screen visibility. While lowering the reflectance comes with an additional manufacturing cost, it can produce a significant improvement in screen visibility and battery running time.

Table 2 includes both the specular and average reflectance for the tablets. The specular value was measured by bouncing a narrow highly collimated beam of light off the screen and the average reflectance was measured by placing each tablet inside a large integrating hemisphere and taking measurements through a small opening near the top. The best mobile displays now show average reflectance values of 4.5%, which is a substantial improvement over the 20+% values I measured in 2006. The higher reflectance values for the LG Optimus G Pro and Apple iPad Retina Display result from an air gap between the cover glass and the display. A version of the LG Optimus without the air gap arrived too late to be included in these tests.

Display Performance in Ambient Light

Displays are almost always lab tested in the dark, but they are never used in the dark. In fact, tablets are often used in very bright ambient lighting, which can significantly degrade their image and picture quality. All of the earlier lab measurements were made in the dark, so in this section I repeat the measurements for a number of different ambient light levels to see how the performance changes (degrades).

Table 3: Four tablets representing different display technologies are compared in terms of lab measurements in ambient light

Categories	Samsung Galaxy Note II (Standard Mode)	LG Optimus G Pro	Google Nexus 7	Apple iPad Retina Display
Contrast Rating for High Ambient Light	59	57	63	55
White Level Luminance (cd/m^2) Small-Window Peak White	291 (at 125 lux) 297 (at 500 lux) 320 (at 2000 lux)	443 (at 125 lux) 452 (at 500 lux) 489 (at 2000 lux)	376 (at 125 lux) 383 (at 500 lux) 411 (at 2000 lux)	424 (at 125 lux) 434 (at 500 lux) 472 (at 2000 lux)
Black Level Luminance at Maximum Brightness (cd/m^2) True Black – Not Dynamic	1.9 (at 125 lux) 7.7 (at 500 lux) 30.9 (at 2000 lux)	3.4 (at 125 lux) 12.7 (at 500 lux) 49.2 (at 2000 lux)	2.7 (at 125 lux) 9.6 (at 500 lux) 37.1 (at 2000 lux)	3.7 (at 125 lux) 13.1 (at 500 lux) 51.2 (at 2000 lux)
True Contrast Ratio	153 (at 125 lux) 39 (at 500 lux) 10 (at 2000 lux)	130 (at 125 lux) 36 (at 500 lux) 10 (at 2000 lux)	139 (at 125 lux) 40 (at 500 lux) 11 (at 2000 lux)	115 (at 125 lux) 33 (at 500 lux) 9 (at 2000 lux)
Color Gamut (%) Relative to sRGB / Rec. 709	112 (at 500 lux) 93 (at 1000 lux) 69 (at 2000 lux)	77 (at 500 lux) 61 (at 1000 lux) 42 (at 2000 lux)	67 (at 500 lux) 54 (at 1000 lux) 38 (at 2000 lux)	76 (at 500 lux) 61 (at 1000 lux) 41 (at 2000 lux)

The popular and often quoted contrast ratio is valid only in the dark and relevant only at very low ambient light levels. For higher ambient light levels, I have defined a "Contrast Rating for High Ambient Light" listed in Table 2, which is the ratio of peak white luminance divided by the average screen reflectance in percent. It is effectively a signal-to-noise ratio that provides a visual figure of merit for displays in high ambient light. This simple metric accurately evaluates high-ambient-light display performance and also demonstrates how luminance and reflectance offset each other. Note that smartphones currently perform much better than tablets on this.

To make the high-ambient light measurements, I placed the tablets inside a large integrating hemisphere with a bright light source that produces a uniform isotropic light distribution. A small opening near the top of the hemisphere is used to make the spectroradiometer measurements and screen shots. I can set the illuminance to any value between 0 and 60,000 lux, which is half the value of direct sunlight at noon during the summer months at middle latitudes. I repeated various measurements at 125 lux, which corresponds to dim residential lighting, 500 lux, which corresponds to typical office lighting, 1000 lux, which corresponds to very bright indoor lighting or outdoor lighting with an overcast sky, and 2000 lux, which corresponds to typical outdoor daylight in heavy shade. The screen shots were also done at 20,000 lux, which corresponds to full daylight not in direct sunlight.

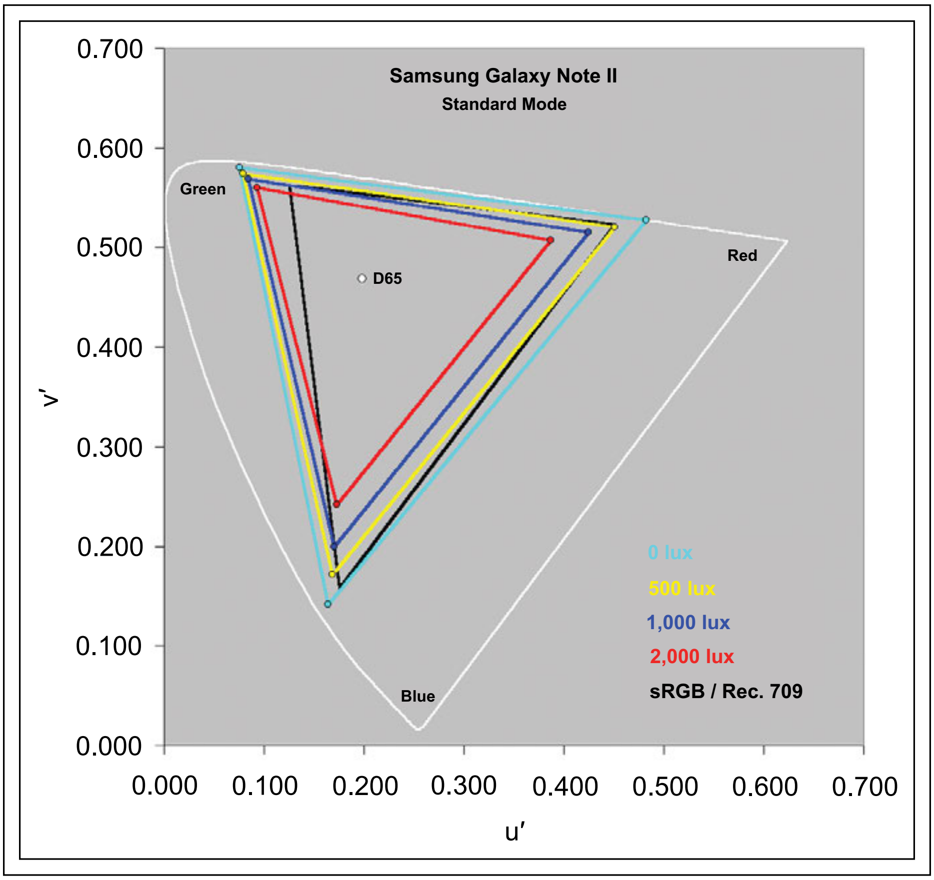

Fig. 3: The measured color gamut of the Samsung Galaxy Note II Standard Mode is shown at various ambient light levels from 0 lux (absolute darkness), 500 lux (typical office lighting), 1000 lux (very bright indoor lighting or outdoor lighting with an overcast sky), and up to 2000 lux (outdoor daylight in heavy shade) plotted on a CIE 1976 Uniform Chromaticity Diagram as in Fig. 1. Note that the color gamut progressively shrinks as the ambient light level increases. This increasingly washes out the image colors.

Table 3 lists the measured luminance, contrast ratio, and color gamut for the tested tablets at the indicated lux levels. Their relative performance closely follows the Contrast Rating for High Ambient Light for the tested tablets, which all (coincidentally for these tablets) have very similar values. Note that the black-level luminance is dominated by reflected ambient light even at 125 lux (but the Galaxy Note II is notably better due to a combination of low reflectance and zero native black luminance). The true contrast ratios fall from roughly 1000 or more at 0 lux, to 150 at 125 lux, to just 10 at 2000 lux.

Display Measurements in Ambient Light

Figure 3 shows the variation in color gamut with ambient light just for the Samsung Galaxy Note II. Since the color gamut decreases monotonically with increasing ambient light, there is a significant advantage to having a native gamut that is much larger than the standard gamut. This is possible for OLEDs and LCDs with quantum dots. At low ambient light levels, color management can be used to progressively reduce the gamut in order to match the standard. With color management connected to an ambient-light sensor, the display would be able to maintain an accurate visual color gamut over a wide range of ambient lighting. We will discuss this further below.

Figure 4 shows the variation in intensity scale with ambient light just for the Apple Retina Display iPad. The intensity scales flatten progressively as the ambient lighting level increases, which reduces image contrast. In order to compensate for the effect of reflected ambient light and improve the perceived visual image contrast, the display's native intensity scale should be dynamically steepened based on the ambient light level measured by the ambient-light sensor so that the composite intensity scale with reflected light still matches the standard intensity scale as far as possible. This will also improve color saturation.

Figure 5 shows screen shots of the displays with a DisplayMate Color Scales test pattern at 0, 2000, and 20,000 lux – the latter corresponds to full outdoor daylight that is not in direct sunlight. At 20,000 lux, the contrast ratios for all four tablets have decreased to roughly 2:1. I have also included the E Ink reflective electrophoretic tablet display mentioned earlier, which maintains color and image contrast independent of ambient light.

While at low ambient light levels, its color saturation and image contrast are less than the other displays; at high ambient light levels, its steady performance eventually matches and then overtakes the other displays.

These are the major trends to follow in the Fig. 5 screen shots as the ambient light levels increase:

- The borders between the photos are at true black. Use them to compare the black levels in the photos. Note the progressive increase in the brightness of what is supposed to be a black background. The tablets with lower average reflectance in Table 2 have the darker backgrounds. The different color tints of the backgrounds indicate differences in the spectra of the light that is being reflected.
- Note the progressive fading and disappearance of the dimmer intensity steps. Because of the differing camera exposure levels, what matters is the number of color and gray steps that can be seen in each photo. The gray scales generally fade differently from the color scales.
- Note the progressive loss of color saturation for the different intensity steps. The tablets with higher color saturation have greater visibility at high ambient light levels.
- The reflective E Ink tablet shows the greatest number of gray-scale steps, and its color saturation is fairly constant with the ambient light level.

Ambient-Light Sensors and Automatic Brightness

Automatic brightness is implemented with an ambient light sensor. Unfortunately, all of the implementations that I have tested are close to functionally useless (and many other reviewers agree), so users frequently turn them off and go back to fixed high manual brightness. It appears that automatic brightness is still primarily a marketing feature that has not yet

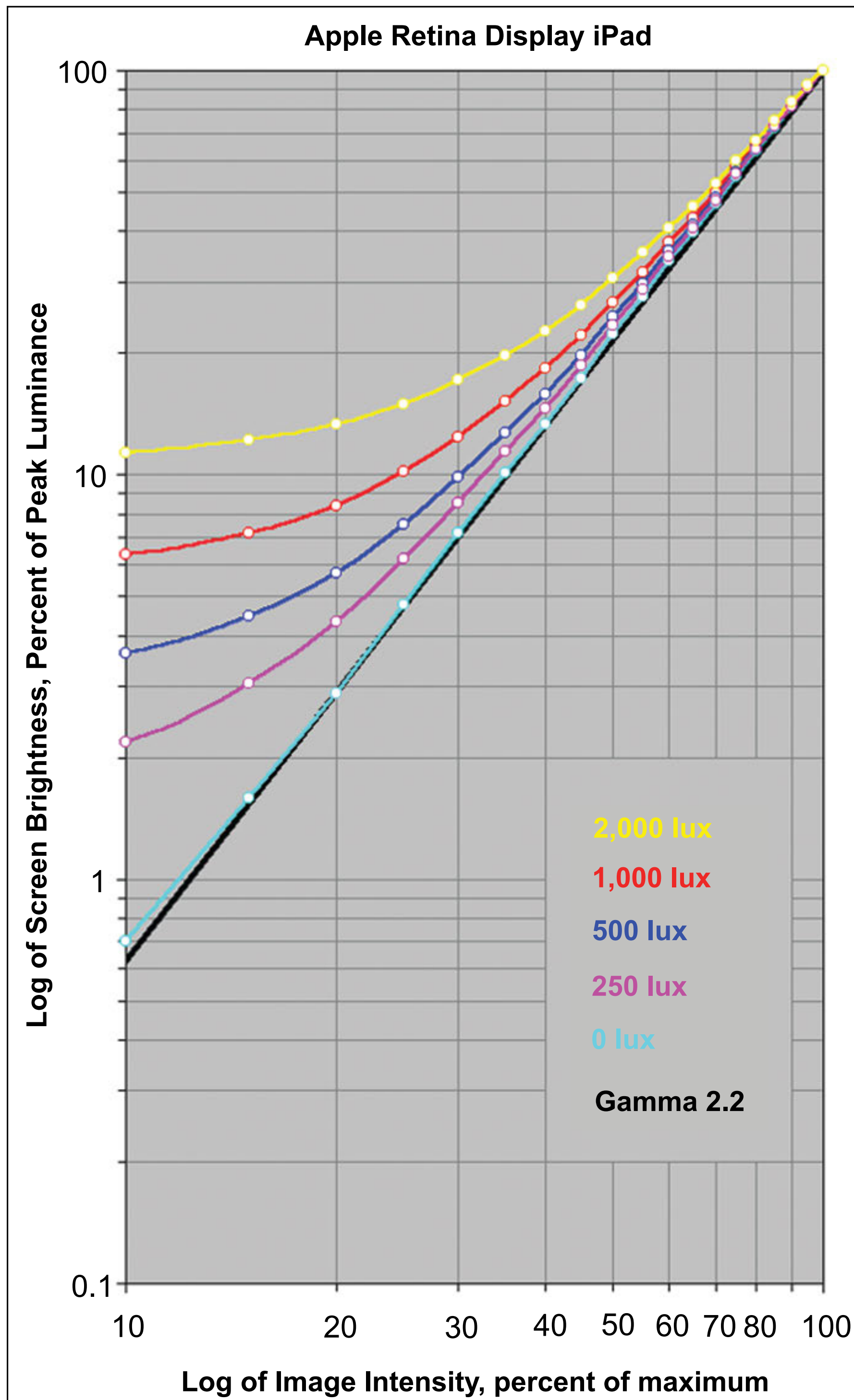

***Fig. 4:** The measured intensity scale for the Apple Retina Display iPad is shown at various ambient light levels from 0 lux (absolute darkness), 250 lux (typical residential lighting), 500 lux (typical office lighting), 1000 lux (very bright indoor lighting or outdoor lighting with an overcast sky), and up to 2000 lux (outdoor daylight in heavy shade) plotted as the log of screen brightness versus the log of the signal image intensity as in Fig. 2. The standard power-law Gamma of 2.2 is the straight black line. Note that the intensity scale progressively flattens as the ambient light level increases. This increasingly washes out the image contrast.*

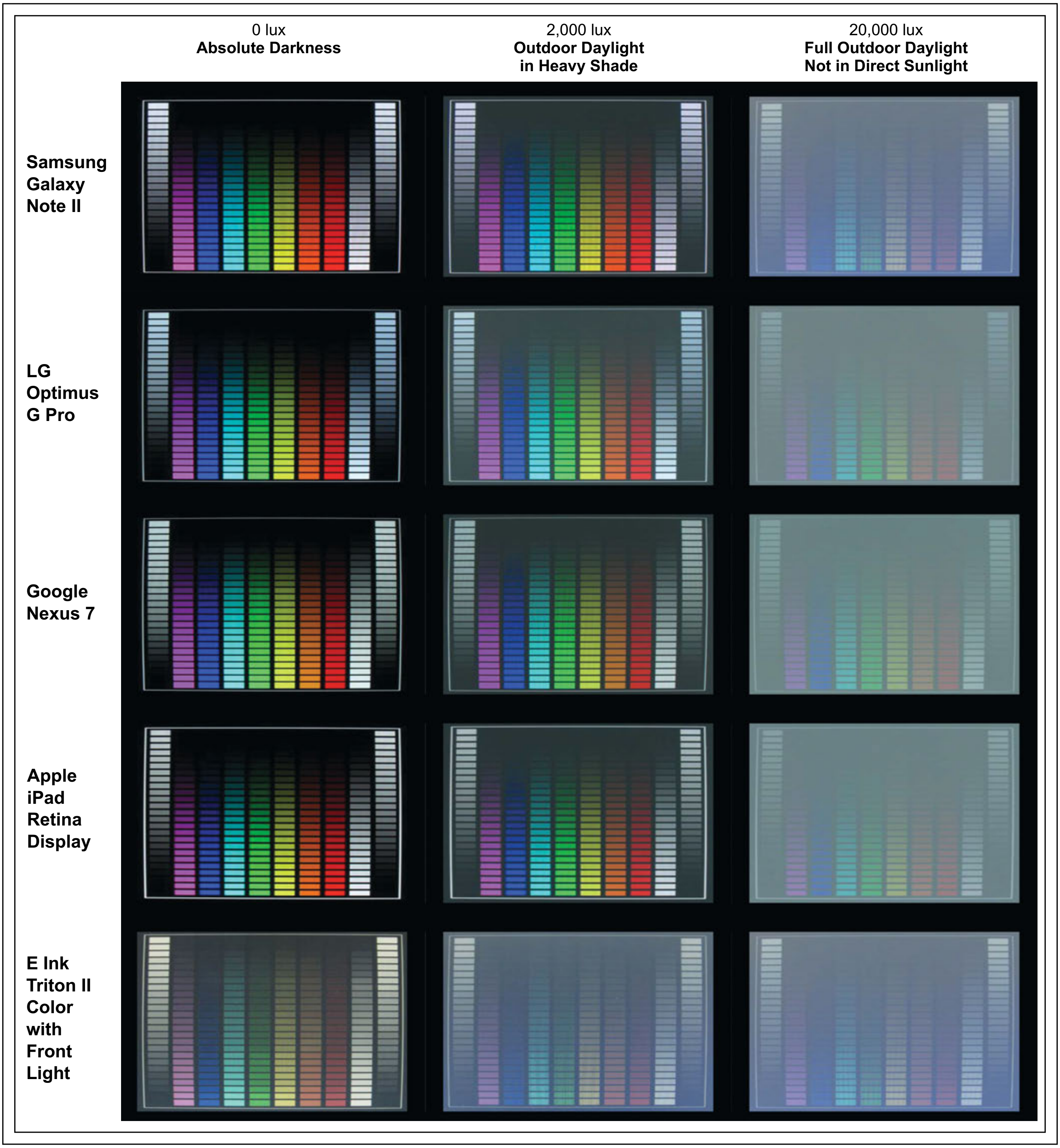

Fig. 5: *Shown are tablet screen shots in high ambient light. Because of the wide range of ambient light levels and screen reflectance values, the screen shots were taken with a camera set for automatic exposure. As a result, the exposure levels vary between the tablets, but that is also the same way that our eyes would process each image. All of the photos were taken at the display's maximum brightness setting.*

received sufficient engineering support and actual lab testing – in most cases the automatic brightness calibration values appear to have been set semi-arbitrarily by a software programmer.

What else is wrong? The ambient-light sensor is generally installed with a narrow acceptance angle and is typically placed near the top center of the display bezel, so it winds up measuring the brightness of the viewer's face instead of the actual ambient light levels that determine the reflected glare and the surrounding light that determines the eye's adaptation level (pupil size). So, more than one sensor is needed. When the brightness changes, the very different time scales and slew rates for increasing and decreasing the screen brightness need to be set appropriately. Furthermore, most Android devices just have a simple check box for automatic brightness, with no way for the user to adjust the brightness based on visual preferences and application. Figure 6 proposes how to properly implement automatic brightness with a user control.

Suggestions for the Next Generation of Tablet Displays

All of these tablets perform better than most HDTVs, computer monitors, and laptop displays from just a few years ago. While a lot has been accomplished, there is still much more that needs to be done. Below, I suggest areas and paths for improvement in the next generation of tablet displays. These suggestions also apply to smartphones, HDTVs, computer monitors, laptops, public signage displays, automobile displays, and just about all existing displays that are used in regular ambient lighting.

Higher Power Efficiency and Pixel Densities: Most current displays use a-Si backplanes, which become increasingly inefficient at high pixel densities. Existing higher-performance LTPS and CGS backplanes are considerably more expensive. The upcoming IGZO technology offers better performance at an intermediate cost. More advanced metal oxides appear to hold an important key to higher-performance and high-pixel-density displays at a lower manufacturing cost.

Lower Screen Reflectance: The best mobile displays currently have an average reflectance of 4.5%. Just lowering the reflectance down to 4.0% is equivalent to a 12.5% increase in luminance (or an 11% decrease in display power) and would also noticeably improve high-ambient-light screen performance. This can be accomplished by eliminating separate touch layers and by using improved anti-reflection optics and coatings.

Versatile and Accurate Color Management and Calibration: Displays that are factory calibrated to produce photos and images with accurate image contrast and color are rare and remain a wish list item that could become a great marketing feature. Users should be allowed to adjust the white point, image contrast, and color saturation of a display according to their personal preferences and application.

Improved Display Performance with Ambient Light: The display system needs to be significantly improved in order to properly and efficiently operate under a wide range of ambient lighting – a major weakness with all existing tablets and smartphones. They need improved ambient-light sensor implementations, properly calibrated automatic brightness together with a user adjustment control, dynamic intensity scales and color management based on the ambient light level, and very different slew rates and time scales for increasing and decreasing the screen brightness.

Most important of all, right now the user interface for all automatic brightness controls is completely backwards – the light sensor

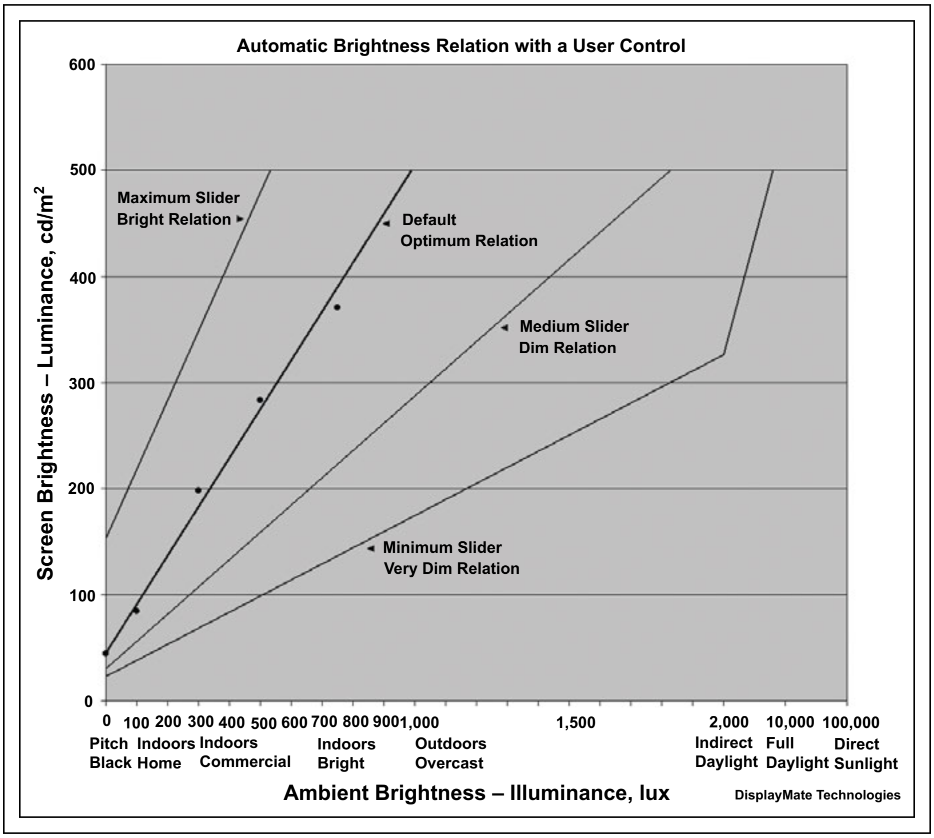

Fig. 6: The test's optimum visual screen brightness settings for different ambient light levels were determined by reading a New York Times *Web page on an iPhone for optimum visual comfort and readability (not too bright or too dim). The luminance and illuminance levels were measured. They are the black data points with their trend line, which is the proposed default brightness versus illuminance relationship. The other lines show a wide range of alternative brightness relationships from aggressively bright to aggressively dim with an ambient light level that should be coupled with an automatic brightness slider to allow the user to choose the relationship they want with ambient light. The graph is linear from 0 to 2000 lux and then jumps in steps to 10,000 and 100,000 lux. The labels from pitch black to direct sunlight roughly identify the lux levels associated with them.*

measures the ambient light and the tablet (or smartphone) sets the screen brightness based on some fixed and poorly designed algorithms. The solution is very simple – do it in the opposite way – the user initially adjusts the screen brightness manually to whatever she wants for the current ambient lighting. The ambient light sensor then measures this light level. The value is recorded and then used to interpolate the screen brightness whenever the ambient lighting changes.

The Next Generation of Mobile Displays

The major necessary developments for upcoming generations of mobile displays will come from improvements in image and picture quality in real-world ambient-light viewing conditions. The key will be improved sensors and algorithms that dynamically change the display's brightness, intensity scale, white point, color gamut, and overall calibration in order to automatically correct or compensate for reflected glare and image washout from ambient light. A significant bonus is that the display can then be used at lower brightness and power settings, which will increase the battery running time. These same issues apply to just about all displays. The companies that succeed in implementing this new strategy will take the lead in the real-world use of display technology.

Acknowledgment

Much of the information in this article is drawn from my extensive *Display Technology Shoot-Out* article series covering tablets and smartphones (and related articles on HDTV and multimedia displays). They are now all available on the www.displaymate.com website. For additional information on any of the topics covered here, refer to the Mobile Display and HDTV Display categories under Display Information for the list of relevant articles provided. ■