…and all the rest you ever needed to know about
display specs and human vision

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The whole story behind display specifications and human vision (1)

Abstract

Nowadays anybody who is interested in information displays, from home flat-panel-TV users to professional broadcast markets, knows the terms "brightness," "luminance" and "contrast" and knows that these should be as high as possible for the display to be any good. Naturally, the same brightness and contrast values are included in typical marketing materials and sometimes a key differentiator between products. In the display industry, of course, we know better, though we are not always willing to admit it. There are many more things that make the display what it is, and many of these depend on the application and the ambient used. This white paper tries to explain some basic terms, concepts and confusion issues frequently encountered in the display world. We will talk in general about displays, encompassing LCDs, plasmas, projection (DLP, polysilicon and LCoS) etc., and specify the display technology only where needed.

Basic display specs and what's behind them

Brightness and luminance

BRIGHTNESS IS NOT LUMINANCE

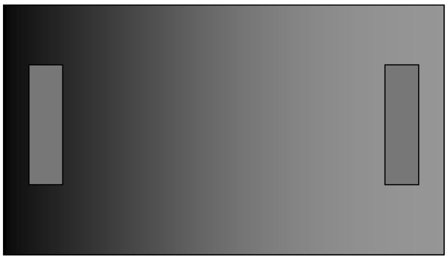

Fig. 1

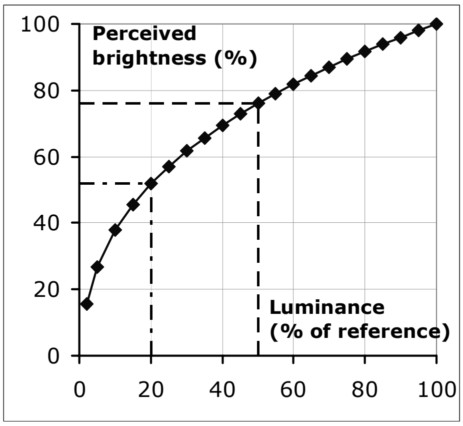

Fig. 2

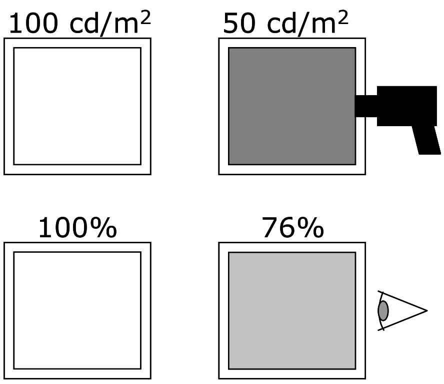

Fig. 3

Take the element called brightness for example. We all know intuitively what it is. But how do we quantify it? The answer is -- we don't. Brightness is a subjective quality, a perception of some object that we humans express in terms of "dark," "dim," "bright," or something intermediate. So what are all these numbers in nit or cd/m^2 that marketers use? Well, in a strict sense, this is called luminance. You will forgive us for using this term: we are not inventing it – it's been there forever. It was just boldly ignored, resulting in confusion that will be explained shortly. Luminance, unlike brightness, can be measured with objective instruments and unlike brightness, can be expressed in absolute numbers.

Now, brightness is not only subjective, it is also relative: it depends on the surroundings of the object we are looking at. Look at the two vertical rectangles in Fig.1 for example. Which one is brighter? The one on the left, we agree. But which one has a higher luminance? The one on the left -- maybe? Wrong. They are the same gray rectangles, copied and pasted on different places of the changing gray background. We see that even though the rectangles have the same luminance, the perception of their brightness is relative.

Keeping everything the same, though, (background, ambient light, etc.), and changing only the luminance, we have to agree that there *is* a one-to-one correspondence between the measured luminance and what we perceive as brightness. In other words, and it can't be otherwise, one display *will* look brighter to us if we increase its *luminance*. Scientists have spent quite some time in translating the perceived brightness into numbers. Eventually a satisfactory model that links luminance and perceived brightness has been proposed (Fig. 2).

The tricky part is that we cannot express the perceived brightness in absolute units, but only relative to a reference. But that is good enough, since most of the time we are *comparing* displays, or between a display and the prevailing ambient light level. The graph in Fig. 2 shows this translation between luminance and perceived brightness. The reference is the brightest white object in the visual field which the eye uses to establish a black-grey-white scale under the prevailing illumination. If you have two displays with different luminances, then the brighter display is the reference (100 cd/m^2 in Fig. 3). The model in Fig. 2 teaches us that if the other display has 50% less luminance than the reference, to the human eye it is only 24% less bright! Or, a display has to have more than 5 times less luminance (18%) in order for us to perceive it twice as dark.

Eye adaptation to various luminance levels

> *THE EYE GETS TIRED WHEN CONSTANTLY ADAPTING FROM BRIGHT TO DARK AND VICE VERSA*

Now, we know how the objective quantity "luminance" translates to subjective "brightness." But this is a "steady state" situation. Our eyes are rather dynamic – they can scan the visual field very fast and they adapt to different luminance levels. However, it takes some time for an eye to adapt (a phenomenon called transient adaptation). As it turns out, adapting to a higher luminance is not a problem, it happens within seconds (up to a minute), but going from bright to dark is a tougher nut for the eye: depending on what light level you start from, it may take from 5 minutes to as long as 30 minutes to completely adapt to a darker luminance level! And what do you get when you have to adapt to bright and then dark and then bright… *all the time*? Well, then your eyes get tired… you have eye fatigue. This is why it is essential to work in an environment with luminances as balanced as possible.

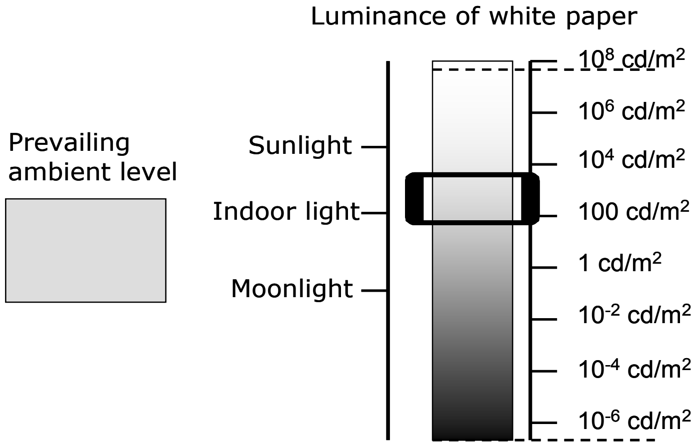

Fig. 4

When the eye is adapted to a prevalent ambient luminance level, it can see (read, perceive contrast, colors, etc.) at the same time a range of around 102 cd/m^2 (window in Fig. 4). Any luminance outside this "window" requires eye adaptation (the "window" slides toward the new level, and this takes some time and effort).

If we are adapted to 100 cd/m^2, we should be able to see objects and displays with luminances in the range of 10 to 1000 cd/m^2 at the same time (Fig.4). Or, if we are adapted to 1000 cd/m^2, we should be able to see simultaneously displays with luminances in the range of 100-10,000 cd/m^2. But if we are adapted to 1000 cd/m^2, our eyes will need at least a few seconds (if not more) before we can read from a paper or a display with about 60 cd/m^2 (Fig. 5). And if you do this frequently enough, you get… you are right: eye fatigue.

Fig. 5 is an example of this kind of problem. In a typical control room environment the prevailing ambient level is around 100 cd/m^2 (office walls, white paper) while laptop screens and computer monitors are anywhere between 150 and 250 cd/m^2. It is clear that a video wall may not have a much higher luminance (high meaning 1000 cd/m^2) than all the rest, otherwise our eyes will adapt to it and will get tired as we constantly adapt to lower levels around us. This is equivalent to going out from an office to an unlit hallway (Fig. 5). So, it is best to have all objects in your control room with as homogeneous luminances as possible.

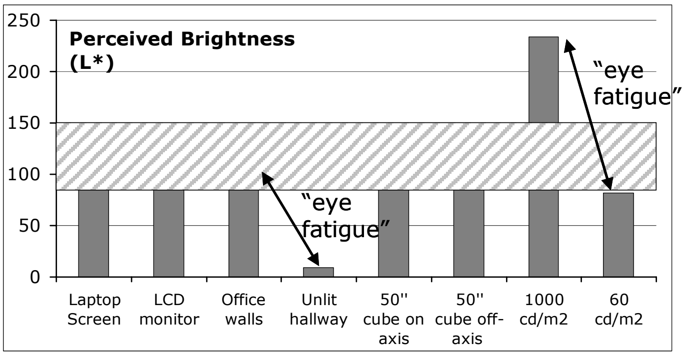

Fig. 5

Lumens

LUMENS ARE LEGACY OF FRONT PROJECTORS AND NOT RELEVANT FOR DIRECT VIEW AND REAR PROJECTION DISPLAYS

So what about the good old lumens in this story? The lumen is a unit that measures the *total* amount of light that comes out of a projector. This is used for projectors, not for flat panel displays like LCDs and plasmas; however, it turns out that even for rear projection displays the lumens are not a suitable unit. Here's why. A front projector projects light (in the form of pixels that carry information) on a white matte screen; that light reflects and reaches our eyes. But so does ambient light, which is more or less homogeneous, and thus diminishes the contrast of the projected image. So for front projectors it is necessary that they are much brighter than any ambient light levels we might have in practice, and lumens are a suitable measure for this "brightness."

However, in rear projection systems the light is projected from the rear (hence the name…) and is transmitted through a transparent screen toward the viewer. If you replace your screen with a 100%

absorbing screen, what does it matter how many lumens the rear projector has when you can't see anything? The whole lumen story is thus a legacy of front projectors: in rear projection technology, what matters is what you see on the screen, and this depends on the projection engine as well as screen type, ambient light, etc, and is expressed in terms of on-screen contrast and luminance. Comparing rear projection units on lumens is like deciding who is a better man based on their weight. So it doesn't make sense.

Ambient light, illuminance and reflections

So, here is what really matters for rear projection and flat panel displays. Illuminance is the technical term expressing how much light falls on how much area. It doesn't directly depend on the surface it falls on (whether it is white or black, flat or grainy). You can think of illuminance in "light density" or "density of light rays" in the ambient. It is measured in lux (lx), and this name may ring some bells. Typical illuminance values in living rooms and offices go from 50 to 200 lx.

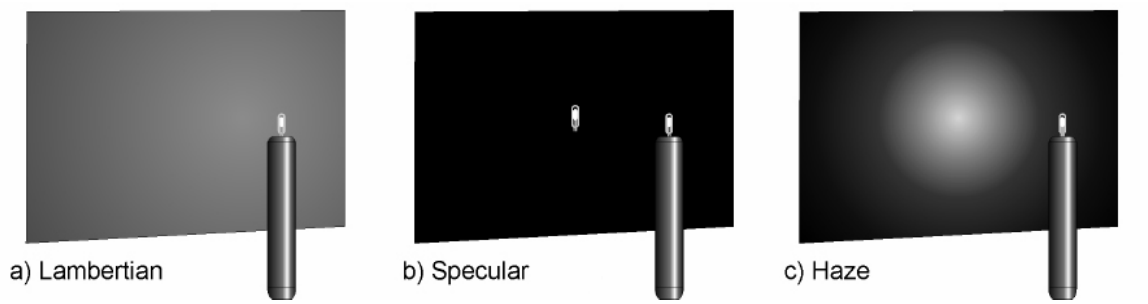

Fig. 6

Ambient light means light that is "everywhere" in the room. Inevitably, this light will fall on your display screen and, as inevitably, it will reflect and mix with the light that is coming out of your display and carrying useful information. There are different reflection mechanisms (Fig. 6), called diffuse or "Lambertian" reflection (Fig. 6a -- every ray of the incident light reflects in all directions so there is no image of the light source), specular reflection (Fig. 6b -- mirror-like reflection where on the screen you see the exact image of the light source) and haze (Fig. 6c -- somewhere in between the other two, it's that fuzzy circle around the reflected image).

Which type of reflection you have depends of course on your screen: most likely you will have a mixture of all three, but with one predominant component. This is why some screens are called diffusive, and some reflective.

Contrast, contrast ratio, on-screen contrast

AMBIENT LIGHT DIMINISHES THE CONTRAST DRASTICALLY

Contrast is another of the infamous terms used in the display industry that is a subject of some misinterpretation and aggressive marketing. If you have a display with a specified contrast ratio of 1000:1 and one with 10000:1, which one would you buy (if price is not an issue of course)? It turns out that these numbers are misleading, and to stick to the goal of this white paper, we will clear up some misunderstandings.

CONTRAST RATIO = BRIGHTEST WHITE/DARKEST BLACK (IN DARK ROOM)

First, the naming and definition. The *ratio* between the *brightest white* and the *darkest black* that a display can produce in a *completely dark room* is called the full field *contrast ratio*. This is because the white and black are measured in the center of the screen, when the whole screen is white or black. Being defined this way, the contrast ratio is anywhere between 1 (white and black equal -- no contrast at all) and infinity (ok, a very, very large number, if the black is very low, or the white very high, or both). We will also use the term *contrast*, even though strictly speaking, *contrast* refers to the *ratio* between the *difference* and the *sum* of the brightest white and darkest black (and thus ranging between 0 and 1).

Second, the conditions. We said a *completely dark room*, and we mean it. This is an absolute must for specifying contrast. Remember, if there is some ambient light, it will reflect from the display screen. But then the black that we get from the screen will mix with this reflected light and will not be quite as black as in a dark room. And since the black is not quite black, the contrast ratio will decrease. You are welcome to do the exercise below, but first take a look at the most famous face in image processing (Fig. 7a), and what happens to it when contrast is decreased (Fig. 7b).

a b

Fig. 7

A practical example

CONTRAST RATIO	1000:1
LUMINANCE WHITE	500 cd/m^2
LUMINANCE BLACK	0.5 cd/m^2
AMBIENT LIGHT	160 lx
REFLECTANCE	0.04 (4%)
LUMINANCE OF REFLECTED LIGHT	=0.04*160/3.14= 2 cd/m^2
ON-SCREEN CONTRAST	=(500+2)/(0.5+2) =200:1

Table 1

To get an idea of this effect, let's make a quick calculation (refer to Fig. 8 and Table 1, which contains all numerical values used below). Say you have a display that claims a contrast ratio of 1000:1 and brightest white luminance L_{FW}=500 cd/m^2, with darkest black luminance accordingly L_{FB}=0.5 cd/m^2. Let the ambient light be 160 lx, which is perfectly normal for an office or a living room.

On a typical diffusive screen with diffuse reflectance 4%, this translates to L_{AL}=2 cd/m^2 reflected light (L_{AL}=reflectance*illuminance/3.14, don't ask why now). In these conditions, we need to add these 2 cd/m^2 to both the bright and the dark luminance, so the actual contrast ratio will be (500+2)/(0.5+2)=200:1! A totally unexpected result! The contrast will be even lower if the screen is specular (mirror-like), because it will be glossy, will create "hot spots" (reflection of ceiling lamps for example) and some regions on the screen will be totally unreadable.

But, don't despair. Even though 200:1 is less than 1000:1, it is still much more than enough for a good display. For good visibility, readability if you wish, a contrast of 10:1 is recommended. Any value above that doesn't contribute to readability that much, but only to the perceived image quality. What eventually matters is not to have an ultra-high contrast of thousands to 1, but to have a screen that handles ambient light properly, and doesn't create hot spots.

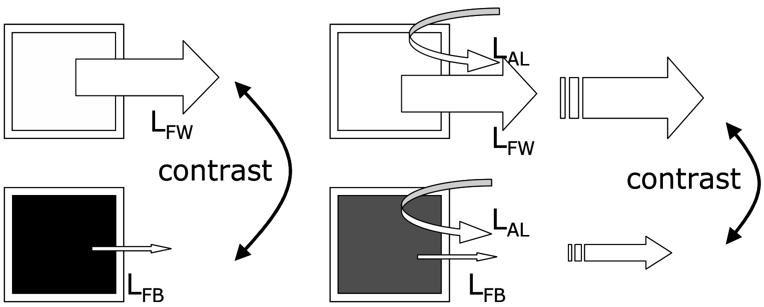

Fig. 8

In projector technology, there is a thing called "projector contrast" that measures the ratio of the white and black produced by the projector. But this still has to be translated to "on-screen contrast" which, as said above, depends on the screen type and of course on the inevitable ambient light. Imagine you have a rear projector with an excellent projector contrast. Do you see anything if you put a 100% absorbing screen in front of it? What do you see when direct sunlight falls on the screen?

Display gain, half-gain angle, viewing angle

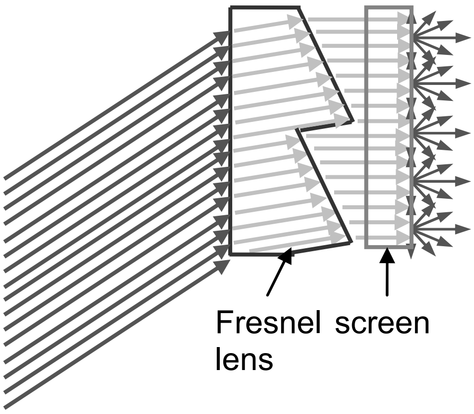

Fig. 9

Before we conclude, we will discuss specifications such as "gain," "half-gain angle" and "viewing angle," seen in projector and flat panel display technology.

Let's first discuss rear projection displays, where the light is projected on the screen from behind (Fig. 9). In order to make the light coming from the projector parallel, a Fresnel lens is used. This parallel light then goes through a screen, which can be built in such a way that the light coming out of it radiates equally in all directions (Fig. 10a). Other kinds of screens can introduce some angle distribution of the transmitted light: the light coming out of the screen will be the strongest in the perpendicular direction, and will become weaker (lower luminance) when we look under an angle (Fig. 10b).

The screen *gain* is the ratio between the light that the screen actually transmits in the perpendicular direction (Fig. 10b) and the light transmitted in this direction if the screen were completely diffuse (Fig. 10a). By definition a perfect diffuse screen has a gain of 1.

Because of the angular distribution, at some point, the luminance will become half the on-screen value: this angle is the half-gain angle. Values found in industry vary between 6 and 40 degrees. Things get more complicated here because we can define a half gain angle in the horizontal direction (when you look at a display from the right or from the left), and in the vertical direction (up-down). These values should be optimized depending on the application.

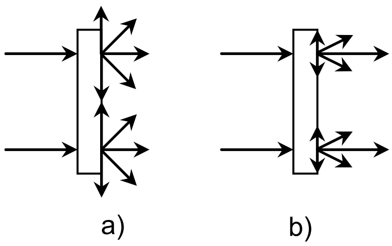

Fig. 10 a) diffuse screen; b) gain screen

Now, remember our previous point about perceived brightness. We said that in order to perceive a display 50% darker, its actual luminance has to be around 20% (more precise 18%) of the reference display luminance. Translating this to the angle dependence of luminance in projection displays, we can define a 1/5 gain viewing angle, at which the luminance is 5 times (1/5=20%) lower than in the perpendicular direction, but the perceived brightness is only half of the brightness in the perpendicular direction. This angle is much wider than the half-gain angle and yet still meaningful with respect to screen visibility.

When talking about flat panel displays, we meet the specification "*viewing angle*." This is not to be confused with the half-gain angle specified for rear projection displays and discussed above. In LCD and plasma display specs we find any value from 160 to almost 180 degrees for the viewing angle. Indeed, in these displays luminance also has an angular distribution from the perpendicular viewing direction. However, the viewing angle in flat panel displays is defined as the angle span within which the dark room contrast ratio remains above 10:1. Remember, a contrast ratio of 10:1 is needed for good visibility (readability). So this is really what the "viewing angle" spec says: outside this angle span, the display is very poorly readable. For example: if a display specifies a viewing angle of 176 degrees, that means that the contrast ratio falls below 10:1 when you look at the display from an angle larger than 176:2=88 degrees. This angle is of course not bad at all –- it means you are looking almost parallel to the screen.

Summary

Summary and conclusions

We have seen throughout this white paper that the display specs are not exactly what many may think they are, and that there are many other important issues to take into consideration when building a good information display.

In control room applications, the areas discussed above can combine and lead to new problems. One of the important issues of this kind is the brightness adaptation combined with the luminance angle distribution. Take, for example, a control room with a display wall consisting of rear projection units. It is clear that, apart from the perpendicular viewing direction, an operator always looks at the wall under some angle (depending on the wall size, the operator's position and display region of interest). If you have a wall with high gain, it inevitably means that whenever you look at a different position on the wall, you see a different brightness. The higher the gain, the larger the brightness difference you see. If you do this quite often, your eyes are subject to brightness adaptation and to… eye fatigue. This is not what the operator wants, sitting in front of that wall all day. Understanding this, Barco Control rooms produces displays with screens that homogenize the angle distribution, instead of maximizing the on-screen brightness for marketing purposes. These screens also have another advantage: they reflect less ambient light, they don't form hot spots, and this results in high contrast even in a well-lit control room.

Since the perceived brightness and luminance are different items, increasing the gain of a screen offers more disadvantages than advantages. Increasing the luminance of a rear projector by a factor of 2 (by using a high-gain screen instead of a diffusive one) increases the perceived brightness by only 30%, but at the same time decreases the half-gain angle, introduces a high brightness non-uniformity across viewing angles and may introduce eye fatigue.

Being experts in the field of information displays, we at Barco Control Rooms use this knowledge and optimize our displays to make them favorable for the human visual system, but also to meet the market requirements for high contrast, high brightness and all the factors that make a display a good display.

References and further reading

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