Chapter 2

High-Fidelity Display Performance

> *All I want to say is that "High Fidelity" has no deep significance.*
>
> —Roger Ebert

The purpose of a display device is to convey information to an observer with minimal alteration of its content. All display devices present the information as a modulated luminance map that is associated with the data in the input signal according to a display presentation function. The amount of information detail (i.e., diagnostic information) to be displayed typically determines the quality with which the device must transfer digital values into luminance output. For instance, an alphanumeric device with only seven pixels can display numbers and letters reasonably well on a billboard. When the amount of information to be displayed increases in spatial detail and intensity variations, some degradation in the image quality conveyed to the observer is unavoidable. This is particularly true for some digital medical imaging modalities where large pixel arrays are acquired with a very large image value luminance range.

When electronic displays are used to present large amounts of information (for instance, in digital medical imaging systems for mammography and chest radiography), the image quality requirements are no longer defined by the information content, but instead by the capabilities of the observer to successfully accomplish the visual task. It is therefore essential for those interested in studying the display of high-information content images in electronic devices to understand the observer's limitations. In this chapter, we review aspects of the human visual system relevant to the high-fidelity display requirements of contrast, luminance range, and resolution.

2.1 Contrast Sensitivity

In human vision research, small visual stimuli containing sinusoidal variations in luminance have been used to measure the ability of an observer to perceive contrast. In psychophysics experiments, it is useful to define a measurable quantity, the physical contrast C_{phys}, as

$$C_{phys} = \frac{L_{max} - L_{avg}}{L_{avg}} , \tag{2.1}$$

where L_{max} is the maximum luminance generated by the display within the pattern and L_{avg} is the mean luminance in the pattern, or mean local luminance.[*] When we refer to mean local luminance, we are assuming that the mean is obtained across the luminance field that contains the pattern or stimulus, as well as some of the background depending on the size of the pattern. However, in this discussion, we will not address the issue of extent of the visual field and its influence on visual detection tasks.

The human eye perceives luminance variations as a change of photoreceptor signal with respect to the viewing angle while scanning a displayed image. It is useful to relate vision data expressed in cycles/degree (cy/deg) to its equivalent in cy/mm at a specified viewing distance VD (mm) using the following expression:

$$\text{cy/mm} = 57.3\ (\text{cy/deg})/VD\ . \tag{2.2}$$

For a typical viewing distance of 600 mm, cy/mm is approximately one-tenth of cy/deg.

The minimum contrast detected by the human eye is called the contrast threshold, expressed in relative luminance increment $\Delta L/L$, where L is the local mean luminance. The threshold is also defined as the inverse of the contrast sensitivity response function. The contrast threshold depends on the spatial frequency of the signal and on the relative orientation of the grating to the eye. The threshold also depends on the maximum luminance in the target. The threshold for detection decreases with increasing luminance, as can be seen in Fig. 2.1. The decrease in sensitivity at low luminance is known as the Weber-Fechner law.[149] For a luminance greater than 100 cd/m^2, the threshold is situated at about 0.005. Extensive experimental models have documented the dependence of contrast detection on spatial frequency, luminance, and orientation. The empirical models of Daly[48] and Barten[18, 20] provide useful descriptions of this experimental data.

At high luminance where the threshold contrast $\Delta L/L$ is approximately constant, a gray-scale map for which $\log(L)$ is proportional to the image values will produce uniform contrast. However, for many display systems, the dim regions occur at a luminance where the contrast threshold is high.[135] A gray-scale map can be defined such that each increment in image value causes the same perceived change in luminance.[30] Systems with fewer gray levels may produce noticeable artifacts appearing as contour lines. The low sensitivity of the human visual system

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[*] Throughout this book, we will use this and other definitions of contrast based on the Michelson contrast.[121] When not specified, the contrast will be given consistently with the above definition, as $\Delta L/L$, where L is the average local luminance.

2.3 Luminance Range

The display luminance range is defined as the ratio of the maximum luminance to the minimum luminance as measured at the screen of the device. Per this definition, the range includes the effect of the ambient illumination as it increases the minimum luminance that the device will output in a dark environment.

The luminance range for which the human eye responds covers eight decades. The neural response of photoreceptors is known to be linear at low light levels and to saturate at high luminance levels.[23, 130] However, in a given scene, the eye adapts to a particular average luminance with a peak response that degrades as the luminance of the target differs more and more from the adapting luminance. Therefore, even though the human visual system is capable of responding to a huge luminance range, the effective range where the eye performs within a fraction of the peak response is limited and depends heavily on the eye's luminance adaptation state.

2.4 Adaptation

The human eye's adaptation to varying luminance levels consists of different phases resulting from the dynamics of the chemicals responsible for vision.[79, 80, 129] Using electrophysiological observations and computer simulations, Norman[128] and Baxter[22] reported on the relationship between photoreceptor sensitivity and image processing at neural centers for visual tasks involving the detection of low-contrast radiological features in nonuniform backgrounds. The sensitivity response function for the complete visual system can be approximately described by an expression of the form $P = R/(R + S)$, where P is the photoreceptor response, R is the retinal luminous intensity, and S represents a constant that conforms with the state of adaptation. Figure 2.3 shows the measured neuronal signal for different adaptation states.

When the observer is adapted to a particular average luminance, the perceived contrast response is maximal near the average luminance and decreases in regions of the scene with higher or lower luminance, as shown in Fig. 2.4. Displaying images using a wide luminance range improves quality due to the high physical contrast (large $\Delta L/L$ for a specific image intensity change). However, the perceived contrast is a combination of the physical contrast and the observer's biological response. Therefore, for a typical scene with luminance variations about a scene average, contrast perception is reduced in the bright and dim areas relative to the maximum performance at the average luminance for which the eye is adapted.

The question arises as to what might be the optimal adaptation luminance (other than the display device). The above-mentioned arguments suggest that for slowly variant luminance fields, the average luminance has to be close to the average image luminance. This observation—that the optimal background luminance for human visual detection tasks has to be close to the average luminance of the observed scene—is opposed to conventional reading conditions with extremely low

2.6 Veiling Glare

In this section, we will discuss two aspects of veiling glare: first, we will consider how veiling glare in the human eye affects detection tasks, and second, we will describe the intrinsic veiling glare characteristics of displays. Both aspects relate to the same physical phenomenon: the undesired degradation in display contrast caused by unwanted scattering processes. In the case of the human eye, veiling glare is caused primarily by optical scattering of light in the anatomical elements through which the light traverses before reaching the photoreceptors in the retina. In displays, the causes of glare are associated with optical and/or electronic scattering. Information about measuring veiling glare in displays is covered in Sec. 6.2.1.

2.6.1 Glare in the human eye

The human eye is able to discriminate the orientation of light photons that enter the eye due to its sharp angular sensitivity response to light that impinges into the retina at oblique angles (see Fig. 2.6). Light that originates at the focused object, which is responsible for the viewed image, is scattered while passing through several media, including the cornea, the aqueous humor, and the crystalline lens. Because of this optical scattering process, even a collimated beam of light coming from an external point source will produce an optical illumination in the retina characterized by a blur, or spread function. That spread of signal, equivalent to the point-spread function of the eye,[*] has been studied by many investigators.[25] A good review of glare processes in the human eye can be found in Ref. [152]. In that paper, Spencer et al. classified glare effects into two components: flare and bloom. Flare, seen as a halo, is caused primarily by scattering events in the lens, while blooming (or "glowing") comes from events in the lens, the retina, and the cornea. The retinal scattering is important only in the same direction as the incident primary beam due to the extremely low sensitivity of the cones to obliquely incident rays (known as the Crawford-Stiles effect[153, 154]). In scotopic conditions (low luminance levels), the magnitude of glare in the eye increases because the rods do not have as high a directional sensitivity as the cones. Although lacking specific quantitative value, the point-spread function of the human eye has been represented in many artistic pieces, including that of Fig. 2.7. Veiling glare in the human eye is not believed to have an effect on typical reading conditions since the luminance of radiologic images consists of small variations about a scene average in an environment with overall low ambient illuminance. On the other hand, veiling glare does affect image quality in some display technologies.

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[*] The point-spread function is defined here as a general response function in the human eye caused by a small light source far away from the receptor, emitting light photons into a collimated pencil beam.

curve according to illuminance measurements made inside the CRT bulb. When the transmitted light intensity through the Al film amounts to 10%, a uniform bright field will be contaminated by an additional constant luminance of 5×10^{-4} times the bright field intensity. This figure assumes 90% absorption of all scattering events at the walls of the tube. Typically, coatings for the inside surfaces of CRT bulbs are carbon-based absorptive materials, although metallic coatings containing Cu and Ag are also used in certain applications. If a small dark spot is placed in the center of an image at a luminance level of 1% of the bright field, its physical contrast will decrease from 99 to 94. In addition, the thin Al coating that covers the phosphor layer may have small cracks or holes that will allow more light generated in the phosphor to escape towards the vacuum cell, resulting in a further decrease in contrast.

Electron backscattering. In addition to an optical component, a significant contribution of glare in displays is caused by electron backscattering. The reduction in contrast due to backscattered electrons has been studied for fluorescent screens[114] and for scanning electron microscopes.[74] To obtain good color saturation, a shadow mask is located in front of the screen to allow each electron beam to selectively pass through the mask holes and excite the corresponding color phosphor. Although the beams are focused and aligned with the holes, a fraction of the Gaussian-shaped beam will directly hit the mask. As some energetic electrons impinge into the shadow mask or the screen, a fraction is backscattered and may eventually hit the phosphor layer at a different location. Short-range contrast degradation is originated by electron scattering in the vacuum region between the mask and the phosphor screen, while the long-range effect comes from backscattering at the mask and at the inner magnetic shield and funnel of the glass bulb.[52] The aperture grille used with in-line electron guns, introduced in 1988, represents another approach employed for color selection. The transmittance of the beam is 15 to 50% greater compared to shadow mask designs.

The backscattered fraction depends on the effective atomic number of the coating, and therefore can be reduced by using low-Z materials such as graphite[161] or Al_2O_3.[162] The amount of contrast reduction from backscattering is directly proportional to the primary beam intensity. It has been reported that the fraction of contrast loss due to electronic backscattering in color tubes can be as much as 98% of the total glare degradation.[52] Reduction by a factor of about 10 in the contrast ratio of 10 × 10 cm black squares can be achieved by careful selection of coating material and thickness. The absence of a shadow mask in monochrome tubes results in a lower backscattered fraction since all the electrons hit the Al conductive coating and phosphor layer.

2.6.2.2 Effect of veiling glare

The human visual system is able to detect a dark region having less than 0.002 of the luminance of a bright surrounding field. We can conclude that a display device should not add significant luminance to dark regions surrounded by bright fields. It

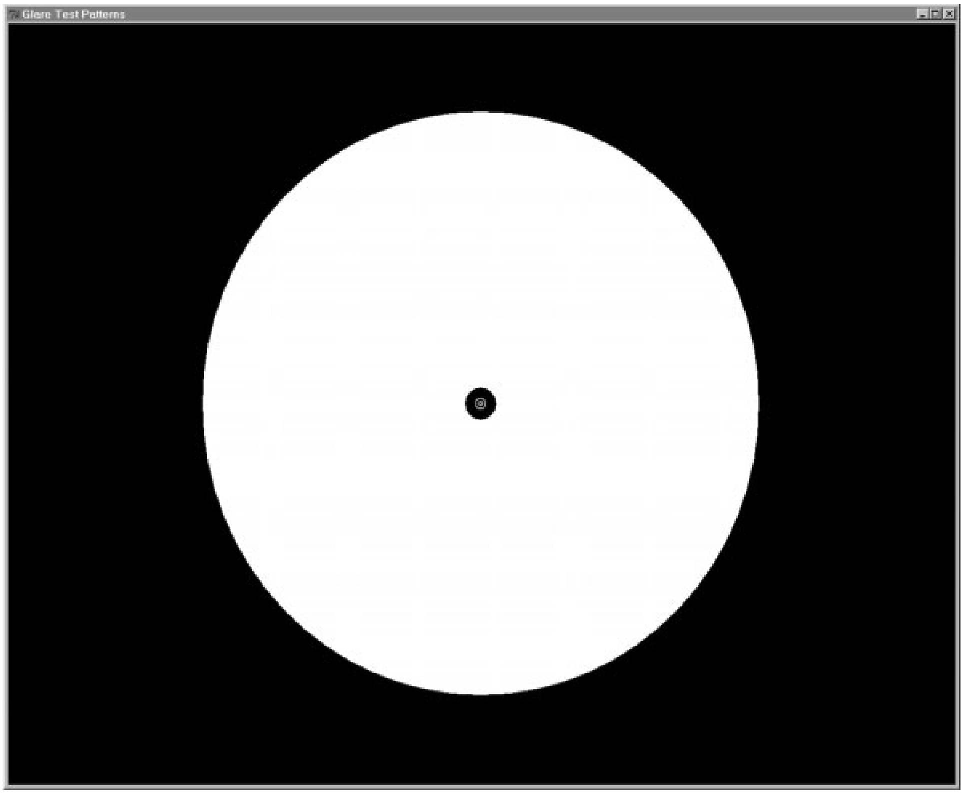

Figure 2.10 Image test pattern to illustrate and measure veiling glare effects.

is useful to define a veiling glare ratio (*G*) as the ratio of the luminance of the bright surroundings to the luminance of a small dark spot [see Eq. (6.2)]. Using this ratio, which can be measured experimentally (see Fig. 2.10), we can determine the requirements for a high-fidelity display device. If the luminance change in dark areas due to veiling glare should be less than 20% with an average luminance range of 80, the contribution from glare in the dark regions should be less than 0.20. Thus, the required glare ratio in this condition is $G = 80/0.20 = 400$.

2.7 Ambient Light Reflections

In this section, we will discuss how the performance of a human observer is critically affected by the level and nature of the ambient illumination. As can be seen in Fig. 2.11, the displayed image can be buried under high reflected luminance. Particularly for CRT devices, reflections can be represented by the addition of a specular and a diffuse component (see Figs. 2.12 and 2.13) with different effects on the quality of the image displayed. More generally, reflections include a third component called “haze,” which becomes important in flat-panel LCDs (see Chapter 4).

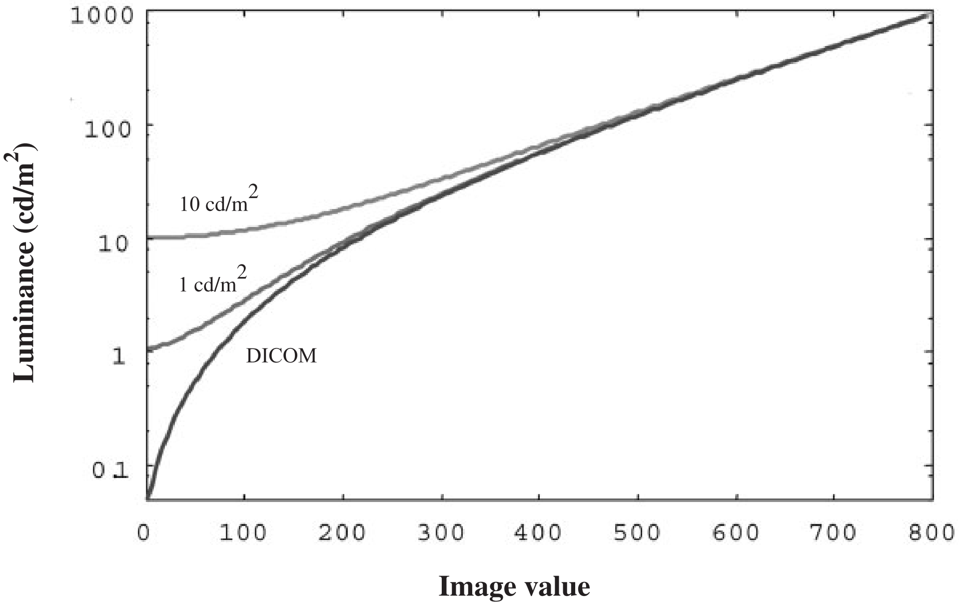

Figure 2.13 Contrast reduction from diffuse added luminance. The slope of the gray-scale display function is directly related to the contrast of the display at a given luminance level. Increasing ambient illumination to 1 and 10 cd/m^2 leads to a reduction in the available contrast in the low luminance regions.

For instance, the contrast threshold at 4 cd/m^2 is 0.012 (see Fig. 2.1). In a room with an illumination of 100 lux at the display screen, the reflected specular luminance is given by $0.9 \times 100/\pi$ (cd/m^2). This reflected luminance should be less than the threshold luminance at 4 cd/m^2, given by 4×0.012 cd/m^2. The specular reflection coefficient, R_S, that satisfies this condition is 0.002. Using this criterion, we can calculate the maximum ambient illumination (in lux) that maintains the specular reflections of white and black objects below C_t. Table 2.3 shows the values calculated for specific display luminance minima. Typical levels of ambient illumination in areas where image displays are found are presented in Table 2.4.

Table 2.3 Ambient illumination (in lux) required for maintaining specular reflections.

L_{min} (cd/m^2)	C_t	R_S				
		0.002	0.004	0.008	0.020	0.040
20	0.007	244	122	61	24	12
10	0.008	140	70	35	14	7
4	0.012	84	42	21	8	4
2	0.017	59	30	15	6	3
1	0.024	42	21	10	4	2

Table 2.4 Typical ambient illumination levels.

Space	***I*** **(lux)**
Operating rooms	300–400
Emergency rooms	150–300
Staff offices	50–180
Clinical viewing areas	200–250
Diagnostic viewing (CT or MR)	15–60
Diagnostic viewing (x ray)	2–10

2.7.2 Diffuse reflection

The diffuse reflection of light adds an unstructured constant luminance to the image that reduces the contrast in dark regions. The diffuse reflection coefficient describes the added luminance per unit illuminance, R_D (cd/m^2/lux). Therefore, the added luminance is given by

$$\Delta L = R_D I \, . \tag{2.3}$$

To limit the contrast reduction, the relative change in contrast produced by ambient illumination should not be less than 0.8:

$$\frac{1}{(1 + \Delta L/L_{min})} \leq 0.8 \ . \tag{2.4}$$

Using Eq. (2.4), we can calculate the minimum reflection coefficient that will result in a given added luminance for a given room illumination in the front of the screen (illumination is defined as the amount of light impinging into the screen from the ambient and should be measured in the center of the screen). For example, for a display with 4 cd/m^2 of minimum luminance in a room with 100 lux ($I/L_{min} = 25$), the diffuse reflection coefficient is given by

$$R_D \leq \frac{1/0.8 - 1}{25} \, , \tag{2.5}$$

yielding a required R_D of less than 0.01 cd/m^2/lux. The values of room illumination that satisfy this condition are shown in Table 2.5.

Table 2.5 Ambient illumination (in lux) for maintaining 80% of the available contrast in dark regions.

L_{min} (cd/m^2)	R_D (cd/m^2/lux)				
	0.002	0.004	0.008	0.020	0.040
20	1000	500	250	125	83
10	500	250	125	62	42
4	200	100	50	25	17
2	100	50	25	12	8
1	50	25	12	6	4

2.8 High-Fidelity Display Requirements

For the purpose of display requirements, medical tasks can be classified into these two categories:

- **High fidelity (diagnostic).** Primary medical interpretations performed by persons qualified to read radiologic studies. Medical review of radiographs by specialists who have skills in reading studies for a particular purpose (orthopedists, rheumatologists, neurologists, surgeons).
- **Good (clinical).** Preliminary interpretations in urgent care situations. Referring physician observation in conjunction with interpretative reports. Clinical management functions requiring basic anatomic observations (fractures, opaque objects).

As we discussed at the beginning of this chapter, display requirements are strongly dependent on the specific visual task that the observer will carry out. Therefore, a general list of display requirements for radiology is not feasible. Nevertheless, our analysis provides a way to define requirements for high-fidelity display based on the limitations of the human visual system.

Table 2.6 is a summary chart presenting ranges of values for the most relevant display parameters. Details of the method to determine these requirements for most of the parameters listed in the table will be discussed in this book. Other parameters such as area distortion and viewing angle are not based on material from this chapter. Instead, we have included them in this listing for completeness, and they should be taken as suggestions coming from our experience with film display. It should be noted that more research is needed in some of these areas in order to ascertain more precisely the high-fidelity requirements for an electronic display.

Another point to note about these values is that they represent general high-fidelity medical display requirements instead of requirements valid for any given applications. When specific applications are considered, these values will need to

Table 2.6 Display requirements for medical imaging applications.

Specification	Film Quality	High Fidelity	Good Quality
Spatial			
Size (cm)	35 × 43	30 × 36	24 × 30
Pixel array	4000 × 5000	2500 × 3000	1200 × 1500
Pixel size (mm)	0.08	0.12	0.20
Refresh rate (Hz)	static	static – 80	static – 80
Geometrical distortion (%)	< 0.1	2	2
Gray scale			
Maximum luminance (cd/m^2)	2000	1000	240
Minimum luminance (cd/m^2)	1	4	1
Gray-scale levels	> 850	> 680	> 530
Emission	Lambertian	Lambertian	Lambertian
Color	monochrome	monochrome	monochrome
Optical			
Veiling glare ratio	> 1000	400	150
Specular reflectance	0.02	0.002	0.004
Diffuse reflectance (cd/m^2/lux)	0.02	0.01	0.02
Viewing angle (V)	full	± 45°	± 30°
Viewing angle (H)	full	± 60°	± 45°

be adjusted. For instance, it is known that in some diagnostic modalities like mammography and skeletal radiography, the image features that need to be detected for an accurate diagnosis are small. This need forces a more stringent requirement on the display's resolution. On the other hand, when the lesions to be detected are low-contrast, subtle variations in the luminance, a precise luminance calibration and appropriate luminance range might be more important.

Some definitions used in the development of Table 2.6 require additional explanation. The display size of 43 × 35 cm is standard for radiographic detectors. Displays should have a horizontal/vertical aspect ratio of about 0.8. We assume that the log-luminance versus pixel value relationships should follow a perceptually linear profile based on the DICOM standard. With respect to display color, general preference in the field has been for displays with a white to slightly blue color. Most film bases are tinted blue. The contrast ratio for veiling glare measurement is defined with test pattern images consisting of a 1-cm, centered, dark circular spot surrounded by a bright field. With respect to the viewing angle performance, we require that the stated contrast and luminance performances are to be maintained within the required viewing angle, and no contrast inversion is allowed.