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Image Quality Figures of Merit for Contrast in CRT and Flat Panel Displays

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The image quality figure of merit of "contrast" is defined, explained, and discussed as applied to both cathode ray tube (CRT) and flat panel displays (FPDs). Currently acceptable requirements are discussed for both panel mounted and helmet mounted displays. The relationship between physical contrast and the human visual system also is discussed.

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Introduction

Visual displays are an increasingly important method of efficiently conveying information in military as well as civilian environments. It is important that the display present the information in an accurate and easily perceived manner. Ensuring operational efficiency and safety in informationally intensive environments, such as military cockpits and command and control centers, requires measures of information transfer in displays. Also, physical criteria evaluating the merit of old and new display technologies are needed for cost effectiveness, system development, and procurement decision making. These criteria, which quantify a display's image quality, are known as figures of merit. A number of image quality metrics, or figures of merit, have been developed to quantify the "goodness" of an image presented on a display. One such class of metrics concerns the range of luminances that can be simultaneously presented in an image. This range, described by the concept of *contrast*, defines the relationship between the minimum and maximum possible luminance values. Information in displays exists by virtue of the presence of differences or contrasts in the display, particularly differences in luminance. Historically, the formulation and use of the concept of contrast have been ambiguous and irregular due to the differing theoretical and practical uses in visual psychology, optics, engineering and physics. Considerable ambiguity exists in the application of this concept, especially when applied to both conventional displays, the cathode ray tube (CRT), and the emerging class of displays known as flat panel displays (FPDs). Additionally, manufacturers often further confuse the issue by focusing on the most favorable criteria for their display product. Our purpose here is to review the basic principles of contrast and its use in describing the image quality of CRT and flat panel technology displays as a tutorial aid to decision makers evaluating display technology.

Image quality

Displays are used to present various types of information. These include text, symbols, graphics, and video. Many factors affect the user's ability to perceive and use the displayed information. If the information is a simple reproduction of computer generated text, symbols, or graphics, then the major factor affecting the fidelity of the information is the capacity of the display to faithfully reproduce the image information. However, if the information is a representation of some external view of the world, as from an imaging system, then, in addition to the display devices's capacity to faithfully reproduce the image, a number of additional factors will affect the user's perception of the information. These include sensor parameters associated with the imaging system, (e.g., camera), transform functions associated with conversions of the scene from one domain to another (e.g., spatial, luminance, temporal, etc.), attenuation and filtering due to processing and signal transmission, noise, etc. However, ultimately, visual performance is limited by the quality of the final image. This quality is based on the physical means of generating and displaying the image on the display technology.

Display technologies

Displays based on CRT technology all operate on the same principle, that of sweeping an electron beam across a phosphor screen. The image on the face of the display is the result of light being emitted from the phosphor when excited by the electrons. Information within the image is accomplished by the modulation of the electron beam and the resulting change in phosphor luminance. In contrast, flat panel displays are a class of electro-optical displays which derive their name from the flatness of the viewing surface and, more importantly, the reduced depth behind the display surface as compared to CRTs. FPDs are based on a number of different technologies which differ greatly in the physical mechanisms used to produce the displayed image. The most important are liquid crystal displays (LCDs), electroluminescent displays, plasma display panels, light emitting diode displays and field emission displays (FEDs). Each of these display types consists of a rectangular spatial array of pixels which are independently controlled by electronic drivers. FPDs differ from each other (and CRTs) essentially in the physics of these picture elements or pixels. (Independently of the physics of different flat panel technologies, displays may differ from each other in the way the pixels are electronically addressed.)

Displays based on the various flat panel technologies can be classified as emissive or nonemissive. Emissive displays present information using light inherently produced by the display's mechanism. (Note: CRT displays would fall within this class since the light energy producing the final image is a result of the electron beam exciting the phosphor.) Nonemissive displays are those that present information by reflecting the ambient light (background) to the observer or by modulating the transmission of light from an integrated source.

Liquid crystal displays (LCD) are nonemissive displays which produce images by modulating light from a background source. The light can be reflected light or transmitted light from a secondary external source, known as a backlight. The mechanism by which modulation is achieved is by the application of an electric field across a liquid crystal material which has both liquid and crystalline properties. The liquid crystal material is sandwiched between layers of glass and polarizers. By applying the electric field, the liquid crystal material acts as a light valve. Each pixel within the image is a liquid crystal cell. A traditional problem with LCDs affecting image quality has been the dependence of the displayed image contrast on viewing angle.

Electroluminescent displays are emissive displays which use an electric field to activate pixels, which consist of a layer of phosphor material sandwiched between two layers of a transparent dielectric (insulator) material.

Plasma (gas discharge) displays are emissive in nature and produce light when an electric field is applied across pixels, which are envelopes containing a gas. The gas atoms are ionized, and photons (light) are emitted when the atoms return to the ground state. A plasma display is an

array of miniature gas discharge lamps, similar to florescent lamps. Images are produced by controlling the intensity and/or duration of each lamp's discharge current.

FEDs are also emissive displays. They consist of a matrix of miniature electron sources, one for each pixel, which emit the electrons through the process of field emission. Field emission is the release of electrons from the surface of a metallic conductor into a vacuum under the influence of a strong electric field. Light is produced when the electrons strike a phosphor screen. This process is also known as cold emission.

The image quality resulting from the various means of generating and presenting images by the different display technologies is evaluated by standards known as figures of merit.

Figures of merit

Image quality affects user performance. Numerous image quality figures of merit have been developed in order to evaluate the physical quality of the image produced on a display with the goal of gauging user performance with the display. A figure of merit is a metric which quantifies some aspect of the image. Task (1979) provides an excellent summary of a number of figures of merit which commonly are used for evaluating image quality on CRTs. These are listed in three categories shown in Table 1.

Table 1.

Cathode ray tube display system figures of merit

Geometric	Electronic	Photometric
Viewing distance	Bandwidth	Luminance
Display size	Dynamic range	Gray shades
Aspect ratio	Signal/noise ratio	Contrast ratio
Number of scan lines	Frame rate	Halation
Interlace ratio	Field rate	Ambient illuminance
Scan line spacing		Color
Linearity		Resolution
		Spot size and shape
		Modulation transfer function
		Luminance uniformity
		Gamma

FPDs have begun to replace the CRT, long the dominant display technology, for many applications. Figures of merit for FPD parameters can be categorized into four domains: spatial, spectral, luminance, and temporal (Table 2). These image domains parallel analogous human

visual performance domains. The spatial domain includes those display parameters which are associated with angular view (subtense) of the observer and coincide with observer visual acuity and spatial sensitivity. The spectral domain consists of those parameters which are associated with the observer's visual sensitivity to color (wavelength). The luminance domain encompasses those display parameters identified with the overall sensitivity of the observer to levels of light intensity. The temporal domain addresses display parameters associated with the observer's sensitivity to changing levels of light intensity.

Contrast

Some of the more important display figures of merit are tied to the ability of the human visual system to detect the luminance difference between two adjacent areas or the same area over time. These figures of merit quantify *contrast,* which is the "difference" in luminance between two (usually) adjacent areas. There can be confusion with the notion of contrast because there is a family of related concepts of contrast, each with its own definition and mathematical expression.

Table 2.

Flat panel display parameters

Spatial	Spectral	Luminance	Temporal
Pixel resolution (H x V) Pixel size Pixel shape Pixel pitch Subpixel configuration Number of defective (sub)pixels	Spectral distribution Color gamut Chromaticity	Peak luminance Luminance range Gray levels Contrast (ratio) Uniformity Viewing angle Reflectance ratio Halation	Refresh rate Update rate Pixel on/off response rates

Contrast, contrast ratio, and modulation contrast are three of the more common formulations of luminance contrast. Further confusion may result from the terminology, because different names are used for the two luminances involved in the definitions. Sometimes, the luminances are identified according to their relative values and, therefore, labeled as the *maximum* luminance (L_{max}) and *minimum* luminance (L_{min}). However, if the area at one luminance value is much smaller than the area at the second luminance, the luminance of the smaller area sometimes is referred to as the *target* luminance (L_t), and the luminance of the larger area is referred to as the *background* luminance (L_b). The more common mathematical expressions for luminance contrast include:

$$C = (L_t - L_b) / L_b \quad \text{for } L_t > L_b \text{ (Contrast)} \qquad \text{Equation 1a}$$

$$= (L_b - L_t) / L_b \quad \text{for } L_t < L_b \qquad \text{Equation 1b}$$

$$= (L_{max} - L_{min}) / L_{min} = (L_{max} / L_{min}) - 1 \qquad \text{Equation 1c}$$

$$C_r = L_t / L_b \quad \text{for } L_t > L_b \quad \text{(Contrast ratio)} \qquad \text{Equation 2a}$$

$$= L_b / L_t \quad \text{for } L_t < L_b \qquad \text{Equation 2b}$$

$$= L_{max} / L_{min} \qquad \text{Equation 2c}$$

and

$$C_m = (L_{max} - L_{min}) / (L_{max} + L_{min}) \quad \text{(Modulation contrast)} \qquad \text{Equation 3a}$$

$$= | (L_t - L_b)| / (L_t + L_b) | \qquad \text{Equation 3b}$$

In the preceding equations, modern conventions are adopted which preclude negative contrast values.[1] The values for contrast as calculated by Equations 1a and 1c can range from 0 to ∞ for bright targets and from 0 to 1 for dark targets (Equation 1b). The values for contrast ratio (Equations 2a-c) can range from 1 to ∞. Modulation contrast (Equations 3a-b), also known as Michelson contrast is the preferred metric for periodic targets such as sine waves and square waves. It can range in value from 0 to 1, and is sometimes given as the corresponding percentage from 0 to 100 percent. Conversions between the various mathematical expressions for contrast can be performed through algebraic manipulation of the equations or through the use of nomographs (Farrell and Booth, 1984). Some of the conversion equations are:

$$C_r = (1 + C_m)/(1 - C_m), \qquad \text{Equation 4}$$

$$C_m = (C_r - 1)/(C_r + 1), \qquad \text{Equation 5}$$

$$C = (2\, C_m)/(1 - C_m) \quad \text{for bright targets,} \qquad \text{Equation 6}$$

and

$$C = (2\, C_m)/(1 + C_m) \quad \text{for dark targets.} \qquad \text{Equation 7}$$

It may be instructive to examine a number of typical luminance patterns for which the contrast figures of merit could be applied and calculate the various contrast values. The patterns in Figure 1 each consist of a small circular area at a given luminance, which will be referred to as

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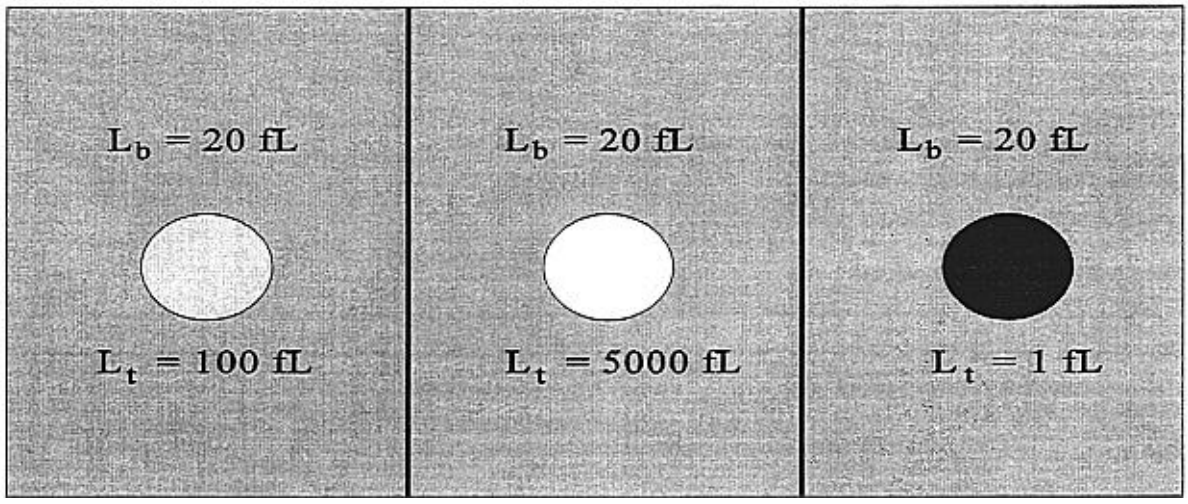
[1] Classical work with the concept of contrast did not concern itself with which had the larger luminance value, the target or the background and, therefore, allowed negative contrast values (Blackwell, 1946; Blackwell and Blackwell, 1971).



(a) (b) (c)

Figure 1. Luminance patterns for several combinations of target and background luminance values.

the target, surrounded by a larger area at a lower luminance value, which will be referred to as the background. The luminances of the targets and backgrounds will be labeled L_t and L_b, respectively. Assume, as in Figure 1a, luminance values of 100 and 20 footlamberts (fL) for the target and background luminances, respectively. Contrast for a target brighter than its background, as defined by Equation 1a, is calculated as follows:

$$C = (L_t - L_b) / L_b = (100 - 20) / 20 = 80/20 = 4$$

Equation 1c would produce the same value. However, applying Equations 2a or 2c for contrast ratio results in the following:

$$C_r = L_t / L_b = L_{max} / L_{min} = 100/20 = 5$$

Assume, now, that the target luminance becomes significantly larger, 5000 fL for example, but with the same background value (Fig. 1b). The contrast value using Equations 1a and 1c would be:

$$C = (5000 - 20) / 20 = 249$$

The contrast ratio using Equations 2a or 2c take the value:

$$C_r = 5000/20 = 250$$

Further increases in the value of the target luminance would continue to produce larger values for contrast as defined by Equations 1a and 1c and contrast ratio as defined by Equations 2a and 2c. Note that as L_{max} (or L_t) becomes significantly greater than L_{min} (or L_b), the contrast values of Equation 1a and 1c approach the contrast ratio values of Equations 2a and 2c. This can easily be seen by rearranging Equation 1a into the following form:

$$C = (L_t / L_b) - 1 \qquad \text{Equation 8}$$

As the ratio of L_t / L_b increases, the significance of subtracting the value of 1 becomes meaningless and Equation 8 takes the form of Equation 2a, that of contrast ratio.

By comparison, if, as in Figure 1c, the target luminance (1 fL) is lower than the background luminance ($L_t < L_b$), the calculated value for contrast (Equation 1b) is:

$$C = (L_b - L_t) / L_b = (20 - 1) / 20 = 19/20 = 0.95$$

and, the calculated value for contrast ratio (Equations 2b and 2c) is:

$$C_r = L_b / L_t = L_{max} / L_{min} = 20/1 = 20.$$

Note: The equation for contrast ratio is defined always by the ratio of the greater luminance to the lesser luminance.

Values for modulation contrast for the luminance patterns of Figure 1 generally are not used. However, consider the luminance pattern in Figure 2. This pattern consists of a series of light and dark bars. While values for contrast and contrast ratio can be calculated, the concept of contrast for such a periodic pattern is best defined by the modulation contrast (Equations 3a and 3b).

For the luminance values in Figure 2, the value of the modulation contrast becomes:

$$C_m = (L_{max} - L_{min}) / (L_{max} + L_{min})$$

$$= (50 - 10)/(50 + 10) = 40/60 = 0.66$$

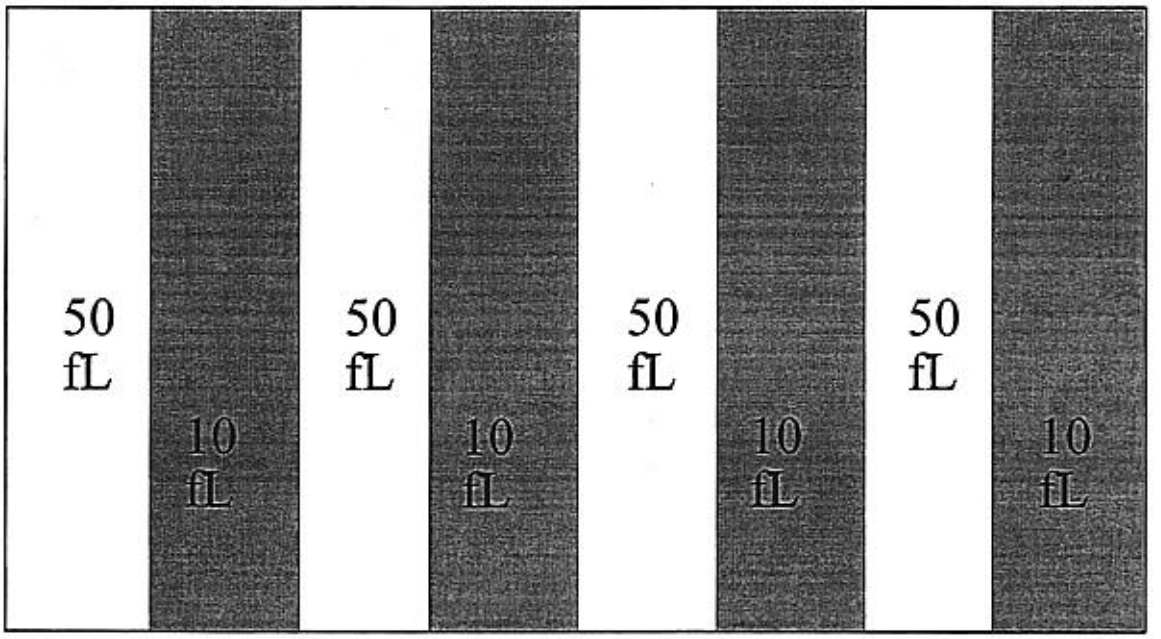


Figure 2. A periodic luminance pattern.

In summary, for any given luminance pattern consisting of two different luminance values, a number of different contrast figures of merit can be calculated. For periodic luminance patterns, the modulation contrast figure of merit is preferred. However, since algebraic manipulation can be used to convert between the various contrast figures of merit, perhaps the most important step in presenting any contrast value is to clearly define the selected figure of merit. In more realistic images, which contain many luminance values, the contrast value is calculated in terms of multiple frequencies using the minimum and maximum luminance value. (See Peli, 1990, for an extended discussion of different formulations of image contrast in terms of human spatial frequency channels.) Appendix A gives a discussion of contrast in complex images.

Contrast and the human visual system

The human visual system's ability to discern information from a displayed image is limited by its capacity to perceive differences in luminance within the image. These luminance contrasts demarcate the available pattern information of the image. Discounting color and temporal differences, image information is conveyed primarily by patterned contrast. Thus the information that can be conveyed by a display to a human observer is fundamentally limited by the human ability to perceive contrast. Different magnitudes of contrast are required to perceive different images. For example, the image of a large sharply demarcated object may require less

contrast than the image of a small blurry object. If the contrast in an image is too low, i.e., below the visual threshold for detecting contrast, the displayed information will not be perceived. To make appropriate use of the figures of merit describing image quality in terms of contrast, one must characterize the human limitations in detecting contrast. The ultimate goal is to ensure an appropriate match between the contrast in the image conveying the displayed information and the human perceiver's ability to use that contrast.

The smallest magnitude of contrast that can be detected is a just noticeable difference (jnd) between two luminances. A "jnd" is a threshold value that is typically defined as some percentage of the time that a stimulus is correctly detected, often arbitrarily set at 75 percent. In other words, a jnd of contrast is the threshold magnitude of the luminance difference between two areas that is required to just detect that difference. In order to understand the relevance of the luminances of a display in terms of human perception, the dynamic range of a display, the difference between the maximum and minimum luminances, can be defined, or scaled, in terms of the number of jnds within that range. The number of jnds from minimum to maximum luminance gives us the luminance range in human threshold units (Schuchard, 1990).

The threshold contrast detection characteristics of the human visual system have been quantified in a number of different experiments (IES, 1984). Examples of data are shown in Figures 3-5. A typical plot of a probability function for detecting a small round test target, for different luminances of the target, against a constant uniform luminance background is given in Figure 3 as a function of the contrast between the target and the background. The plot shows that the probability of "seeing" the target increases from zero until the contrast between target and background reaches 1.0, where the target can be detected 100 percent of the time. [This is a typical threshold curve with an ogival (monotonically increasing s-shaped) region between perfect visual performance and chance performance, where the threshold point is defined as one of the values on the curve, usually the 75 percent correct point for a yes/no detection paradigm.] The contrast threshold value is affected by many factors, including, for example, target size, background luminance, and viewing duration as shown in Figures 4 and 5. Threshold contrast decreases with increasing size and with increasing background luminance as shown in Figure 4, where target size is held constant.

An efficient way of characterizing the contrast threshold responses of the human visual system is the contrast sensitivity function shown in Figure 6, where "contrast" refers to modulation contrast. This plots contrast threshold values as a function of target spatial frequency. Spatial frequency refers to the number of a periodic pattern's repetitions, or cycles, within a unit length. [This unit length is typically expressed as a degree of visual angle when the perceiver is emphasized or as a display width when the image is emphasized.] Contrast sensitivity (on the vertical axis) is the reciprocal of the contrast threshold. The curve indicates that the human visual system is maximally sensitive, i.e., requires the least contrast to detect the pattern's presence, for patterns with a spatial frequency somewhere between 2 and 5 cycles per degree of visual angle. Sensitivity drops off for lower and for higher spatial frequency targets. Targets smaller or larger than the optimum size need more contrast to be seen.

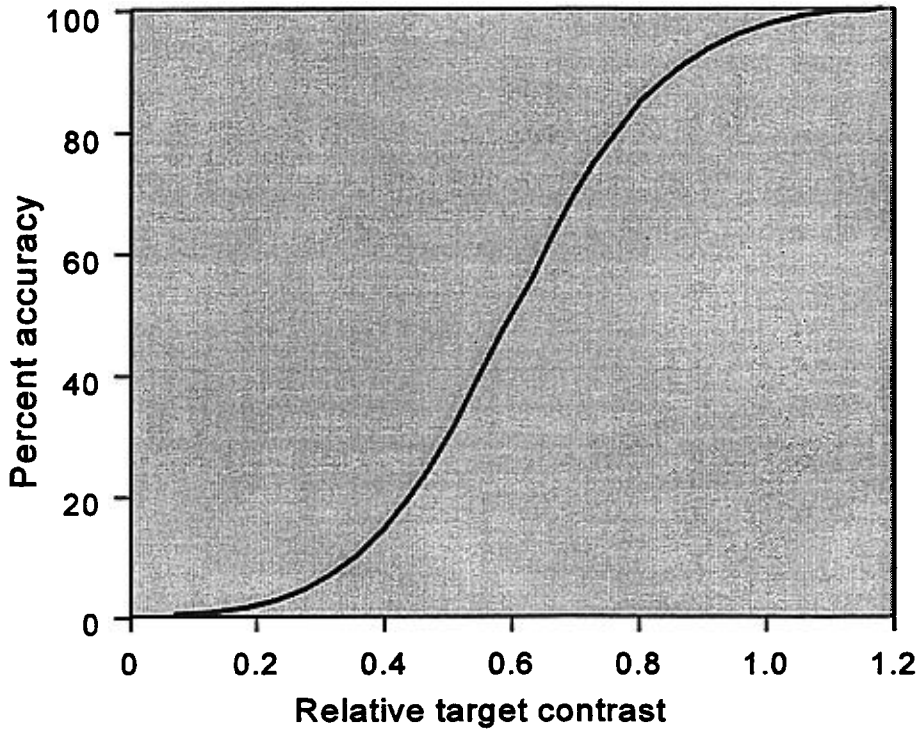


Figure 3. Probability of detecting a small round target luminance against a uniform background luminance (IES, 1984).

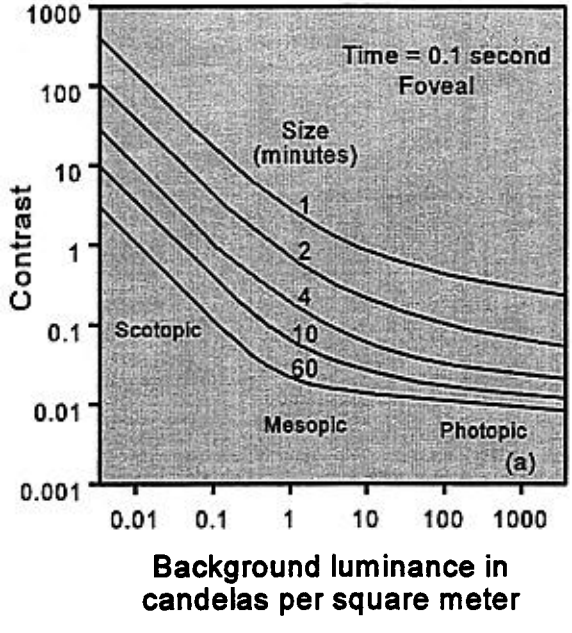


Figure 4. The relationship between foveal threshold contrast and background luminance for various sized targets (IES, 1984).

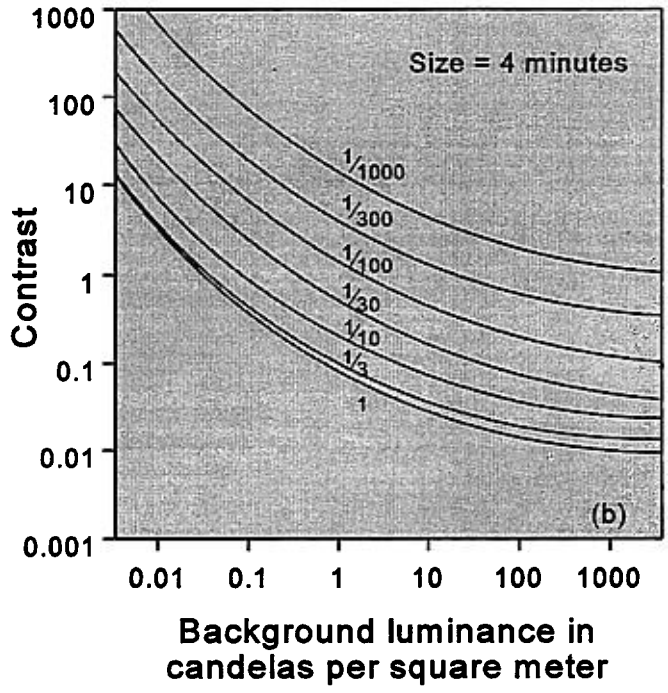


Figure 5. The relationship between threshold contrast and background luminance for various viewing times (IES, 1984).

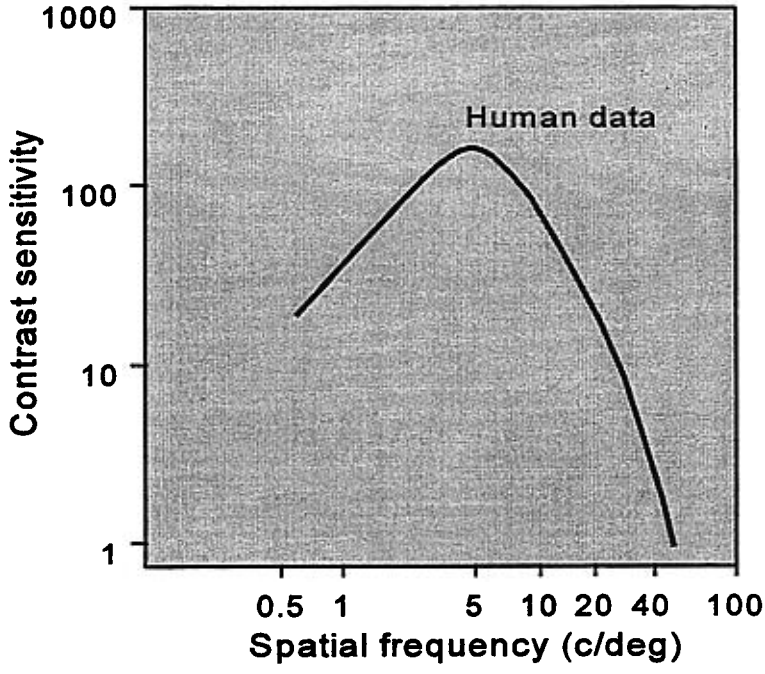


Figure 6. The contrast sensitivity function.

Sine wave gratings are typically used as the stimulus in generating human contrast sensitivity functions because the mathematical tools available (Fourier analysis and linear systems theory) allow one to generalize the results to a wide range of imaging conditions. [It also allows one conceptually to integrate the human perceiver component into a description of the total imaging context.] The human contrast sensitivity curve essentially describes the ability of the human visual system to perceive luminance differences for different gradients of luminance change across an image in one orientation. For example contrast detection threshold is dependent on whether the stimulus is a thin and sharp edge, i.e., a high spatial frequency stimulus with a sharp gradient in luminance, or a blurry edge, i.e., a low spatial frequency stimulus with a slow gradient, or an intermediate edge, to which the visual system is maximally sensitive. An analogous function for display devices, the sine wave response (SWR) curve, is a contrast based figure of merit describing image quality in terms of a display's efficiency in converting voltage (scene contrast data) into displayed image contrast for different spatial frequencies. The human contrast sensitivity curve can likewise be considered as the visual system's efficiency curve in transmitting a physical stimulus contrast into a perception. These contrast transmission curves are also known as modulation transfer function (MTF) curves. A CRT display's MTF curve, unlike the human curve, typically is a monotonic function, maximum at the lowest spatial frequency available (determined by the display width) and decreasing to zero at the limiting highest spatial frequency of the display. A typical MTF is shown in Figure 7. This means that a very small object cannot be displayed with the same high contrast as a larger object.

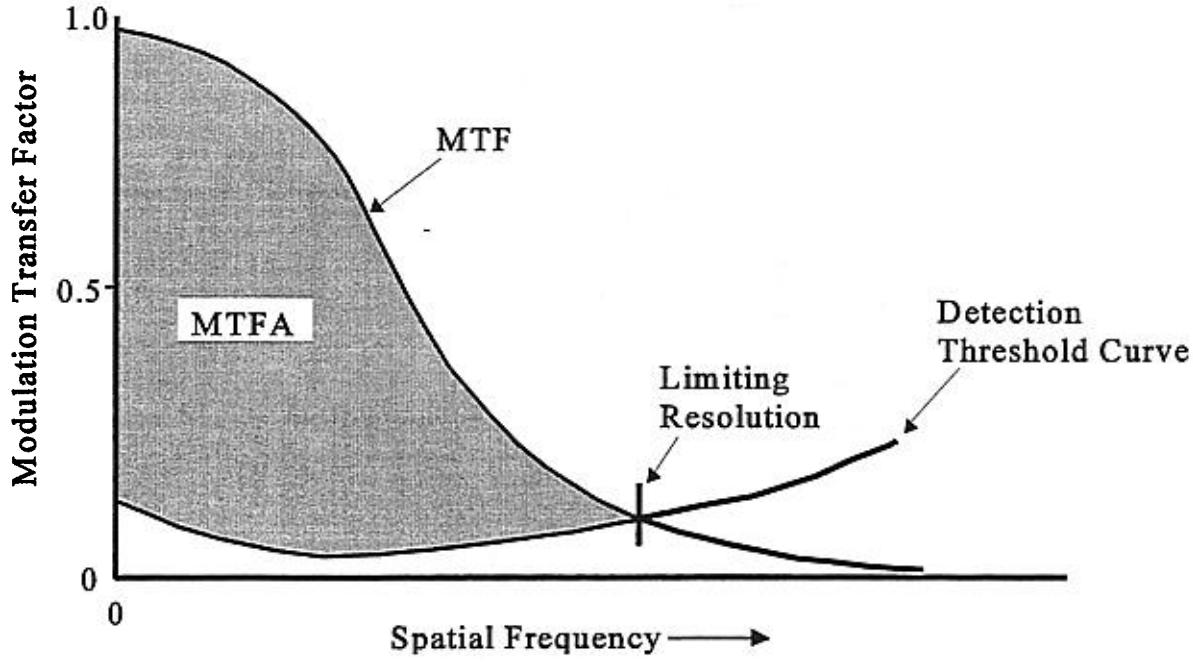


Figure 7. Modulation transfer function (MTF) and modulation transfer function area (MTFA)

Image display scientists have theorized and researched the question of how to mathematically combine the human and the display's contrast transmission efficiency curves in order to predict the suitability of a display's capacity to present contrast in terms of the human's ability to perceive it (Snyder, 1980). One attempt at combining human and display contrast transmission curves is the figure of merit known as the modulation transfer function area (MTFA), which quantifies the area of overlap between the contrasts available in the display at various spatial frequencies and the human contrast sensitivity curve, which is the ability to perceive contrast at the various spatial frequencies (Figure 7). Additional theoretical and empirical work has concentrated on the appropriate methods of refining the scaling of the physical parameter in terms of the observer's visual sensitivity. Examples include Task and Verona's (1976) "jnd" rescaling incorporating the logarithmic luminance compression of the human visual system, and more recently, Barten's (1990) work incorporating additional factors modeling the behavior of human vision. Determining the best figure of merit formulation for contrast transmission efficiency, which incorporates both human display contrast factors, is currently an active area of research and debate.

Color (chromatic) contrast

While the ability to discriminate between two luminance values has been the major point of emphasis, images where the background and target have the same luminances can still be discerned by color differences (chromatic contrast). These equal luminance chromatic contrasts are less distinct in terms of visual acuity than luminance contrasts, but can be very visible under certain conditions (Kaiser, et al., 1971).

The sensation of color is dependent not only on the spectral characteristics of the target being viewed, but also on the target's context and the ambient illumination (Godfrey, 1982). The sensation of color can be decomposed into three dimensions: hue, saturation, and brightness. Hue refers to what is normally meant by color, the subjective "blue, green, or red" appearance. Saturation refers to color purity and is related to the amount of neutral white light that is mixed with the color. Brightness refers to the perceived intensity of the light.

The appearance of color can be affected greatly by the color of adjacent areas, especially if one area is surrounded by the other. A color area will appear brighter, or less gray, if surrounded by a sufficiently large and relatively darker area, but will appear dimmer, or more gray, if surrounded by a relatively lighter area (IES, 1984). To further complicate matters, hues, saturations, and brightnesses may all undergo shifts in their values.

The use of color in displays increases the information capacity of displays and the natural appearance of the images. CRTs can be monochrome (usually black and white) or color. Color CRTs use three electron beams to individually excite red, blue, and green phosphors on the face of the CRT. By using the three primary colors and the continuous control of the intensity of each beam, a CRT display can provide "full color" images. Likewise, FPDs can be monochrome or

color. Many flat panel displays that produce color images, are still classified as monochrome because these displays provide one color for the characters or symbols and the second color is reserved for the background, (i.e., all of the information is limited to a single color). An example is the classic orange-on-black plasma discharge display, where the images are orange plasma characters against a background colored by a green electroluminescent backlight (Castellano, 1992).

Full color capability has been achieved within the last several years in most all of the flat panel technologies, including liquid crystal, electroluminescent, light emitting diode, field emission, and plasma displays. Even some of the lesser technologies, such as vacuum fluorescence, can provide multicolor capability. Research and development on improving color quality in flat panels is ongoing. Figures of merit describing the contrast and color generating capacities of displays are an ongoing area of development.

Figures of merit defining color contrast are more complicated than those presented previously where the contrast refers only to differences in luminance. Color contrast metrics must include differences in chromaticities as well as luminance. And, it is not as straightforward to transform chromatic differences into jnds in a perceived color space. This is due to a number of reasons. One, color is perceptually a multidimensional variable. The chromatic aspect, or hue, is qualitative and two dimensional, consisting of a blue-yellow axis and a red-green axis. Additionally, the dimensions of saturation and brightness, as well as other factors such as the size and shape of a stimulus, affect the perceived color and perceived color differences. The nature of the stimulus, whether it is a surface color, reflected off a surface, or a self-luminous color, as present in a display, will affect the perceived color space in complex ways. Delineating the nature of perceived color space has been an active area of research with a vast literature (Widdel and Post, 1992).

As a consequence, there is no universally accepted formulation for color contrast. One figure of merit combining contrast due to both luminance and color, known as the discrimination index (ID), was developed by Calves and Brun (1978). The ID is defined as the linear distance between two points (representing the two stimuli) in a photocolorimetric space. In such a space, each stimulus is represented by three coordinates (U, V, log L). The U and V coordinates are color coordinates defined by the CIE 1960 chromaticity diagram. The third coordinate, log L, is the base ten logarithm of the stimulus luminance. [A concise discussion of the discrimination index is presented in Rash, Monroe and Verona (1981).] The distance between two points (stimuli) is the ID and is expressed as:

$$\mathbf{ID} = \left[\left(\frac{\log(L_1/L_2)}{0.15} \right)^2 + \left(\frac{\left[(\Delta U)^2 + (\Delta V)^2\right]^{1/2}}{0.027} \right)^2 \right]^{1/2} \qquad \text{Equation 9}$$

where L_1 and L_2 refer to the luminances of the two stimuli, and (ΔU) and (ΔV) refer to the distances between the colors of the two stimuli in the 1960 CIE two dimensional color coordinate space.

A more recent figure of merit, ΔE (Lippert, 1986; Post, 1983), combining luminance and color differences into a single overall metric for contrast, has been provisionally recommended for colors which present only an impression of light, unrelated to context, only recently by the International Organization for Standardization (ISO, 1987) for colored symbols on a colored background. It is defined as follows:

$$\Delta E = \left[(155\ \Delta L/L_{Max})^2 + (367\ \Delta u')^2 + (167\ \Delta v')^2\right]^{1/2} \qquad \text{Equation 10}$$

where the differential values (Δ) refer to the luminance (L) and chromaticity (u', v') differences between symbol and background and L_{max} refers to the maximum luminance of either symbol or background. Developing the appropriate figure of merit to describe the color contrast capacities of displays is an ongoing area of development (Widel and Post, 1992).

Analog and digital displays

An analog device is one in which the signal varies continuously over some predetermined range. An analog display is one where the displayed luminances can take on any possible value between the minimum and maximum values. For example, in a CRT display, the luminance value at a given point on the face of the display is determined by the intensity of the electron beam as it sweeps over the point. Changing luminance values is achieved by varying the beam intensity. In a single sweep of the electron beam of a CRT display, points along the resulting line can take on any luminance value within the allowable range. (How much the beam can change luminance values between neighboring points during a sweep is specified by the MTF of the display.) CRTs are capable of producing luminance patterns (such as an outdoor scene) which contain a large variation of luminance values. The range from minimum to maximum luminance values that can be produced is referred to as the dynamic range of the display.

CRT displays often are characterized by measuring and plotting the luminance of an arbitrary area of the display as a function of the voltage on the anode of the CRT, which controls the electron beam current. Figure 8 shows a typical light output vs. voltage curve, which is called a "gamma curve." The continuous nature of this curve illustrates the analog nature of this type of display. This analog characteristic has led to an often used, but often misunderstood, method of describing an analog display's dynamic range (Tannas, 1985). This descriptor for the luminance dynamic range within a scene reproduced on a CRT display is the number of shades of gray (SOG).

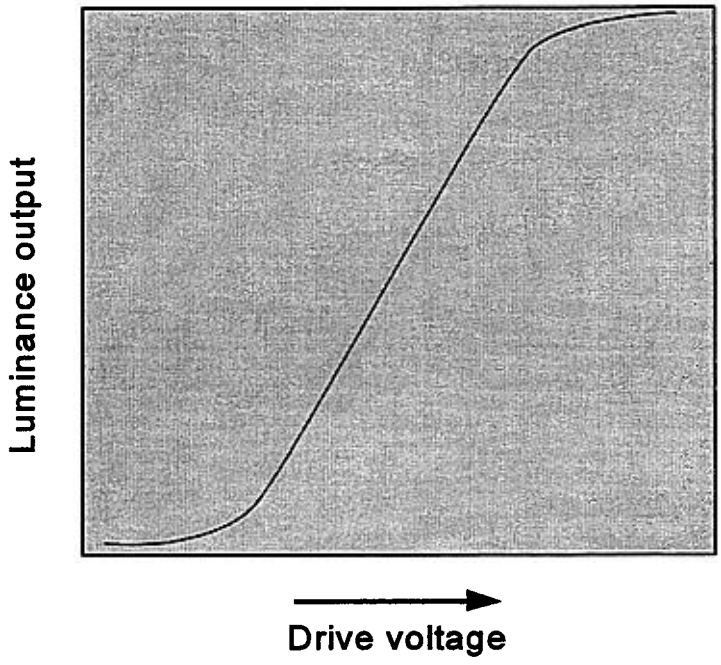


Figure 8. Typical gamma curve.

SOG are luminance steps which differ by a defined amount. They are by convention typically defined as differing by the square-root-of-two (approximately 1.414). For example, if the lowest (minimum) luminance value within a scene is 10 fL, then the next square-root-of-two gray shade would be 10 multiplied by 1.414 or 14.14 fL. The next gray shade, if present, would be 14.14 multiplied by 1.414 or 20.0 fL, and so on. Therefore, a scene having 10 and 20 fL as its minimum and maximum luminance values, respectively, would have a dynamic range of 3 shades of gray (10, 14, and 20 fL). Its contrast ratio (C_r) would be 20/10 or 2.0.

For a linear system, which CRTs are considered to be over most of their dynamic luminance range, there is a straightforward relationship between the number of shades of gray and the contrast ratio. This relationship is:

$$\text{Number of SOG} = [\log(C_r)/\log(\sqrt{2})] + 1 \qquad \text{Equation 11}$$

The addition of the 1 takes into account the first luminance level (gray shade). This can be illustrated by considering the number of SOG in a scene which is of uniform luminance, i.e., the minimum and maximum luminances are the same. For this special case, the contrast ratio is 1/1 or 1, and using Equation 11:

$$\begin{aligned}\text{Number of SOG} &= \log(C_r)/\log(\sqrt{2}) + 1\\ &= \log(1)/0.1505 + 1\\ &= 0/0.1505 + 1 = 0 + 1\\ &= 1,\end{aligned}$$

which means that a scene of uniform luminance has one gray shade. Table 3 shows SOG and corresponding contrast ratios.

Table 3.

Shades of gray (SOG) and corresponding contrast ratios.

Shades of gray	1	2	3	4	4.5	8	16
Contrast ratio	1.00	1.41	2.00	2.83	3.40	11.3	181

It is worth noting that the square-root-two choice as the unit of the gray shade scale does not imply that the threshold for the human eye requires two luminances to differ by a ratio of 1.4 in order to reach a jnd. In fact, for targets of a wide range of spatial frequencies, the human eye can detect differences in luminances which are several times smaller than the square-root-of-two unit. The consistent use of square-root-of-two differences instead of empirical jnds is a practical compromise between an engineering and a psychophysics philosophy.

Square-root-of-two SOG have been used historically for CRTs, which have enjoyed a position of preeminence as the choice for given display applications for decades. However, within the past few years, the FPD technologies have begun to gain a significant share of the display application market. Displays based on these various flat panel technologies differ greatly in the mechanism by which the luminance patterns are produced, and all of the mechanisms differ from that of CRTs. In addition, FPDs differ from conventional CRT displays in that most flat panel displays are digital with respect to the signals which control the resulting images. (Note: There are FPD designs which are capable of continuous luminance values, as well as CRTs which accept digital images.) As a result, usually, luminance values for flat panel displays are not continuously variable but can take on only certain discrete values. Figure 9 graphs the 16 available luminance values, the gray levels, of a typical graphic LCD. A difference between analog and digital displays is the way in which the incoming signal (usually a voltage) can change. In analog displays, the input signal voltage can vary continuously (i.e., can take on any value in the range) and, therefore, so can the output signal, i.e., the luminance. However, for most digital displays, e.g., FPDs, the input signal voltage takes on certain discrete values; thus, the output luminance also can take on only certain discrete values. In other words the luminance output of a digital flat panel display is quantized as shown in Figure 9. Discrete luminance values of the 16 gray levels of a graphic LCD measured in our laboratory, where minimum and maximum values were 3.6 cd/m^2 (1.05 fL) and 44.6 cd/m^2 (13.0 fL), respectively, give a contrast ratio of 12.4.

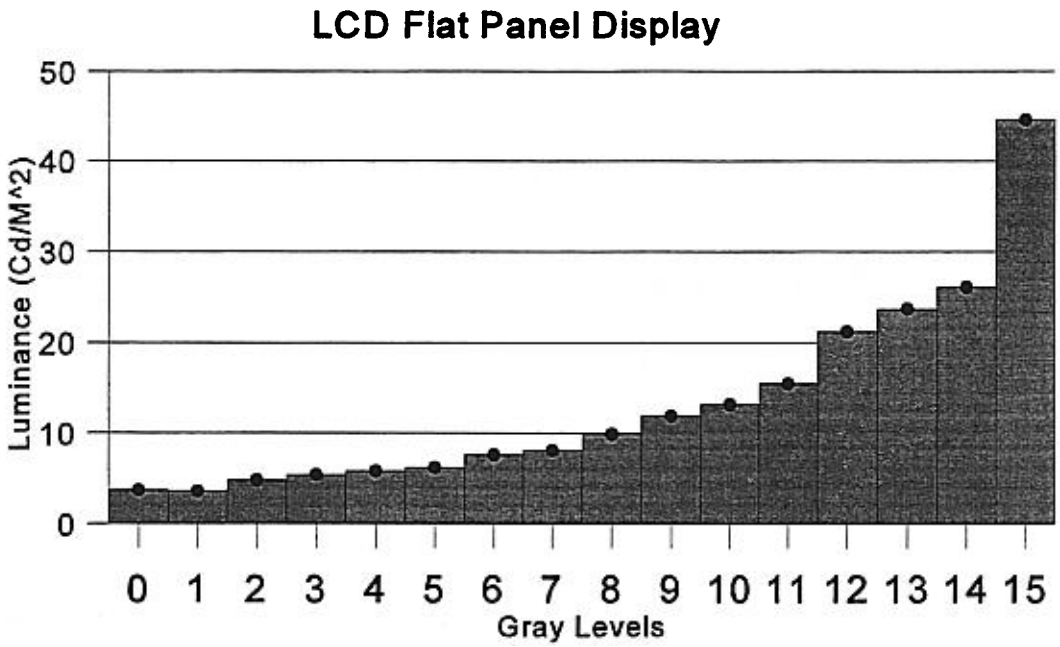


Figure 9. Discrete luminance values of the 16 gray levels of a graphic LCD display.

Confusion can occur when the term gray shades, historically used to express the number of discriminable luminance levels in the dynamic luminance range of analog CRT displays, is applied to digital FPDs. Since these displays, in most cases, can produce only certain luminance values, it is reasonable to count the total number of possible luminance steps and use this number as a figure of merit. However, this number should be referred to as "gray steps" or "gray levels," not "gray shades." For example, a given LCD may be specified by its manufacturer as having 64 gray levels. The uninitiated may misinterpret this as 64 shades of gray, which is incorrect. It's true meaning is that the display is capable of producing 64 different electronic signal levels between, and including, the minimum and maximum values, which generally implies 64 luminance levels. If one insisted on using an SOG figure of merit for discrete displays, it would appropriately depend on the value of the 1st and 64th levels.

This is not advisable as misinformation can easily result from confusing gray shades and gray levels. Consider the 16 gray level specification of the LCD flat panel display, whose luminance levels are shown in Figure 9. If this 16 gray level specification is misinterpreted as 16 gray shades, a contrast ratio of 182.0 would be falsely implied as shown by Table 3. If, instead, we conversely use the LCD's available contrast ratio of 12.4 to compute an SOG, an appropriate figure of merit only for analog systems, we get a value of only 8.3, which is less than the 16 gray levels of the display. (It should be noted here that since SOG is assumed to refer to discriminable luminance levels in analog displays, there is a further question as to whether the 16 discrete gray levels adequately sample the range in terms of discriminable luminance levels.) To reiterate, for analog displays, a SOG specification is computed from the contrast ratio consisting of the minimum and maximum luminances. To actually produce a contrast ratio of 181.0 (equivalent to

16 SOG if it were an analog display), the LCD display in Figure 9 would need a maximum luminance of 651.6 cd/m^2 if its minimum luminance was 3.6 cd/m^2.

In summary, to avoid confusion, one should limit some figures of merit to either discrete or analog displays. Contrast ratio, computed from maximum and minimum luminance is applicable to both. The concept of SOG is most appropriate for analog displays and can be computed from contrast ratio. The number of gray levels is most appropriate for displays with discrete luminance steps, but additional information on how these gray levels sample the luminance range needs to be specified.

Other contrast figures of merit may still be applicable to FPDs. However, in some cases they have been adapted to conform to the unique characteristics of these displays. For example, because of the discrete nature of FPDs, where the image is formed by the collective turning on or off of an array of pixels, the concept of contrast ratio is redefined to indicate the difference in luminance between a pixel that is fully "on" and one that is "off" (Castellano, 1992). The equation for pixel contrast ratio is:

$$C_r = (\text{Luminance of ON pixel})/(\text{Luminance of OFF pixel}) \qquad \text{Equation 12}$$

It can be argued that this pixel contrast ratio is a more important figure of merit for discrete displays. Unfortunately, the value of this figure of merit as cited by manufacturers is intrinsic in nature. That is, it is the contrast value in the absence of ambient lighting effects. The value of this figure of merit which is of real importance is the value which the user will actually encounter. This value depends not only on the ambient lighting level, but also on the reflective and diffusive properties of the display surface (Karim, 1992). Additional factors may need to be taken into consideration. An example is the dependance of luminance on the viewing angle, where a liquid crystal display's luminance output given by a manufacturer may only be reliable for a very limited viewing cone. Here the luminance and contrast need to be further specified as a function of viewing angle. On the other hand, the propensity of manufacturers sometimes to define "additional" figures of merit which put their products in the best light must always be kept in mind.

The term gray scale is used to refer to the luminance values available on a display. (The term as used usually includes available color as well as luminance per se.) Gray scales can be analog or digital. The display may produce a continuous range of luminances, described by the shades of gray concept; or, it may only produce discrete luminance values referred to as gray steps or gray levels. The analog case is well specified by the SOG figure of merit and more compactly by the maximum contrast ratio of the dynamic range. Also the gamma function succinctly describes the transformation from luminance data (signal voltage) to displayed image luminance. (The MTF additionally describes the display's operating performance in transferring contrast data to transient voltage beam differences over different spatial scales.) In an analog image, easily applicable image processing techniques, such as contrast enhancement algorithms, are available to reassign the gray levels to improve the visibility of the image information when

the displayed image is poorly suited to human vision. (The techniques are easily applicable because they often simply transform one continuous function into another, where computer control over 256 levels is considered as approximating a continuous function for all practical purposes.) Poor images, in need of image processing, often occur in unnatural images, such as thermal images; and artificial images, such as, computer generated magnetic resonance medical images. Since only certain discrete luminance levels are available in the digital case, the description of the gray scale and its effect on perception is not as simple and straightforward as in the analog case. One would like to know if there is a simple function which can describe the luminance scale; but one would also like to know how the function is sampled. A problem is, many image enhancement techniques may not be as effective if the discrete sampling of the dynamic range is poor. For example, consider an infrared sensor generated image presented on an LCD with a small number of discrete gray levels. A contrast enhancement algorithm in reassigning pixel luminances must pick the nearest available discrete gray level and so could inadvertently camouflage targets by making them indistinguishable from adjacent background. Also the original image might contain spurious edges because neighboring pixel luminance values which would normally be close and appear as a smooth spatial luminance gradient become widely separated in luminance due to the available discrete levels, thus producing quantization noise.

There are numerous ways the different technologies can generate gray scales. The CRTs analog gray scale is generated by amplitude modulation of the electron beam current to produce a continuous range of luminances. A number of methods are used in flat panels. Each method relies on electronic controllers to translate gray level data to the form used by the display's circuitry. In pulse-amplitude modulation, transient voltage levels directly control luminance at each pixel.

Instead of voltage, a number of methods use timing to achieve gray scale. The luminance is controlled by the amount of time a pixel is turned off versus turned on. For example, in pulse-width modulation, the variation in the width of the pulse to a pixel during an addressing cycle determines the pixel's luminance. Other methods use different variations of the timing method such as duty cycle modulation, multiple pulse widths per frame, or combinations of pulse-width and pulse-amplitude modulation. Each of these methods trade temporal resolution for gray scale. This can become a problem if the duration of the timing intervals needed to generate the gray scale become too large. This occurs in some LCDs that use this technique over multiple frames to control the luminance. This results in perceived smearing during image motion.

Other methods trade spatial resolution rather than temporal resolution for gray scale. One simple method uses physical subpixels. A common example is the case, where each pixel consists of four subpixels, with areas in the ratio of 8, 4, 2 and 1, where area of the pixel is equal to the luminance it generates. The subpixels are below human spatial resolution, so turning on different combinations of them are seen as brightness differences. In this case the gray scale will consist of 16 linearly spaced luminance levels. These steps can also be logarithmically spaced. Another method trading spatial resolution for gray scale is dithering. This involves turning on

random pixels in small unit areas to control the overall luminance of each unit area, where more pixels turned on increases the luminance. This method reduces the spatial resolution of the display by adding spatial noise to achieve the gray scale.

Each method of generating gray scales has advantages and limitations (Sobel, 1992, for a review). The desirability of the trade-offs between the contrast figures of merit, quantifying gray scales, and other figures of merit, quantifying other spatial and temporal parameters, need to be weighed in light of the display's intended use. Contrast figures of merit quantifying the display's image are not only the result of the technology's method of image generation, but also of the method of image presentation, whether, for instance, the image is presented by a projection system, is seen as a head-up display, is seen directly as a panel-mounted display (PMD), or through the optics of a helmet- or head-mounted-display (HMD).

Panel- vs. head-mounted displays

Imagery can be presented in a direct or indirect viewing mode. PMDs represent the direct viewing mode. Imagery is present on the display which is located at a near to moderate distance range. The user views the display directly.

In some advanced display system designs, the head is used as a mounting platform for the display. This has been most prevalent in military systems. The U.S. Army fields a helmet mounted display (HMD) called the Integrated Helmet and Display Sighting System (IHADSS) on the AH-64 Apache helicopter. Integral to this system is a miniature, 1-inch diameter, CRT which is attached to the right side of the helmet (Figure 10). A number of other proposed display systems are based on the use of the miniature CRT or small (3/4-inch diagonal) liquid crystal and electroluminescent FPDs.

Most of these advanced HMD designs, such as the IHADSS, present the imagery on a display which is viewed indirectly by means of some optical relay system. These systems incorporate see-through optics in which the imagery (and/or symbology) is superposed on the real world scene. While these see-through optical designs have numerous advantages (e.g., sensor or
unaided vision with overlaid symbology) and have proven successful, as in the AH-64 IHADSS, ~~However,~~ imagery displayed on see-through optics is subject to contrast attenuation from ambient lighting. This effect can be significant during daytime flight when ambient illumination is highest.

Such designs require a number of optical elements between the display and the viewer, which may result in reductions in luminance transmittance. In see-through designs the imagery or symbology is superimposed against a direct view of the outside world consisting of varying luminances. This results in contrast attenuation of the image viewed against the background ambient lighting. In these systems, the contrast available to the viewer, not merely that generated

Figure 10. Integrated Helmet and Display Sighting System (IHADSS).

by the display, must be specified. That is, the image contrast as seen through the display optics is degraded by a superimposed outside image from the see-through component which is transmitting the ambient background luminance. The effect can be very significant during daytime flight when ambient illumination is highest.

A typical HMD optical design in a simulated cockpit scenario is shown in Figure 11. The relay optics consist of two combiners, one plano and one spherical. Light from the ambient scene passes through the aircraft canopy, helmet visor, both combiners, and then enters the eye. Simultaneously, light from an image source such as a CRT partially reflects first off of the plano combiner and then off of the spherical combiner, and then is transmitted back through the plano combiner into the eye. The resulting image is a combination of the modified ambient (outside) scene and CRT images. Nominal values for the transmittances and reflectances of the various optical media are: 70 percent canopy transmittance; 85 percent and 18 percent transmittance for a clear and shaded visor, respectively; 70 percent transmittance (ambient towards the eye); and 70 percent reflectance (CRT luminance back towards the eye) for the spherical combiner, and 60 percent transmittance (ambient towards the eye) and 40 percent reflectance (CRT luminance) for the plano combiner. An analysis of this design shows that approximately 17 percent of the luminance from the CRT image (and CRT optics) and approximately 25 percent of the ambient scene luminance reaches the eye for the clear visor (5 percent for the shaded visor).

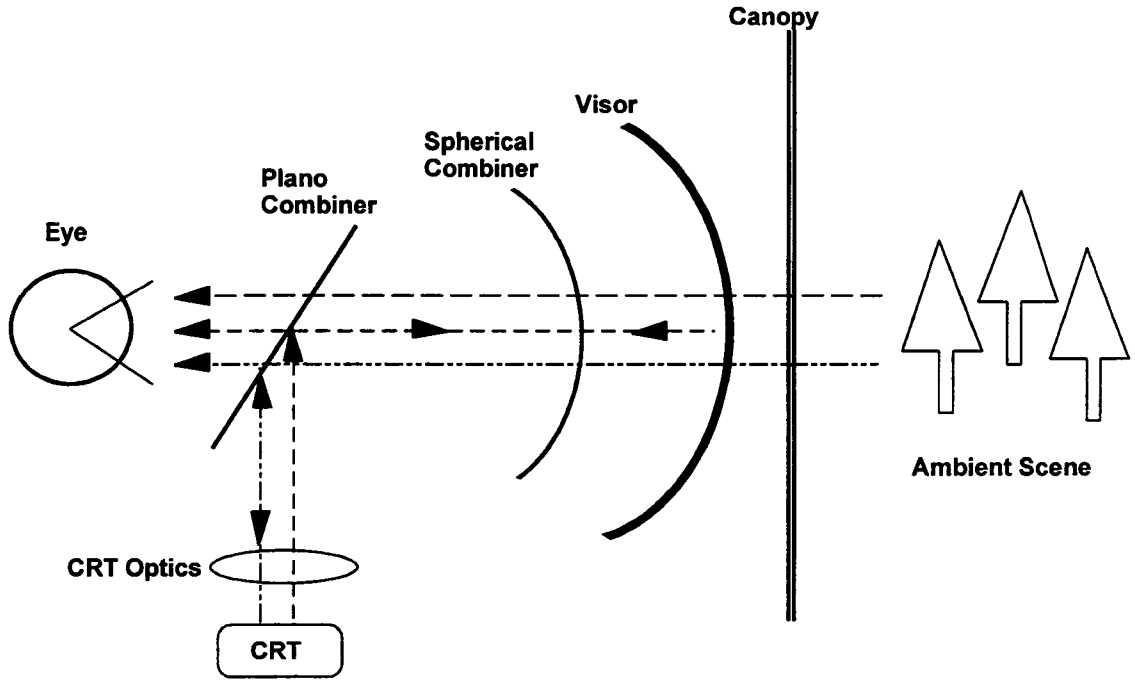


Figure 11. Typical catadioptric HMD optical design.

Ambient scene luminances vary greatly over a 24-hour period. They can range from 0.001 fL under moonless, clear starlight conditions to 10,000 fL for bright daylight. Daytime luminances begin at approximately 300 fL. The image source used in Figure 11 is a miniature CRT. Depending on viewing time, day versus night, luminance values provided by the CRT and its associated optics can be selectively ranged from 100 fL (for night use) to an optimistic 1600 fL (for day use). A luminance of 800 fL may be a more typical daytime value.

Image contrast during night operations is usually not a problem. However, the use of HMDs for daytime imagery (versus for symbology) is not well defined. Based on the design in Figure 11 and the nominal values provided, Table 4 provides the theoretical values for Michelson contrast (C_m, Eq. 3a and 3b), contrast ratio (C_r, Eq. 2a), and shades of gray (SOG, Eq. 11) for various combinations of visors, ambient scene luminances, and CRT display luminances. In these equations, the ambient luminance reaching the eye assumes the role of the background luminance and the sum of the CRT and background luminances reaching the eye assumes the role of the target luminance. Note that for the purpose of these calculations, the background luminance is a combination of the light reaching the eye due to both the ambient and the CRT luminances. See Appendix B for a sample calculation of Michelson contrast, contrast ratio, and shades of gray values for the set of conditions for viewing an 800 fL CRT against a 3,000 fL ambient scene using both clear and shaded visors.

Several obvious trends are present in the data of Table 4. These are: (1) for a given ambient background luminance, increasing the CRT display luminance increases contrast; (2) for a given CRT display luminance, increasing ambient background luminance decreases contrast; and (3) for a given set of CRT display and ambient background luminances, the use of a shaded visor over a clear visor increases contrast.

Table 4.

Michelson contrast, contrast ratio, and SOG values for HMD design

	Ambient luminance					
	3,000 fL		1,000 fL		300 fL	
Display luminance	Clear visor	Shaded visor	Clear visor	Shaded visor	Clear visor	Shaded visor
100 fL	$C_m = 0.01$ $C_r = 1.02$ SOG= 1.06	$C_m = 0.05$ $C_r = 1.11$ SOG= 1.29	$C_m = 0.03$ $C_r = 1.07$ SOG= 1.19	$C_m = 0.14$ $C_r = 1.32$ SOG= 1.80	$C_m = 0.10$ $C_r = 1.22$ SOG= 1.59	$C_m = 0.35$ $C_r = 2.06$ SOG= 3.09
400 fL	$C_m = 0.04$ $C_r = 1.09$ SOG= 1.25	$C_m = 0.17$ $C_r = 1.42$ SOG= 2.02	$C_m = 0.12$ $C_r = 1.27$ SOG= 1.69	$C_m = 0.39$ $C_r = 2.27$ SOG= 3.37	$C_m = 0.32$ $C_r = 1.90$ SOG= 2.85	$C_m = 0.68$ $C_r = 5.23$ SOG= 5.79
800 fL	$C_m = 0.08$ $C_r = 1.18$ SOG=1.48	$C_m = 0.30$ $C_r = 1.85$ SOG= 2.77	$C_m = 0.21$ $C_r = 1.54$ SOG= 2.25	$C_m = 0.56$ $C_r = 3.54$ SOG= 4.66	$C_m = 0.47$ $C_r = 2.79$ SOG= 3.97	$C_m = 0.81$ $C_r = 9.45$ SOG= 7.50
1600 fL	$C_m = 0.15$ $C_r = 1.36$ SOG= 1.89	$C_m = 0.46$ $C_r = 2.69$ SOG= 3.87	$C_m = 0.35$ $C_r = 2.08$ SOG= 3.11	$C_m = 0.72$ $C_r = 6.07$ SOG= 6.22	$C_m = 0.64$ $C_r = 4.58$ SOG= 5.40	$C_m = 0.89$ $C_r = 17.91$ SOG= 9.35

Contrast requirements

Once appropriate figures of merit have been established for quantifying contrast, an obvious question is what are their recommended values. Unfortunately, there is no single value or set of values, for minimum contrast requirements. The amount of contrast required to perform a task on a display depends on numerous factors. These factors include the type of visual task (e.g., rapid target detection or status indicators), the viewing environment (e.g., ambient light level, presence of glare sources, the size and distance of the display, etc.), the nature of the displayed information (e.g., text, symbology, video, graphics), and the other display characteristics (such as screen resolution, blur and sharpness, jitter, color, pixel geometry, etc.).

Despite the inability to establish a singe set of contrast requirements, a considerable amount of research has gone into determining requirements for viewing and interpreting information in various display scenarios (Farrell and Booth, 1984; Masterman, Johnson and Silverstein, 1990; Silverstein, 1989). For example, for text to be legible on a directly viewed display, it is recommended that the modulation contrast for small characters (between 10 and 20 arc minutes) displayed on a monochrome CRT should be at least that defined by the equation:

$$C_m = 0.3 + [0.07 * (20 - S)], \qquad \text{Equation 13}$$

where S is the vertical size of the character set, in minutes of arc (American National Standard for Human Factors Engineering of Visual Display Terminal Workstations, 1988). This equation is based on studies by Crook, Hanson, and Weisz (1954) and Shurtleff and Wuersch (1979). Consider, for example, characters 17 arcminute in size. Equation 13 specifies a minimum contrast modulation of 0.5 (contrast ratio of 3 to 1). However, in practice, a modulation value of 0.75 (contrast ratio of 7 to 1) is recommended. For example, if the background luminance is 3.3 fL, than the character luminance should be at least 10.0 fL.

Fortunately, even with the absence of well defined minimum contrast values, several rules of thumb can be applied. For displayed text, the above recommendation of a minimum contrast ratio value of 3:1, with 7:1 as the preferred value, can be used in benign viewing conditions. For displayed video, a minimum of 6 SOG is recommended.

The recommendations above generally apply to direct view monochromatic displays. Contrast recommendations for color displays are even more difficult to develop. Snyder (1980) reported that, while a number of studies have produced a large amount of data on color discrimination, most of these data are "threshold measurements which are not easily extrapolated to suprathreshold tasks, such as legibility." Some recent studies have attempted to address this deficiency (Imbeau et al., 1989; Lovasik et al., 1989; Pastoor, 1990; Travis et al., 1992), but fall short of definitive recommendations.

In applications where direct view displays are supplemented or replaced by helmet-mounted displays, the task of defining minimum contrast values is further complicated by optical and electro-optical design considerations. The U.S. Army's most current HMD program is the Helmet Integrated Display and Sighting System (HIDSS) being designed for use in the RAH-66 Comanche helicopter. The current version of this design is similar to that of Figure 11. The HIDSS specification for contrast and shades of gray, as available at the eye, addresses high ambient daylight (up to 10,000 fL background luminance) requirements. A contrast value (Equation 1a) of >4.66 with a minimum of 6 shades of gray is required. This contrast value of 4.66 is equivalent to a C_r value of 5.66 which corresponds to 6 SOG. For day symbology, the contrast ratio is required to equal or exceed a value of 1.5:1 for a 3000 fL background and equal to or exceed 7:1 for a background of 100 fL; both values are based on the use of a tinted visor. For nighttime viewing of sensor imagery, a minimum contrast ratio value of 11.2 which corresponds to 8 SOG is required.

Summary

One of the more basic figures of merit specifying the quality of an image produced by a display is the description of the available luminance contrast in the image. We have reviewed a number of figures of merit defining contrast. These different formulations of the concept of contrast should be kept clearly in mind when design tradeoff decisions and cost/effectiveness evaluations are made. Likewise, manufacturers' specifications should be carefully scrutinized. Different formulations of contrast may more suitably focus on the relevant image parameters of different display technologies. SOG are particularly well suited for specifying the contrast properties of analog CRTs, which have a continuously sampled luminance range. SOG are not the most suitable figure of merit for digital FPD, where the luminance range consists of discrete steps. Rather, gray levels should be used for FPDs, where the minimum and maximum luminance values need to be specified. Confusing SOG and gray levels could result in erroneous evaluation of a display's suitability in terms of human vision. Ongoing research is developing new figures of merit for specifying display image contrast in terms which are relevant for human visual performance. Image contrast should be specified for actual use conditions rather than for perfect laboratory conditions. This is particularly pertinent in integrated display systems such as helmet-mounted displays, where optical elements between the display and the observer attenuate the luminance of the image, and superimposed ambient light attenuates the contrast in the image available to the observer.

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Appendix A.

Contrast in complex stimuli

The contrast in complex spatial scenes is difficult to define, but a convenient way is to describe the contrast of the base elements of the pattern. For example, complex spatial patterns can be described by a sum of base sinusoidal patterns. This type of description follows from the mathematics of Fourier. By describing the pattern in frequency space rather than by spatial terms, even complex patterns can be analyzed and defined. Lets say that G is a complex pattern (Figure A-1a,b) composed of six sinusoidal grating patterns (Table A-1).

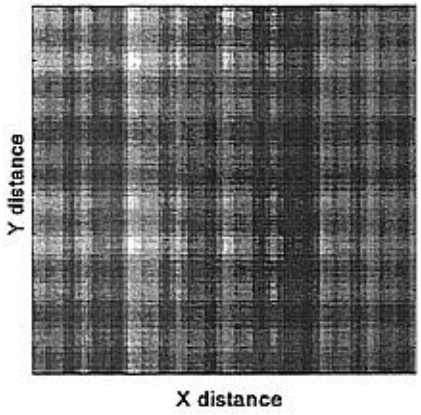

Figure A-1a. Image of sum of gratings.

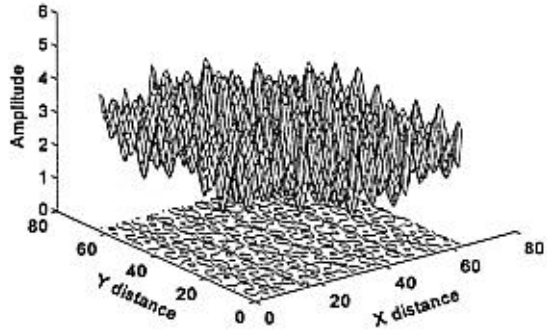

Figure A-1b. Three dimensional plot of sum of gratings.

Table A-1.

Characteristics of the six grating patterns

Grating #	Frequency	Orientation	Amplitude	Phase
1	1	Horizontal	1	0
2	2	Vertical	1	0
3	4	Horizontal	1	0
4	8	Vertical	1	0
5	8	Horizontal	1	0
6	16	Horizontal	1	0

Although such a target stimulus is constructed easily, it is difficult to identify the building blocks unless we look at the image in frequency space. Figure A-2a,b shows the shifted amplitude spectra for the sum of the gratings. Note that each grating is uniquely represented. (We purposely took out the average or dc component of the sum of gratings so that the grating amplitudes could be observed easily.) Also note that the amplitudes of the grating patterns are equal since each individual grating had an amplitude of 1. In frequency space, amplitudes are equal to a scalar times the grating amplitude. Please note that each frequency has corresponding positive and negative frequency components; but the reason for this does not need to concern us here.

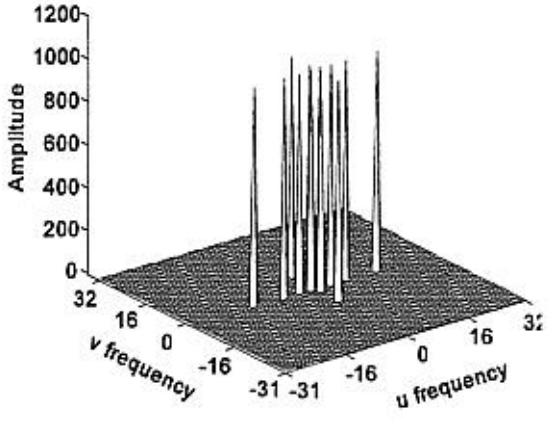

Figure A-2a. Amplitude spectra of the sum of gratings image. The dc or zero frequency component was eliminated so as the grating amplitude spectra could be viewed readily. The spectra were shifted to show the zero frequency in the center.

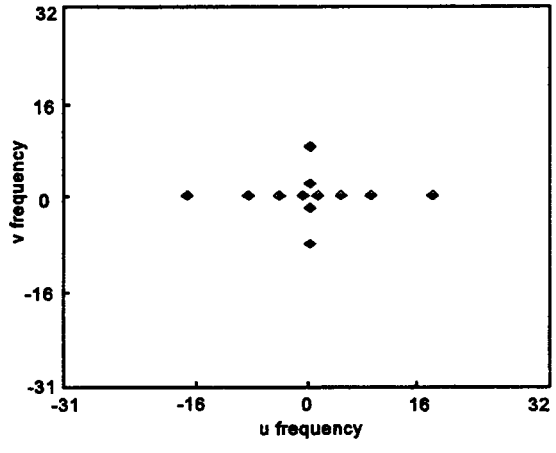

Figure A-2b. Contour plot of the amplitude spectra shown in Figure A-2a. Note that each grating component is readily identifiable.

Another reason to define complex contrast components in frequency space is due to the way spatial patterns are actually processed by the visual system. Years of vision research support the notion that spatial vision is mediated by a system of parallel pathways, where each pathway is tuned to a narrow band of spatial frequencies. These pathways are often characterized by filters whose tuning is along spatial, temporal and orientation dimensions. Along a given orientation, a case can be made for approximately seven unique and independent spatial mechanisms. Six of the mechanisms can be closely aligned to the mechanisms described by Wilson, McFarlane and Phillips (1983) with one additional mechanism accounting for higher spatial frequencies (Marr, Poggio, and Hildreth, 1980). Gabor type filters and derivative of Gaussian filters are often used to define the spatial characteristics of these spatial mechanisms. There is no compelling reason to use these filters other than they approximate the behavior of these psychophysical mechanisms, and units in visual cortex often have receptive field patterns that are similar to these types of filters. In reality, more spatial mechanisms are likely to exist at each orientation, however there is psychophysical evidence only for seven statistically independent mechanisms. Billock and Harding (unpublished results) developed a model that described seven mechanisms to account for idealized behavior and that derivative of Gaussian

filters provided the essential characteristics required by their model. In their model, they chose wide band filters for lower spatial frequencies and narrower band filters for higher spatial frequencies. The bandwidth of a derivative of Gaussian filter naturally follows from the order of differentiation. Figure A-3 shows a 4th derivative of Gaussian filter. Please note that a Gaussian filter has been applied to the axis orthogonal to the filter modulation. This Gaussian filter helps to define the frequency coordinates for the filter by limiting the orientation bandwidth. Seven spatial mechanisms at every 15 degree increment in orientation provide suitable coverage of spatial space. Figure A-4 shows the power spectra for the 4th derivative of Gaussian filter. Note the narrow bandwidth selectivity of the filter. We found that the required bandwidth of these filters needed to ideally cover visual space ranged from 2.6 octaves at low spatial frequencies to 0.77 octaves at high spatial frequencies (Billock and Harding, unpublished results).

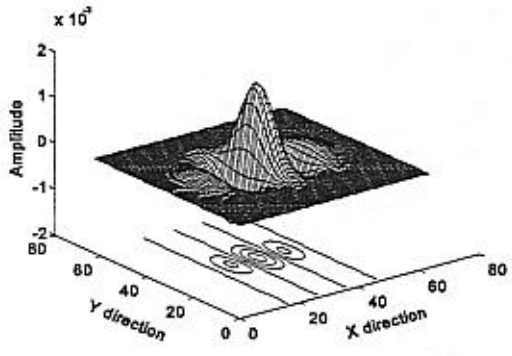

Figure A-3. Spatial profile of a 4th derivative of Gaussian filter. In the Y direction, the filter has been multiplied by another Gaussian which limits the orientation bandwidth of the filter.

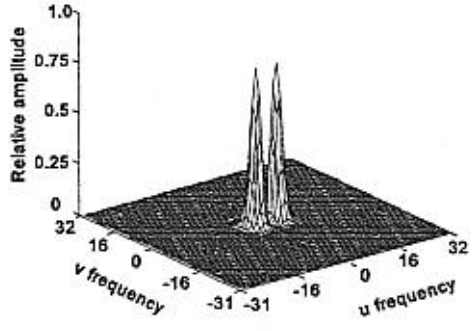

Figure A-4. Relative amplitude spectra of the derivative of Gaussian filter shown in Figure 3. The spectra is relatively narrow band and approximates the kind of bandwidth observed for visual channels. Again the spectra have been shifted.

Using seven spatial filters for every 15 degrees of orientation yields 84 unique spatial filters (filters oriented from 0 to 165 degrees cover all spatial orientations). Another way of thinking of this process is to imagine 84 filters selectively filtering a part of the visual scene and the summed output of these filters providing a visual image of the scene. If we consider Figure A-5a to be the visual scene, then Figures A-5b and 5c show the output of the 4th derivative of Gaussian filter (Figure A-3) tuned to 0 degrees and 90 degrees. By summing these two filters (Figure A-5d), we begin to see shapes that have shapes similar to one or two objects observed in the original. If we carefully define these 84 filters, their summed output then would look just like the original (if we do not include contrast threshold effects).

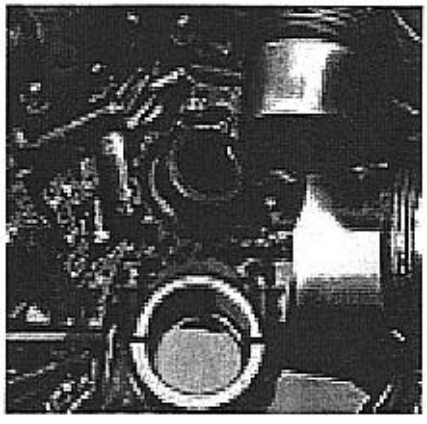

Figure A-5a. Original image before processing by derivative of Gaussian filters.

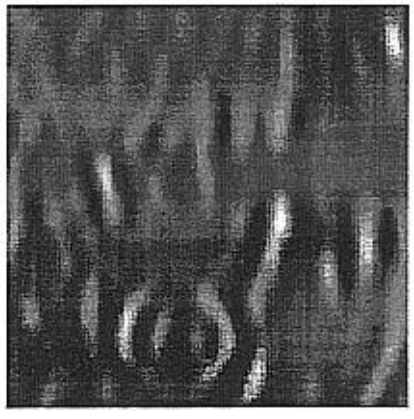

Figure A-5b. Image in Figure A-5a processed by a 4th derivative of Gaussian filter like the one shown in Figure A-3.

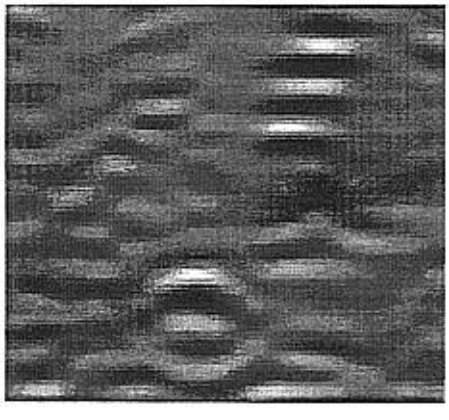

Figure A-5c. Image in Figure A-5a processed by a filter identical to the filter in Figure A-5b except that the filter is oriented vertically instead of horizontally.

Figure A-5d. The sum of images shown in Figures A-5b and A-5c.

Since the real world, as we view it, is made up of very complex spatial relationships, we must consider the contrast of each base component if we truly are to understand the way in which visual information is processed by the visual system.

Appendix B.

Sample calculations for contrast figures of merit in an HMD design

For the HMD scenario depicted in Figure 11, assume a CRT (and optics) luminance of 800 fL and an ambient scene luminance of 3,000 fL. The 3000 fL passes through the aircraft canopy (T_{Canopy}= 0.7), the visor (T_{Visor}= 0.18 or 0.85), the spherical combiner ($T_{SpherCom}$= 0.7), and the plano combiner ($T_{PlanorCom}$= 0.6). Therefore, the luminance reaching the eye from the outside ambient scene ($L_{Ambient\text{-}Eye}$) is

$$
\begin{aligned}
L_{Ambien\text{-}Eye} &= (3000\ \text{fL})(T_{Canopy})(T_{Visor})(T_{SpherCom})((T_{PlanorCom}) \\
&= (3000\ \text{fL})(0.7)(0.18)(0.7)(0.6) \\
&= 159\ \text{fL for the shaded visor, and} \\
&= (3000\ \text{fL})(0.7)(0.85)(0.7)(0.6) \\
&= 750\ \text{fL for the clear visor.}
\end{aligned}
$$

The 800 fL CRT luminance reflects off the plano ($R_{PlanoCom}$= 0.4) and spherical ($R_{planoCom}$= 0.7) combiners and passes back through the plano combiner ($T_{PlanorCom}$= 0.6) to the eye. Therefore, the luminance from the CRT reaching the eye ($L_{CRT\text{-}Eye}$) is

$$
\begin{aligned}
(L_{CRT\text{-}Eye}) &= (800\ \text{fL})(R_{PlanoCom})(R_{planoCom})(T_{PlanorCom}) \\
&= (800\ \text{fL})(0.4)(0.7)(0.6) \\
&= 134\ \text{fL.}
\end{aligned}
$$

Since the luminance reaching the eye is a summation of light originating from both the ambient scene and the CRT, then for the purpose of the calculations, the target luminance is the sum of 750 fL and 134 fL for a total of 884 fL when using the clear visor, and the sum of 159 fL and 134 fL for a total of 293 fL when using the shaded visor. For the clear visor, the background luminance is 750 fL. For the shaded visor, the background luminance is 159 fL.

Michelson contrast

Michelson contrast is defined as follows

$$C_m = (L_{max} - L_{min}) / (L_{max} + L_{min}) \quad \text{(Modulation contrast)} \qquad \text{Equation 3a}$$

$$= |(L_t - L_b)| / (L_t + L_b)| \qquad \text{Equation 3b}$$

For the values above,

$$C_m = |(L_t - L_b)| / (L_t + L_b)|$$

$= (884 - 750) / (884 + 750)$
$= 134 / 1634$
$= 0.08$ for the clear visor,

and

$= (293 - 159) / (293 + 159)$
$= 134 / 452$
$= 0.3$ for the shaded visor.

Contrast ratio

Contrast ratio is defined as follows

$$C_r = L_t / L_b \quad \text{for } L_t > L_b \quad \text{(Contrast ratio)} \qquad \text{Equation 2a}$$

$$= L_{max} / L_{min} \qquad \text{Equation 2c}$$

For the values above,

$C_r = 884/750$
$= 1.17$ for the clear visor, and

$= 293/159$
$= 1.84$ for the shaded visor.

Shades of gray

Number of shades of gray is defined as follows:

$$\text{Number of SOG} = [\log (C_r) / \log (\sqrt{2})] + 1 \qquad \text{Equation 11}$$

For the values above,

$SOG = [\log (1.17) / 0.15] + 1$
$= 0.45 + 1$
$= 1.45$ for the clear visor, and

$SOG = [\log (1.84) / 0.15] + 1$
$= 0.1.76 + 1$
$= 2.76$ for the shaded visor.