III

Displays

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Human Factors in Displays

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30.1 Introduction

The display system is the final link between the measuring process and the user. If the display is not easy to see and easy to understand, then that process is compromised. The user's sensory capabilities and cognitive characteristics, therefore, must both be addressed in display system selection. Furthermore, display technologies and performance capabilities are easier to evaluate in the context of their intended application. Consideration of the following issues can narrow the search for candidate systems, and can prevent needless frustration during system use:

Environment. Will the display be operated in sunlight or at night?
Application. Will the display present alphanumeric data, video images, graphics, or some combination?
Task scenario. Are portability, handheld operation, or group viewing required?
System characteristics. Weight, volume, power, maintenance, cost, etc.

This chapter begins with basic treatments of light and vision. It then proceeds to discussions of visual capabilities and the display characteristics that must be matched to them.

30.2 Fundamentals of Light Measurement

The foundation metric of light is *luminous flux*, which is the rate at which light energy is emitted from a source, and is expressed in lumens (lm). *Luminous intensity* is luminous flux per unit solid angle, and its unit of measurement is the candela (cd). This is distinguished from *illuminance*, or illumination, which is simply luminous flux per unit area, expressed as lux (lx). *Luminance* is a measure of the brightness, i.e., the amount of light, per unit area, either emitted by or reflected from a surface. Units of luminance measurement are candelas per square meter (cd/m^2) or nits. Finally, *reflectance* is a unitless ratio of the amount of light striking a surface to the amount of light leaving it:

$$R = \pi \times \frac{\text{luminance}}{\text{illuminance}} \tag{30.1}$$

High reflectance can create glare, dramatically reducing visual performance.

30.3 Fundamentals of Vision

The eye functions very much like a conventional camera. Light enters the eye through a transparent *cornea* and is modulated by the *pupil*, a variable aperture opening controlled by muscles of the *iris*. The pupil grows larger in dark surroundings and smaller in bright surroundings to control the range of light intensity to the eye. Light rays are then refracted by an adjustable *lens* and brought into focus on the *retina*, where neural imaging begins. The retina contains both *cones* and *rods*, two distinctly different types of photoreceptors. Cones are concentrated near the *fovea*, or the central 2° of the visual field, and decrease rapidly with distance from this region. In contrast, rods are essentially absent in the fovea and increase in density with distance.

The eye is sensitive to three characteristics of electromagnetic radiation: (1) *brightness* (the intensity of ambient or incident light, measured in lux), (2) *hue* (the wavelength of light, measured in nm), and (3) *saturation* (relative concentration of specific hues in light, measured as a dimensionless ratio from 0 to 1). Cones are differentially sensitive to wavelength, i.e., hue, and have greater resolving power than rods because of their one-to-one mapping onto visual nerves. Cones can be further divided into three types, each maximally sensitive to a different portion of the visible light spectrum: (1) red (670 nm peak), (2) green (470 nm peak), and (3) blue (400 nm peak). Rods are more sensitive to light than cones and have many-to-one connections with the nerves that exit the eye, a feature that permits neural summation of low light signals. Human ability to discriminate differences in levels of brightness, saturation, or hue is governed by a psychophysical function known as *Weber's law:*

$$K = \frac{\Delta I}{I} \tag{30.2}$$

where ΔI is the difference, or change, in intensity, I is the initial intensity, and K is the Weber fraction. Values of K have been experimentally determined for brightness (0.079), saturation (0.019 for red), and hue (≈0.02 to 0.04, depending on the region of the visible spectrum).

Photopic vision occurs at light levels where both rods and cones are sensitive. The minimum light intensity required for photopic vision is approximately 2 lx; colors are seen in this region. As brightness decreases, a transition from photopic to scotopic vision takes place and color perception drops out gradually, a phenomenon that can impact the interpretation of color-coded information in poor light. Perception of blues and reds is lost first, then cyan and yellow-orange, and finally green, i.e., the wavelengths where the eye is most sensitive. The eye becomes most sensitive to wavelengths of about 550 nm (green) near the limit of photopic vision. *Scotopic vision* occurs at low light levels (2×10^{-7} lx to 2 lx) and primarily involves the rods; only achromatic shades of gray are seen. The transition from photopic to scotopic vision occurs slowly, requiring approximately 30 min for complete adjustment from photopic to scotopic visual sensitivity.

30.4 Visual Performance

Visual acuity is the ability to discriminate detail. The action of the lens, to change focus for objects at different distances, is called *accommodation. Minimum separable acuity,* the most common measure of discrimination, is determined by the smallest feature that the eye can detect, and is measured in terms of the reciprocal of the visual angle subtended at the eye by that feature. *Visual angle,* in minutes of arc, is calculated as

$$\mathrm{VA} = \frac{3438H}{D} \tag{30.3}$$

where H is the height of the object and D (in the same units) is the distance from the observer. The ability to distinguish an object from its surroundings is known as *visibility.* The term is related to visual acuity, but implicitly combines factors of object size, contrast (i.e., including differences in hue and saturation), and brightness that all interact to determine true visual detection performance. On a more functional level, *readability* or *legibility* describes the ability to distinguish meaningful groups of objects (e.g., words extracted from groups of letters on a display).

Other parameters affecting visual performance include viewing angle and viewing distance. *Viewing angle* at the eye is measured from a line through the visual axis to the point being viewed, and determines where an object will register on the retina. The best image resolution occurs at the fovea, directly on the line of gaze, and visual acuity degrades with increasing angle away from this axis. *Viewing angle* at the display is the angle, in degrees, between a line normal to the display surface and the user's visual axis. The best viewing angle is, of course, on the visual axis and normal to the display surface, as luminance falls off for most displays as the angle from normal increases. Luminance reduction with viewing angle can be calculated as

$$E = E_{\mathrm{m}} \cos^4 \theta \tag{30.4}$$

where E_{m} is the illuminance at the center of the display and θ is the viewing angle. Note that two viewing angles — at the eye and at the display — have been defined. *Viewing distance* is determined primarily by the minimum size requirements (i.e., visual angle) for objects that the user must see. A conventional reading distance is about 71 cm, although VDTs are frequently read at 46 cm. Most design criteria assume a viewing distance of between 50 and 70 cm.

Visual fatigue is an imprecise term, but one in common use, referring to the annoyance, irritation, or discomfort associated with visual tasks performed under poor conditions or for extended periods of time. A common cause of visual fatigue is *glare,* which can be due to a combination of high brightness, high reflectance, and specular (mirrorlike) reflections causing source light to reflect directly into the eye. Minimizing or eliminating glare is essential for effective display performance, and usually involves a thoughtful placement of the display, proper positioning of room lights, control of ambient light (e.g., window shades), or the use of display hoods.

30.5 Display Performance Considerations

Resolution is a measure of the smallest resolvable object on a display, and is expressed as display lines per millimeter or centimeter. Although *sharpness,* and its converse *blur,* are normally defined by the subjective reaction of the display user, sharpness has been formally measured as the ratio of the blurred border zone of letters to their stroke width [3]. Legibility is related to character quality, or readability, and depends on the sharpness of characters.

Contrast, or contrast ratio, is the measure of the luminance difference between an object and its background. While different definitions exist in the literature, luminance contrast as adopted by the International Lighting Commission (CIE) is given as

$$C_R = \frac{\text{luminance of brighter object} - \text{luminance of darker object}}{\text{luminance of brighter object}} \tag{30.5}$$

Lower luminance displays require greater contrast to achieve the same visibility of objects. The *contrast,* or *luminance ratio* between two surfaces in the central field of vision (e.g., a display and the desk on which it rests) should be around 3:1, while the ratio between the central field and surfaces farther away (e.g., around a room) can be as high as 10:1. Ratios greater than this can induce glare. The simplest methods for contrast enhancement are the use of hooded shades or displays that can be tilted away from the offending light. Contrast-enhancing *filters,* however, can be more effective. All filters involve reducing the amount of ambient light reflected back to the user, while leaving the emitted light from the display content as unchanged as possible. Several strategies for filtering exist, including *etching* or *frosting* the display surface to break up and scatter specular reflections. *Neutral density filters* increase contrast by reducing the amount of light passing through them; ambient light must pass through twice before reaching the user's eye, while display content must only pass through once. Micromesh filters placed on the display surface limit light penetration so only rays falling perpendicular to the mesh can penetrate; this stops both specular and diffuse reflections and increases contrast. *Circular polarizers* are neutral density filters that polarize incident light, which is then prevented from returning through the filter. *Quarter-wave thin film coatings* interfere with both specular and diffuse reflections.

Gray scale refers to the number of luminance levels, or shades of gray, available in a display. The common definition is a luminance ratio of 1.4 between levels, although the eye can discriminate changes as small as 1.03 (a Weber's K value of 0.03). The number of gray shades is useful for evaluating the capability of a display to render pictorial information or the range of luminance levels that can be used for coding. The highest luminance level is determined by display capabilities, but the lowest level is determined by the luminance of the display surface when no signal is present. Bright light incident on the display can elevate this minimum level and reduce the number of usable gray shades.

Flicker is the term for detectable changes in display luminance, and occurs when the frequency of those changes is below the integrating capability of the eye. The minimum frequency at which this occurs is the *critical flicker fusion* frequency, or CFF, which depends on the luminance level of the image, i.e., displays which do not flicker at high luminance levels may still flicker at low levels. The CFF is calculated as

$$CFF = a \log L_{\mathrm{a}} + b \tag{30.6}$$

where a = 12.5 for high (photopic) ambient light levels and 1.5 for low (scotopic) levels, L_{a} is the average luminance of the image in cd/m^2, or nits, and b = 37. This is an empirical formula, and the values for a and b are only approximate. Because the eye cannot adapt to flicker fast enough to control the light on the retina, visual irritation usually occurs where flicker is present.

Many display parameters are stated in terms of the *pixel,* or picture element. The pixel is the smallest addressable element in an electronic display, or the smallest resolvable information element seen by the user. *Refresh rate* is the frequency with which display pixels are reilluminated. Refresh rates below 50 to 80 Hz may induce perceptible flicker. The *update rate* is the frequency with which the information content of display is changed.

Linearity is the deviation of a straight line from its exact form, expressed as a percentage of total line length. Pattern distortion is the deviation of any element of a pattern (e.g., a grid) from its exact location, expressed in dimensions of the total pattern. While no specific limits are associated with these parameters, interpretation of measurement data can obviously be affected if nonlinearities are observable on the display.

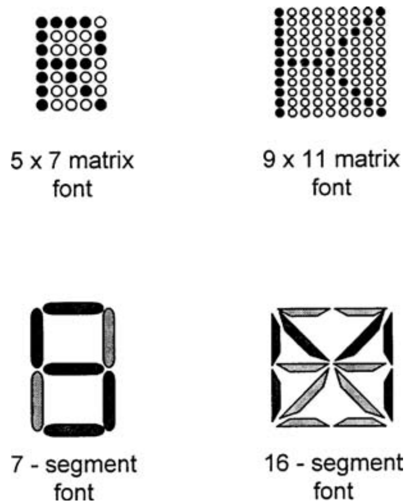

FIGURE 30.1 Examples of alphanumeric displays.

Several mathematical models have been developed to quantify display *image quality* as single "figures of merit." These models, while useful, are too involved for treatment here and the reader is referred to excellent summaries in the literature [1] for further information.

30.6 Display Content Considerations

Configurable software packages for scientific measurement (e.g., LabView™) allow great flexibility in the design of display formats. Human factors principles for display content, therefore, are as important to effective measurement as the electronic characteristics of the display itself. The following principles are an introduction to the kinds of issues that must be considered when designing display content. The interested reader is referred to Helander (1987) and Grandjean [3]) for information on human factors and design guidelines beyond those presented here.

Alphanumeric Displays

The size of a letter is its *pitch.* A general recommendation is that characters should subtend a minimum of about 12 min of arc at common reading distances. Alphanumeric displays are usually constructed of pixel arrays or segmented bars (Figure 30.1). A 5×7 pixel array is considered the minimum necessary to represent the ASCII character set. More pixels can increase legibility, but at higher cost for the control electronics. The seven-segment bar matrix is also a common design and has good performance, but up to 16-segment arrays are available for better appearance.

Stroke width is the ratio of the thickness of the stroke to the height of the letter. Recommendations for legibility are 1:6 to 8 or 1:8 to 10 [2]. As illumination is reduced, thick letters are easier to read than thin ones. With low illumination and low contrast, letters should be boldface type with low stroke width–height ratios (e.g., 1:5).

Quantitative and Status Displays

While numeric readout displays are easy to implement in software, analog pointer displays show an advantage when it is important to observe the direction or rate of change of the values presented [4]. If the measurement application involves "more or less" or "up or down" interpretations, a straight-line or thermometer scale is preferred because it shows the measurement in relation to zero. *Moving pointers* are better able to convey minor changes in readings than fixed pointers or numeric readouts. *Scale* *markings* should reflect the length of the smallest unit to be read. It is desirable to have a marker for each unit, so that no interpolation is required.

Check reading indicators are used to determine whether a condition is "normal." The normal criterion point, therefore, should be clearly coded. If several indicators are grouped together, they should be arranged so that the deviant reading stands out (e.g., by indicating a different column height or dial angle, etc.).

Color is an excellent method for organizing information on a display and for locating objects rapidly. Although display users can distinguish between many different colors, they usually cannot remember more than seven to ten of them, so the number should be limited if color is going to be used as a coding dimension.

Summary

The next sections address different display technologies in light of the principles discussed here. While display guidelines are available for essentially any parameter, it is important to remember that visual perception is an integrative process. No single guideline functions alone, and display quality is usually a product of interacting needs and trade-offs.

30.7 Cathode Ray Tube Displays

The cathode ray tube (CRT, see Chapter 31) is by far the most common display technology in use today, and its widespread use in televisions and computer monitors should guarantee its continued presence throughout the foreseeable future. Advantages of CRT-based displays include (1) versatility (the same CRT can be used for alphanumerics, pictures, or graphics), (2) high-resolution capability and high luminous efficiency, extremely fast dynamic response (which can be important for rapidly changing signals), (3) extensive commercial availability (e.g., 2.5 to 64 cm, diagonally), (4) high reliability, (5) long life, and (6) relatively low cost. CRT displays can function well in high ambient illumination if filtering is used. Potential disadvantages of CRT displays are bulk (the depth of conventional CRT tubes can match or exceed their diagonal dimension, although flat CRTs are available), and vulnerability to ambient reflections and high illumination. Light falling on the smooth display surface can produce a veiling illuminance that **washes out** screen contrast and reduces the number of colors that can be perceived.

CRT Performance

Many characteristics of CRT displays depend on the type of phosphor selected for the design. Phosphor materials vary widely in their luminous efficiency, their color, and their decay time. **Decay time** interacts with display refresh rate; a phosphor with a short decay time will require a higher refresh rate to avoid observable flicker effects. Selecting a CRT with a high phosphor decay time will also result in selecting a tube with a high average luminance. Resolution depends on the **spot size** of the energized phosphor (which is effectively the thickness of the raster line). Spot size will also depend on the acceleration voltage and beam current of the cathode gun, so manufacturer's data must be noted for the voltage and current where the measurements were recorded, and compared with expected operating conditions. CRT resolution is measured in two ways. *Television lines* are the number of the most closely spaced, discernible lines that can be distinguished on an EIA (Electronic Industries Association) test chart. *Shrinking raster lines* involve a process of reducing the spacing between lines of a test pattern until no lines can be seen. This point is then expressed as the number of lines per centimeter, and is a better metric for measurement display applications. Increasing numbers of scan lines improve symbol legibility and image quality. Most conventional CRT monitors have 525 scan lines, but up to 5000-line systems are available [5]. The primary method for achieving *color CRT* displays is the use of single or multiple electron beams to energize phosphors for three primary colors — red, blue, and green. A complete range of colors is obtained by selectively energizing appropriate combinations of these three basic phosphors. Beam efficiency is reduced in this process, which means that color CRT displays are not as bright as monochrome CRT systems.

Contrast ratio is diminished by high ambient light levels, and it is often necessary to compromise between light requirements for work tasks and light levels for optimum CRT visibility. In low ambient lighting conditions, a CRT contrast ratio of 10:1 is usually attainable. A ratio of 25:1 can be achieved with contrast-enhancing filters, but at the expense of brightness.

Types of CRT Displays

In addition to the conventional, raster-scanned CRTs used for computer monitors and workstations, two variants of CRT technology should be mentioned, the direct-view storage CRT and the flat CRT. *Direct-view storage CRTs* have been designed to get around the need to refresh phosphors constantly. Direct-view systems usually add an additional, electrically charged layer — the storage element — somewhere behind the phosphor layer and an additional electron gun to maintain this charge. Displayed information is retained until it is actively erased. *Flat CRTs* have been developed to answer the need for CRT performance in a smaller physical package. The basic design technique places the electron gun at right angles to the screen and, through additional focusing circuitry or a slightly angled phosphor screen, writes the raster pattern at a high angle. Additional detail on these and other CRT designs can be found in Sherr [1].

30.8 Liquid Crystal Displays

Liquid crystal displays (LCDs, see Chapter 32) belong to the class of nonemissive technologies, i.e., displays that do not generate light of their own but control the transmission or reflection of an external light source. LCDs alter the optical path of light when an electric field is placed across the liquid crystal (LC) material.

The principal advantages of LCDs include (1) very low power consumption (important for battery-operated and portable systems such as calculators), (2) a flat display package, (3) low cost of the basic materials, and (4) excellent contrast in high ambient illumination. Some LCDs, however, have slow dynamic response (i.e., for switching display elements on and off); 100 to 500 ms rise times, for example, are visually noticeable and such systems may be unacceptable for measurement applications. Low luminance is another drawback, and can make the display difficult to read in low-light conditions without an external light source. In addition, viewing angle is limited by inherent LC characteristics, and is usually less than 45° without special designs. Many LCD features, such as switching thresholds and response times, are temperature dependent.

LCD Performance

A full range of resolution capabilities is available, from simple alphanumeric displays to systems with 63 million pixels and resolutions of 47 lines/cm [6]. LCDs are primarily used in small display applications (e.g., calculators, watches, etc.), although 53 cm diagonal, full-color video-capable displays have been developed [7].

Contrast in polarized systems is determined by the *extinction ratio* of the polarizer, i.e., the ratio of light transmitted in the parallel polarizing orientation to light transmitted in the cross-polarizing orientation. Polarizers with good extinction ratios, however, also suffer high loss of light in the transmitting orientation, so maximum brightness is traded for contrast. Contrast ratios of up to 50:1 [6] have been achieved, although 20:1 is more common.

Color displays can be achieved by placing a color mosaic over the LCD and switching the cells behind the proper combinations of mosaic holes into their transmission states. This method reduces resolution and brightness, however, as the available pixels must be assigned to each of the three primary colors. The use of thin-film transistors (TFT) as a switching technology for LCDs is the latest approach to generating large, high-resolution displays and is the subject of extensive engineering research [8].

30.9 Plasma Displays

The simplicity and durability of plasma displays (see Chapter 33) makes this technology an attractive candidate for diverse measurement needs, especially where harsh environments are expected. In addition, the switching characteristics of plasma gases have not yet been fully exploited, and this technology offers excellent potential for future engineering improvements. Plasma methods are used extensively for alphanumeric displays in portable, laptop, and handheld computers, and for the display of video imagery. Advantages of plasma displays include enhanced memory capability, brightness, and luminous efficiency. It is also possible to retain pixels in the on state without continuous refresh signals, which means that increased brightness can be obtained for the same power and driving circuitry. This advantage also allows for excellent contrast ratios in high ambient illumination.

Plasma displays also exhibit long display life and ruggedness. It is not unusual for the display to outlast the life of the product in which it is installed, and the relatively simple panel construction can tolerate high shock and vibration environments, or extremes of temperature. Some disadvantages of plasma displays include high cost (relative to CRTs) and high power requirements (relative to LCDs). Other technologies can compete effectively with plasma devices for small alphanumeric displays in benign conditions.

Plasma Display Performance

Commercial plasma displays are available with resolutions of 40 lines/cm, and systems with almost 50 lines/cm are under development. Systems of 2 million pixels have been constructed [9]. Gray scale is achieved with dc displays by adjusting the discharge current in each cell. Displays using ac voltage can trade resolution for gray scale with spatial modulation methods, i.e., by controlling the number and location of activated pixels, rather than the level of pixel illumination. While plasma displays have good gray scale, their brightness is not yet equivalent to that of CRTs. Plasma displays show the color of the ionized gas, usually orange (i.e., where neon is used), although different gas mixtures or phosphors have been successfully used to expand the range of colors. The *hybrid ac-dc display* was designed to combine the memory capability of ac systems with the efficient matrix circuitry of dc devices [10]. The display uses both types of current to generate gas discharge; the dc component controls the pixel addressing, while the ac component controls the memory states of the cells. The *hybrid plasma–CRT display* attempts to use the gas discharge effect of the plasma panel as a matrix-addressable source of electrons for the CRT. The result is a full-color system with high brightness and good luminous efficiency.

30.10 Electroluminescent Displays

With the exception of light-emitting diodes (LEDs, see Chapter 35), electroluminescent (EL, see Chapter 34) technologies are not as prominent in the commercial arena as other types of display systems. EL materials are complex (i.e., driven and controlled by processes related to solid-state semiconductor physics) and are more difficult to work with than other display materials. Nevertheless, they offer great potential for high brightness and low cost that deserves consideration, especially as new designs become available. Matrix addressing is used for control of information display applications. EL materials are applied in two forms — powders (PEL) and thin films (TFEL) — and are controlled by both ac and dc voltages, generating four basic design approaches. Some advantages of EL displays are (1) high luminous efficiency (except ac powder designs), (2) readability in sunlight, (3) color capability, (4) compact, flat panel designs, and (5) significant potential for low-cost manufacture. A disadvantage of EL displays is that ac powder (ACPEL) systems have low luminance and contrast ratio. In addition, phosphors in powder designs scatter and reflect ambient light, reducing their contrast.

EL Display Performance

Contrast ratios of 50 to 150:1 have been demonstrated with monochrome thin-film (ACTFEL) systems, while 15 to 20:1 have been achieved with dc designs. ACTFEL designs also show excellent brightness, with demonstrated luminance levels of over 157 cd/m^2 (monochrome) and 26 cd/m^2 (color). DCPEL designs, representing newer technologies, have achieved over 100 cd/m^2 with monochrome designs, but may soon meet or exceed ac-based values. Resolution of EL displays is limited by the duty factor of matrix addressing; a finite amount of time is needed to energize each row, and a minimum luminance level is needed for adequate display performance, so the remaining variable becomes the number of addressable lines. A demonstrated ACTFEL display with 640 × 400 elements, with six colors and a resolution of 27 lines/cm, is typical of this technology.

30.11 Light-Emitting Diode Displays

Light-emitting diode (LED) displays (see Chapter 35) involve single-crystal phosphor materials, which distinguishes them from the polycrystal EL materials discussed in the previous section. The basic physics behind their operation is, however, quite similar. LED displays are highly versatile and well suited to a variety of measurement applications. Advantages of LED displays include high reliability and graceful degrades; individual LED elements can fail without affecting overall display performance. LEDs are rugged, for operation in harsh environments, and they are more tolerant of temperature extremes than other technologies. LEDs demonstrate better viewing angles than LCDs, and excellent brightness for visibility in sunlight. Unfortunately, LED displays also have high power consumption when packaged in large, flat panel displays, and the cost is high for the complex assembly. Optical cross talk between array elements can occur if transparent substrates are used. LEDs are the most restricted display in terms of color range (e.g., no blue device is commercially available).

LED Display Performance

LED devices have excellent brightness, but because display brightness is also a function of the filters or magnification lenses used over the LED elements, device luminance is not, by itself, a reliable measure of overall system performance. LED displays also show very good luminance contrast. *Chrominance contrast*, however — the color difference between the LED and its background — is a factor in evaluating LED performance that is not found in other technologies. Chrominance contrast is significant because of the high saturation of most LED phosphors. It is affected by display filters, and can have significantly more influence on display performance than luminance contrast.

LED displays with resolutions of 20 to 25 lines/cm have been constructed. Flat panel displays of 38,400 discrete elements have also been demonstrated with luminance levels of around 137 cd/m^2 (increasing to 240 cd/m^2 with reduced resolution), and at least one aircraft display with 49,000 elements has been built. CRT-equivalent displays with 600 × 400 elements have also been realized with engineering development models.

Defining Terms

Decay time: The time required for the peak brightness of a phosphor to drop to a defined fraction of peak luminance; a measure of how long the phosphor remains illuminated after being energized by the electron beam.

Duty cycle: The time spent addressing each pixel during a refresh cycle; inversely proportional to the number of pixels.

Font: Refers to the form in which alphanumerics and symbols are produced.

Spot size: The size of the illuminated spot from the electron beam; limits the size of the raster line.

Transillumination: Illumination from the side of a display surface, to highlight information on the surface itself, e.g., lighting for automobile or aircraft instruments.

Wash out: The loss of contrast (i.e., reduction in dynamic range) in an LED as the ambient light reflected off the background of the display surface approaches the light level of the active area.

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Further Information

E. Grandjean, *Ergonomics in Computerized Offices*, London: Taylor & Francis, 1987, is an excellent all-around treatise on the principles of effective VDT selection and use. Summarizes a wide range of research literature. If this volume is difficult to obtain, a chapter by the same author is also included in the *Handbook of Human Factors* (Reference 2).

M.G. Helander, Design of visual displays, in G. Salvendy, Ed., *Handbook of Human Factors,* New York: John Wiley & Sons, 1987, is an excellent and concise review of major human factors principles for display design and use. Includes a critical review of the foundation literature in this area.

S. Sherr, *Electronic Displays*, 2nd ed., New York: John Wiley & Sons, 1993, offers clear presentations of all important display technologies, together with a good summary of performance measurement methods for display systems. Well illustrated with a variety of commercial products.

L.E. Tannas, Jr., Ed., *Flat-Panel Displays and CRTs*, New York: Van Nostrand Reinhold, 1985, provides a thorough, yet highly readable examination of the physical principles behind essentially every major display technology. Although the technology capabilities have become dated since publication, this is well worth review.