LEGIBILITY
OF
VISUAL DISPLAY UNITS

by

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I dedicate this report to my parents, Indrajit Prasad and ChandraKala Prasad, for their love, emotional support, and encouragment throughout my life and during hard times.

INTRODUCTION[a]

Visual Display Terminals (VDTs) are used as a primary person-machine interface for interactive computing, data entry, word processing, database access, and the like. In most applications the user reads only limited amounts of text from the display screen at any one time. However, recent developments in information-system design suggest that VDTs increasingly will be used as a medium for the presentation of a large amount of connected text, as in videotex (enables reading of continuous text on television screen) (Sawchuk, Storey, and Treurniet, 1980; Muter, Latremouille, Treurniet, and Beam, 1982), electronic journals (Moray, 1980; Senders, 1977), dynamic books (Kay and Goldberg, 1977; Weyer, 1982), or similar applications. Estimates are that by 1990, the number of terminals will increase to 1 for 3 office workers (Smith, 1985).

The first research publications on the visual quality of VDTs emanated from IBMs human factors laboratories. It was determined that the quality of marketed VDTs was not adequate in terms of flicker, character-forming dot-matrix, and luminance contrast (Gould, 1968). Twenty years later, the very same laboratories acknowledged, that,

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[a] Some important terms used throughout the text are

defined in a glossary (page 79).
despite continuous product improvements, reading is still about 25% slower from traditional VDTs compared to equivalent print on paper. Several reports have further confirmed that people read more slowly from VDTs than from paper (Gould and Grischkowsky, 1982, 1984; Heppner, Anderson, Farstrup, and Weiderman, 1985; Kak, 1981; Mills and Weldon 1984; Muter, Latremouille, Treuniet, and Beam, 1982; Wright and Lickorish 1983).

For any display to be useful, the information that it displays must be legible and readable. This paper discusses the more important legibility parameters affecting the readability of VDTs. The dominant parameters are divided into categories of character, equipment, workstation, and general factors. However, the parameters discussed are not independent of each other. Altering one parameter may have an effect on one or more parameters. For example, decreasing character size may decrease resolution. Conversely, if one parameter cannot be changed, one or more of the others may be altered to get the same resultant readability. For example, at a fixed character size, increasing resolution or decreasing viewing distance will improve readability (Winkler and Konz, 1980).

2 CHARACTER

2.1 BETWEEN-CHARACTER SPACING

The intercharacter or between-character spacing, together with the width of the character matrix, determines the number of characters which can be recognized with a single fixation of the eye. Between-character spacing is crucial to legibility (Stewart, 1980), and is, therefore, an important attribute of written, printed or displayed text, both from the point of view of readability and the visual effort required for reading (Cakir et al., 1979). Character spacing is an important consideration where text is displayed in justified form, and where the technique of line length justification involves increasing intercharacter spacing.

If the characters or words are spaced apart, readability problems occur from increased number of eye fixations and perceptual effort required to scan a set of characters to perceive a word. Perhaps, worst of all is irregular spacing between adjacent characters and/or words because it disrupts the scanning pattern of the eye. Characters too closely spaced will not be readily discriminated (Sauter et al., 1984). The number of characters per line can affect reading speed (Duchnicky and Kolers, 1983; Kolers et al., 1981, Tinker, 1963). Irregular spacing among words occurs when the text is "justified".

The spacing between the character should be 20% to 50% of character height (Cakir et al., 1979). Shurtleff (1980) found that intercharacter spacing can be reduced to 10% of character height if other display characteristics such as resolution, contrast, etc. are optimum. Accuracy is reduced if the symbol width is narrow and intercharacter spacing is less than 25% of character height (Blewett, 1987). Figure 2.1.1 shows intercharacter spacing as the space between the letter M.

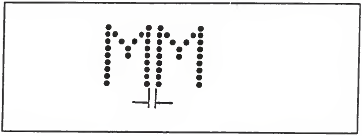


Figure 2.1.1 Between-Character Spacing (American National Standard, 1986).

In summary, the character spacing should be more than 20% of the character height to permit adequate discrimination between individual characters. Likewise, to ensure good readability and to maintain visual distinction between individual characters and words, the character spacing should not exceed about 50% of the character height.

2.2 BETWEEN-LINE SPACING

A minimum of two stroke widths or pixels, whichever is greater, should be used for spacing between lines of texts. The space between lines of texts should not be used for upper case accent marks or for lower case descenders of characters (Figure 2.2.1) (American National Standard, 1986).

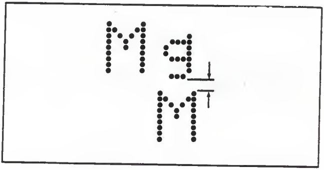


Figure 2.2.1 Between-Line Spacing (American National Standard, 1986).

The vertical spacing between lines has a significant effect on readability. Reducing the number of lines and the number of characters in a line increases the legibility of the characters in a display (Cakir et al., 1979). Line spacing affects the image quality of characters (Gould et al., 1987).

Until recently, the dynamic procedure assessing actual visual performance employed a standard technique (Tinker, 1963), which involved measuring the speed of reading or time on task for different sorts of display, and testing for or assuming equivalence of comprehension. With this method, almost all information regarding perceptual constituents of the task was lost, and the only available data was the total time taken for the task. A good analytical method would evaluate the eye movement as people read the text. The difficulty, discriminability, comprehensibility and related features of processing text reveal themselves through changes in the frequency, duration and location of eye fixations (Levy-Schoen and O' Regan, 1979). Kolers et al. (1981), using this method, showed that single-spacing required more fixations per line; slightly fewer words were read per fixation and total reading time was slightly longer. Double-spaced text requires twice as much screen as does single-spaced text. This doubling of space reduced number of eye fixations by 3% and total time taken to read a passage by 2%. However, single-spacing can be used in preference to double-spacing in situations where the display space is costly. The mean reading speed was 10.9% slower in the single-space condition than in the double-space condition (Kurk and Muter, 1984). This contradicts Kolers et al. (1981) finding of 2.2% as compared to 10.9%. This discrepancy may be, perhaps, attributable to the fact that spacing was confounded with lines per page and words per page in the study by Kolers and coworkers; the lines per page and words per page were constant in Kurk and Muter's study. On the other hand, the data of Duchnicky and Kolers (1983) suggested that doubling the number of printed lines per page had little effect on reading speed. A more likely explanation is that in the single-space condition, the space between lines (as a proportion of height of the characters) was apparently greater in Koler's than in Kurk and Muter's study.

Morrison and Inhoff (1981) have suggested that an increase in blank area between lines (lateral masking) decreases the interference of surrounding letters on word perception. Wilkins and Nimmo-Smith (1987) showed that judgments of clarity of text are affected by spatial characteristic of the pattern, in particular, the spacing between lines. The average area of the page occupied by a letter (i.e. the percent of the separation between the lines and the mean horizontal spacing between the centers of the letter) account for less variance than does the separation between the lines of text. Within the constraint of conventional typeography, the clarity of text could be improved without increasing costs by slightly reducing the typical space between the letters in order to increase the spacing between the lines.

In practice, between line spacing (between vertical adjacent non-accented capital letters) results in a space of 50% to 100% of character height (American National Standard, 1986). For conventional text, interline spacing of about 100% of character height probably is appropriate. This distance will assume adequate separation of ascenders and descenders of adjacant lines. Much greater spacing results in unnecessary loss of text space (Sauter et al., 1984).

In summary, the between line-spacing according to Cakir et al. (1979) should be as follows:

1. Equal to or more than 100% of character height, and
2. Equal to or less than 150% of the character height

2.3 CHARACTER FORMAT

Characters usually are created on a video display from a pattern of dots (dot-matrix) or horizontal line segments (raster-written). In a dot-matrix character, the number of dots allowed for each character in the horizontal and vertical dimensions constitutes the dot-matrix size. A 5x7 dot-matrix has a maximum of five dots in the horizontal dimension and seven in the vertical. A 7x9 dot-matrix has two additional dots in each dimension. A raster-written character has no spacing in the horizontal dimension (in any single scan line). A 5x7 or 7x9 dot-matrix character would correspond to a raster-written character with a height of 7 or 9 line segments respectively.

There is general agreement that 5x7 is the minimum acceptable matrix size for a VDT character. Below this size, insufficient variation in arrangement of character elements occurs, creating serious ambiguity among characters (see Figure 2.3.1).

In reality, many VDTs used in offices today have a matrix size greater than 5x7. Although research shows a marginal increase in legibility for matrices greater than 5x7, a VDT with a larger character matrix, such as 7x9, is probably a better choice. This increased size may be important when the display is not of the best quality (eg., small characters) or when raster-written characters are used (raster-written is less legible than a comparable dot-matrix character) (Sauter et al., 1984).

Research has shown that legibility is enhanced when a dot generated character resembles a stroke generated character. Therefore, the more dots in a dot-matrix, the better the legibility (Snyder and Maddox, 1978). However, a character resolution beyond 9x11 produces only marginal improvements in legibility. The shape of individual dots also affects legibility. Because rectangular or square dots fill more of the empty space between dots, they are preferred over round and oblique dots (Snyder and Maddox, 1978).

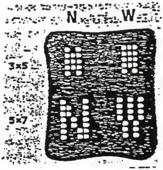


Figure 2.3.1 Matrix Size (Sauter et al., 1984).

2.4 CHARACTER WIDTH TO HEIGHT RATIO

The width to height ratio of a given character is the ratio of the horizontal distance between the left and right edges, and the top and the bottom edges of a nonaccented capital letter (see Figure 2.4.1).

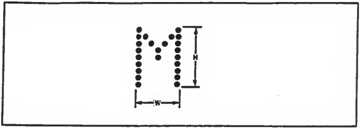


Figure 2.4.1 Character Width to Height Ratio (American National Standard, 1986).

Character width to height ratio, also known as "aspect ratio" of the characters, is important for legibility (Stewart, 1980). Some letters are seen customarily narrower than others. For example, in a given character set the letter I and sometimes the letter J, appear narrower than M and W. Lower case letters may, similarly, vary in width. The width to height ratio of a given character set should be the modal character width, that is, the width that occurs most often in the set of capital letters.

Hart (1966) recommended an optimum character width to height ratio of 3/4 (i.e. 75%). This ratio should approach 1/1 (i.e. 100%) on displays being viewed at large acute horizontal angles. According to Sauter et al. (1984), the best character width to height ratio is 3/4 (i.e. 75%). Recent data indicated that width less than 3/4 (i.e. 75%) of the height produces a slight decline in legibility. Figure 2.4.2 shows a 3/4 (i.e. 75%) ratio on the top line and 1/2 (i.e. 50%) on the bottom line.

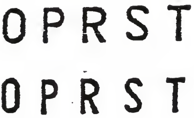


Figure 2.4.2 The Figure Shows a Width to Height Ratio of 3/4 and 1/2 (Sauter et al., 1984).

In summary, character width to height ratio should be:

1. For fixed (as opposed to proportionally spaced) column presentation, the width to height ratio should be between 0.7/1 (i.e. 70%) to 0.9/1 (i.e. 90%). For display formats requiring more than 80 characters on a line, a ratio of 1/2 is

permissible.

2. For proportionally spaced presentation, a width to height ratio of about 1/1 shall be permitted for some characters (for example capital letters M and W).

2.5 CHARACTER SIZE

Character size is the vertical distance between the top and the bottom of a nonaccented capital letter (Figure 2.5.1).

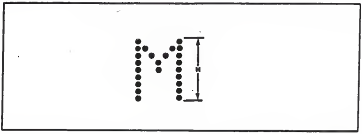


Figure 2.5.1 Character Size (American National Standard, 1986).

People read more slowly from VDT displays than from paper (Gould and Grischkowsky, 1984) because of differences in the image quality of the characters (Gould et al., 1987). Factors affecting image quality are especially determined by character size (Stewart, 1980) since the size of the displayed character is one of the important readability factors (Winkler and Konz, 1980).

The required size of characters is dependent on the task and the display parameters (resolution, contrast, glare, etc.). Characters that are too small or too large make reading difficult. Earlier workers have concentrated on recommending minimum character sizes. As a result, it has been incorrectly assumed that characters should be as large as possible. When characters are dot matrix generated, the dots appears to be separated if characters are too large (Vartebedian, 1971). A series of complex laboratory procedures involving the measurments of eye movement of subjects while reading a VDT screen suggested that smaller, rather than larger, letters required less ocular and cognitive work in comprehending the letters (Kolers et al., 1981). In seeking to optimize character size, the lower limit of perceptibility is less important than the ability to simultaneously and clearly recognize consecutive groups of characters (Cakir et al., 1979).

The perceived size of a character depends upon its visual angle. The concept of visual angle is illustrated in Figure 2.5.2. As seen in the figure, a small character that is close to the eye can have the same visual angle (and will be perceived as the same size) as a large character further away. For this reason, specifications for critical character size are commonly given in terms of visual angle rather than in absolute character size (Sauter et al., 1984).

The general opinion is that the VDT character size should usually be larger than 16 to 18 minutes of arc. It corresponds to character height of about 2.8 to 3.1 mm, at a viewing distance of 600 mm. This size is slightly greater than a 10 point type.

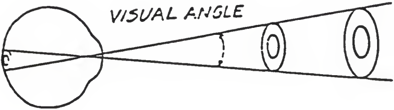


Figure 2.5.2 Visual Angle (Sauter et al., 1984).

It is acceptable to use characters as small as 10 minutes of arc (1.1 mm), if characters are bright, sharp, and the contrast is good. This was confirmed by Miyao et al. (1988). Miyao and coworkers found that, for very small characters, high resolution improves readability. A formula to calculate character height in inches which yields a visual angle of 16 to 18 minutes at various visual distances is shown below:

$$CH = \frac{(VA \times VD)}{3500}$$

Where

CH is character height in inches,

VA is visual angle minutes of arc, and

VD is the viewing distance in inches.

Common display tasks require rapid and accurate legibility of individual characters. The legibility of single characters is not significantly improved for characters larger than about 16 to 18 minutes of arc. Larger character size certainly may be used, but it requires a larger screen, which may hamper some tasks that require visual searching. This is one of the trade-offs that should be considered.

Where the readability of continuous text is important, the use of character size not smaller than 14 or larger than 22 minutes of arc in height is acceptable (Figure 2.5.3). This corresponds to 8 to 12 point type when viewed at typical reading distances. Ten and 12 point types are generally preferred, and are the most frequently used sizes (IBM, 1984).

In summary, character size for VDTs should be

1. more than 16 to 18 minutes of arc, or 0.10 inch

(2.6 mm) whichever is less, and

2. no less than 22 minutes of arc for general reading purposes.

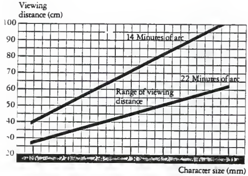


Figure 2.5.3 Graph Showing an Increase in Viewing Distance with Increase in Character Size for VDT (IBM, 1984).

2.6 STROKE WIDTH

The stroke width of a VDT character corresponds to the width of dots or lines comprising the character. A stroke width may be more than one pixel wide (American National Standard, 1986).

Stroke width to height also is dictated by symbol generation technique and resolution. The ratio should not be too small or the character stroke will blur or run together (Winkler and Konz, 1980). Sherr (1970) recommended a minimum stroke width ratio of about 14%, Bucker (1977) about 10%-17%, and Gould (1968) about 10%-13%. Stroke width generally should be greater than 8% of the character height. Once the character is well above the minimum size, with proper contrast and luminance level, the stroke width of a character is less critical for reading (American National Standard, 1986).

The influence of stroke width and polarity on the threshold legibility of numeric symbols indicated that maximum visual performance was attained with light symbols on a dark background with a stroke width of about 6% of the character height (Berger, 1944). Performance on the positive polarity presentations was superior only when stroke widths were larger than 17% of character height. The results of a more recent study (Taylor and Rupp, 1987) confirmed the findings of Berger (1944).

In summary, the stroke width should lie between 10% to 25% of character height. Stroke width of 12% to 17% of character height is, however, preferable (Cakir et al., 1979).

3 EQUIPMENT

3.1 FLICKER

Flicker is a temporal luminance change of a luminous field caused by the fading and subsequent regeneration of that field and display (Dill and Gould, 1970). When a light source is slowly flashed on and off, the light will seem to flicker. As the flashing rate increases, at some point the light will appear to stop flashing and become steady. This point is called the critical flicker frequency (CFF). As a person's eyes move normally around the CRT to interpret a display, the image is presented to many areas of the periphery of the retina as well as the fovea (the fovea is the retinal area of the highest resolution). In fact large portions of the image are presented, most of the time, to areas far into the periphery of the retina. As a result, the flicker characteristics of the periphery are far more important than the flicker characteristic of the fovea. If the person's CFF threshold is greater than the refresh rate, some portion of the image will flicker. Many images typically encountered in computer terminal usage are, therefore, likely to flicker due to an increased CFF threshold in the peripheral retina (Grimes, 1981). Different types of flicker are discussed below:

SCREEN ATTENTION FLICKER: When the operator is looking directly onto a positive polarity screen, he may perceive flicker, probably because of the screen characteristics. The regeneration rate has been considered earlier as the only important factor. But it has been shown that the phosphor persistence time is quite important too. Phosphors with short persistence give rise to more flicker than a long persistence phosphor. In addition, the ability to perceive flicker diminishes if the operator has been watching an oscillating light source (in this case, the screen) for a while. The ability to perceive flicker, therefore, is highest when the operator starts to look at the screen.

PERIPHERAL FLICKER: The ability of human eyes to detect flicker increases when the oscillating source is placed peripherally. A screen that is perceived as free of flicker when viewed directly can be perceived as flickering when it is viewed peripherally (for example, when performing tasks besides the screen as reading a manuscript or serving a customer). The peripheral flicker is affected by the same factors as screen attention flicker.

DOWNWARD DIRECTED EYE MOMENTARY FLICKER: As the operator moves his gaze downwards onto the screen, the operator sometimes perceives a brightly shining horizontal band on the screen for a very short moment. This phenomenon can give rise to a slight glare effect, and it causes discomfort if frequent vertical eye movements are performed. As the eye ball is rotated downwards, the same light receptors are exposed to freshly excited lines for a prolonged time, giving an impression of a lighter area (the brightly shining line). The phenomenon is caused by the downward directed vertical line displacement (Nylen, 1985). This phenomenon is only perceived on screens with short persistence.

TALK GENERATED FLICKER: Positive polarity screens with short persistence sometimes appear to flicker more to the operator when the operator is talking. The persistence threshold of this flicker is lowered when the operator's distance from the screen is increased. This type of flicker sometimes can be perceived on a screen on a neighboring colleague's desk but not on the operator's own screen.

The use of visual display units, with a bright background, has introduced the problem of flicker perception into the work place of today. Flicker is one of the most common complaints of the VDU users. Stammerjohn et al. (1981) reported that 68% of the VDU operators surveyed complained of flicker. Flicker may result in operation of the internal and external muscles of the eye in excess of that required for normal level of focusing and eye movement (Dainoff et al., 1981). Such excess muscular activity may be perceived as visual fatigue or eye strain by the operator

(Weston, 1962). Very little information exists on the discomfort caused due to flicker on VDT displays.

In general flicker is much more apparent and annoying when a VDT is in the periphery of the visual field. In many work environments, VDTs are placed off to one side of the workstation or on a counter that is well below the eye level of a standing operator. This results in the VDT being in the operator's peripheral visual field. The greater susceptibility to flicker in peripheral vision apparently is due to greater density of rods in the periphery of the retina, which are sensitive to changes in luminance (Isensee and Bennett, 1983). The international endeavor to formulate a standard in this context emphasized the need for flicker free VDUs. However, it is not clear how a strict requirement can be formulated and under which conditions the CFF can be measured. The reason for this state of uncertainty is that previous research has demonstrated CFF varies between 5 Hz to 60 Hz, depending on specific combinations of effective stimulus variables (e.g. luminance, retinal position, size of stimuli) and observer variables (e.g., age, adaption state, pupil size) (Eriksson and Backstrom, 1986).

Several factors affect flicker. These are described below.

STIMULUS INTENSITY: The most important of the variables that determines flicker is the intensity or luminance of the stimulus field. At low luminance (about 0.03 cd/m^2) the CFF is as low as 5 Hz, then it reaches a maximum (60 Hz) at about 1 cd/m^2 and finally declines somewhat at higher intensities (Hecht and Smith, 1936). Isensee and Bennett (1983) suggested that low to moderate levels of ambient illuminance (approximately 100 to 260 lux) and moderate level of video luminance (in the range of 65 cd/m^2) minimizes discomfort due to flicker. Video luminance appears to be of much greater importance in producing flicker than ambient illuminance for video clarity. Filters used to reduce glare also can be used to reduce flicker, since flicker is also a function of video luminance (Isensee and Bennett, 1983).

REFRESH RATE (FREQUENCY): Refresh rate is the frequency of the electron beam that excites the phosphor. If the frequency is high enough (about 65 Hz or more), the light will appear to be steady and non-flickering, regardless of other factors. Most VDTs operate with a refresh rate of considerably less than 65 Hz (IBM, 1984). Bauer et al. (1983) reported that a refresh rate of about 90 Hz was necessary in order to avoid perceived flicker on the computer screen. According to Barlow and Mollon (1982), the visual system cannot detect flicker above 60 Hz.

PHOSPHOR PERSISTENCE: The persistence of a phosphor, i.e., duration of phosphor illumination after the electron beam has excited it, affects refresh rate. A phosphor with short persistence must be refreshed more frequently than a phosphor with a long persistence (IBM, 1984). Figure 3.1.1 shows the difference in persistence rate of two phosphors-- P4 (a phosphor commonly used in black and white TV sets) and P39 (commonly used in VDTs).

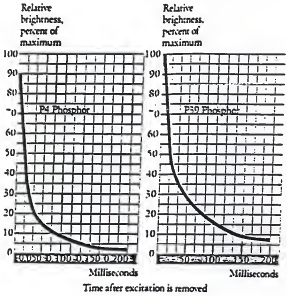


Figure 3.1.1 Decay Curves for Two Different Phosphors (JEDEC, 1975).

A display with a very fast phosphor will have a large amplitude coefficient and requires less energy or screen luminance. Displays with fast phosphors appear to flicker at low luminances. The screen luminance for a perceived flicker is proportional to the decay constant of the phosphor (Farrel, 1987).

JITTER: Jitter is one form of image instability noticed in refresh CRT and increases perceived flicker. In CRT displays, jitter is caused by a slight displacement in dot location from refresh cycle to refresh cycle. Jitter is affected by the external magnetic environment as well as display design parameters (IBM, 1984). Eriksson and Backstrom (1987) reported a strong effect of jitter on the perception of flicker. Operators, carefully instructed to disregard jitter and only judge flicker, confused flicker and jitter. Thus, flicker testing in VDUs should be interpreted carefully since jitter may inflate flicker judgment.

Other factors that need to be considered are display size and video polarity. The smaller the flicker display the lower the CFF (Farrell, 1987). This result reiterates the fact that smaller displays are less likely to flicker (Kelly, 1974). Positive polarity video is likely to flicker when the display luminance is above 20 foot-lamberts, and the negative polarity above 80 foot-lamberts. The probability of seeing flicker decreases with high refresh frequencies and long phosphor persistence and increases with screen luminance and display size.

3.2 IMAGE POLARITY

Image polarity refers to the contrast between letters and the background. If the letters are light on a dark background it is called negative polarity and if letters are dark on a light background it is called positive polarity. Until recently, it was difficult to produce a positive polarity VDT screen which could compete both in price and quality with the conventional negative polarity screen. With the availability of an economically viable flicker-free positive screen, the designers and the users have become concerned with the question of screen polarity with regard to level of performance, legibility, and subjective discomfort.

Past experiments have shown that dark characters (on paper) on a light background can be read faster than light characters on a dark background (Tinker, 1963). With respect to VDTs, there is some evidence that dark characters on a light background are read faster and more accurately than light characters on a dark background (Bauer and Cavonius, 1980). Rauf and Hatami (1985) reported that the overall character legibility of displays was much better using light characters on a dark background VDT display.

Zwahlen and Kothari (1986) conducted a study to determine the effect of positive and negative image polarity screens on operator behavior, performance and comfort. The average discomfort scores at the end of the session were recorded; the differences were observed to be relatively small. Based on their study, Zwahlen and Kothari concluded that operators can work in either environment as long as sufficient character background luminance contrast is provided. Every time the operator sees the white manuscript (high luminance) and then the dark VDT (negative polarity), there is substantial risk of experiencing contrast glare, which causes eye discomfort. Berns and Herring (1985) reported that in a situation when the screen quality is high and the working environment optimized for screen work so that visual strain could be minimized, image polarity does not appear to be an important factor.

In contrast with the above conclusion, Gould et al. (1987) suggest that reading speeds equivalent to paper can occur on VDT displays with high resolution character fonts that resemble those on paper, and that have polarity of dark characters on light background. Thus, however small the difference may be, positive polarity does favor faster reading. Bauer (1987) evaluated the visual comfort based on four criteria: readability, sharpness, flicker and contrast. The comfort estimations for "sharpness" and "readability" were significantly higher for light than for dark background. Judgments of flicker tended to favor dark backgrounds because the quality of the bright screen was not strictly comparable with that of the dark screen. Thus, if the quality of the VDT displays with positive polarity can be improved, then significant improvement in reading speeds can be obtained.

Bauer (1987) reported that reflections of external light can be reduced to non-interfering levels at real work places only by using light background screens, but not with dark background screens. This result prompted Bauer to look into the possibility of developing a VDU which, with regard to vision, that has the properties of a printed document. The same paper has recommendations for the construction of a light background VDU which is physiologically matched to the visual system of the VDU worker (see Figure 3.2.1).

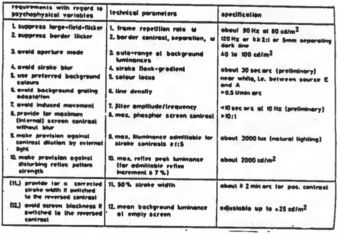
Though most of the studies do not indicate a definite preference for positive polarity screens over negative polarity screens, it has been noted that with better VDUs which are flicker-free, the bright screens will be able to give :

1. increased adaptation level with increased visual acuity and contrast sensitivity,

2. smaller average pupil diameters with faster accomodation, and

3. less restriction on work place and lighting design.

Thus, under the constraint of "reflections from artificial office lighting are present," the light background screen may be designed in such a way that even under conditions of high lighting levels (which are necessary to optimize the information-handling ability of the visual system and to minimize the visual work load), reflections are suppressed to such a degree that the text on the screen closely resembles the text of a well printed document. It may be that VDUs with bright, flicker-free screens and dark characters will increase substantially in the future.



requirements with regard to psychophysical variables	technical parameters	specification
1. suppress large-field-flicker	1. frame repetition rate w	about 90 Hz at 80 cd/m^2
2. suppress border flicker	2. border contrast, separation, w	120 Hz or k ≥ 2:1 or 5mm separating dark line
3. avoid aperture mode	3. auto-range of background luminances	40 to 100 cd/m^2
4. avoid stroke blur	4. stroke flank-gradient	about 30 sec arc (preliminary)
5. use preferred background colours	5. colour locus	near white, i.e. between source E and A
6. avoid background grating adaptation	6. line density	>0.5 l/min arc
7. avoid induced movement	7. jitter amplitude/frequency	<10 sec arc at 10 Hz (preliminary)
8. provide for maximum (internal) screen contrast without blur	8. max. phosphor screen contrast	>10:1
9. make provision against contrast dilution by external light	9. max. illuminance admittable for stroke contrasts ≥1:5	about 3000 lux (natural lighting)
10. make provision against disturbing reflex pattern strength	10. max. reflex peak luminance (for admittable reflex increment ≤ 7 %)	about 2000 cd/m^2
(11.) provide for a corrected stroke width if switched to the reversed contrast	11. 50 % stroke width	about ≥ 2 min arc for pos. contrast
(12.) avoid screen blackness if switched to the reversed contrast	12. mean background luminance of empty screen	adjustable up to ≈25 cd/m^2

Figure 3.2.1 Recommendations for the Construction of a Light Background VDU (Bauer, 1984).

3.3 LUMINANCE AND CONTRAST

Some of the terms used in the context of luminance and contrast are defined below (Wibom and Carlsson, 1987):

Luminance ratio (C_R), also called contrast ratio, is defined as the ratio of the luminances of the two surfaces and is given by

$$C_R = L_1/L_2, \quad L_1 >= L_2$$

where L_1 and L_2 represent the comparing luminances.

Contrast (C) is the relative difference in luminance between surfaces (L_1 and L_2) and is given by

$$C = 100 \times (L_2 - L_1)/L_1 \quad \text{(percent)}$$

Contrast Reduction (CR) expresses the relation between observed contrast and the best possible contrast,

$$CR = 100\ (1 - C/C_{max})\ \text{(percent)}$$

It is a well known fact that the lighting in a workplace can affect the readability of electronic displays. Large luminance differences between two adjacent objects in the working visual field can cause contrast glare which may adversely affect the visual performance. Every time the operator first regards the white manuscript (high luminance) and then the dark VDT (low luminance), there is a substantial risk of experiencing contrast glare. In what follows, the three terms defined in the beginning of this section will be discussed in detail.

Luminance ratio: The legibility of the screen information depends greatly on its relative contrast with respect to the screen background. To improve the readability, the contrast between display luminance and ambient luminance must be controlled. Displays with low luminance are preferable to bright displays, as brighter symbols have edge blurring and tend to run together. Luminance ratios in the region of 3:1 are required for a good visual environment. A screen background that is not quite black, but has luminance in the medium range, has the added advantage of decreasing the impediment caused by specular reflections on the shining screen and filter surfaces. Specular reflections occur when illuminated images of the environment can be seen into the video screen. To have a well observable information-containing image, its luminance has to be at least 10 times as high as the luminance of the interfering image. This is another reason for having a lower contrast on the screen.

Screen filters can be used to reduce the disturbing reflections. However, Wibom and Carlsson (1987) reported that such usage is unfavorable with regards to luminance although it increases the contrast which enhances legibility. Also, their data indicated an increase in eye discomfort with the use of screen filters. The alternative approach of reducing illuminance levels and making extensive use of low-brightness luminaries will merely result in an unacceptable luminous environment in the office.

The colors used in a room will affect the ambient illumination present. Light colors and diffused light will provide more uniform room illumination and eliminate shadows. If colored displays are used, then care must be taken with the selection of the luminaires, since the lamps may produce different color effects.

Contrast: Information displayed on a VDT must have either higher or lower luminance than the surrounding areas. The difference between the target and its background is referred to as contrast. Generally, the higher the contrast between symbols and the background, the better the readability. However, these bright symbols on dark background do not contribute to a good environment when working for prolonged periods. VDT users may improve performance and reduce fatigue if contrast is moderate (Bjorset, 1987). High contrast causes increased fatigue and will produce more discomfort, although it may be justifiable when using old equipment with low screen luminance.

Taylor and Rupp (1987) reported that operators do not set limits on preferred contrasts but rather seek contrast levels which are comfortable. An inverse relationship was found to exist between comfortable contrast ranges and the background luminance of a bright character display. However, contrast was confounded with symbol illuminance and display resolution in their study.

Eastman (1968) addressed the issue of the relative importance of color contrast and luminance contrast for a wide range of color combinations and contrast values and observed an increase in visibility levels with increase in contrast. However, as the visibility approached the maximum, large increases in the contrast were needed to achieve small increases in visibility. The visibilities of all combinations of hues of the high-contrast targets were nearly the same as for the neutral targets. This suggested that color contrast is relatively unimportant for high contrast targets. Dark on light targets seemed to have the advantage in visibility over light on dark targets of the same contrast value, only if the contrast values were low.

Contrast Reduction: To improve legibility and minimize eye discomfort, the contrast reduction should be as low as possible. Bjorset (1987) recommended that relative contrast reduction should not be more than 15% for reading at the VDT workplace.

In conclusion, higher luminance ratios in the working field of vision cause greater eye discomfort. Large luminance ratios are attributable to dark screens. Thus, the introduction of bright screens can help to improve the situation by reducing the occurrence of eye discomfort.

3.4 RASTER MODULATION

Raster modulation is a significant factor in image quality (American National Standard, 1986), and it is derived from resolution and addressability. The interrelationship between these two factors constitutes Raster Modulation. Resolution is a property design of the display device, and is derived from the width of a line or spot image on the screen. Addressability is a characteristic of the display controller and represents the ability to select and activate specific points or x,y coordinates on the raster display screen. This is usually stated in terms of the number of lines scanned from top to the bottom of the display screen as well as the number of points along each raster line. Since addressability is controlled by the hardware driving the VDT, and since resolution is determined by the design of the VDT, these two display characteristics are independent of one another. However, to obtain a high level of image quality, certain relations need to be maintained between resolution and addressability. For example, if resolution is too low (large slot sizes), successive lines will over-write preceding lines. Under some conditions this may produce false images. Conversely, if addressability is too low (large spot separation) then adjacent raster lines will not merge and they will appear as visible spots (Murch and Beaton, 1987).

RELATING RESOLUTION AND ADDRESSABILITY: The primary goal in engineering a visual display system is to attain sufficient image quality to maximize the transfer of "information" from the display screen to the human operator. Although numerous factors contribute to the overall image quality (e.g. ambient illumination, screen format, etc.), resolution and addressability directly impact two fundamental criteria underlying the design goal.

The first criterion, termed as the adjacent raster line or pixel (pixel is the smallest discrete addressable subsection of a visual display) requirement, states that the raster structure of a display must be imperceptible to an operator located at a typical (40 cm) viewing distance. This requirement is intended to eliminate visible "noise," which arises from the discrete picture of the display systems, and which bears no relevant information for the operator. A display system that meets the adjacent raster line (pixel) criterion presents uniform bright solid-filled areas and alphanumeric characters, which appear continuously constructed and highly legible.

The second-image quality criterion, termed the alternate raster line (pixel) requirement, states that individual lines (pixels) which are in an alternating on-off-on-off pattern must be visible to an operator from a typical viewing distance. This requirement optimizes the visibility of high spatial frequency components, such as narrow lines and fine details within an image. For a VDT system with a smoothly decreasing modulation transfer function(MTF), optimizing the alternate raster line criterion also optimizes the information transfer of the low spatial frequency component as well (Beaton, 1984). The two above mentioned image-quality criteria place opposing demands upon the optimal specification of display resolution and adressability. For example, increases in display addressability favor the adjacent raster line criterion since the modulation (luminance contrast) between adjoining raster lines is reduced; however, the same reduction in modulation also reduces the detectability of individual lines within an on-off-on-off pattern, thereby penalizing the alternate raster criterion. A similar trade-off occurs with changes in display resolutions (Murch and Beaton, 1987).

PERCENT RASTER MODULATION AND PERCENT ACTIVE AREA: For a VDT display having a pixel density of less than 30 pixels per degree the luminance modulation in the direction perpendicular to adjacent raster lines shall be equal to or less than 20% when all lines and all pixels are in their "on" state. For displays having luminance control, this requirement is to be met when pixel luminance is one half of the maximum luminance.

For non-VDT matrix displays, the percent active area or fill factor should be at least 75% of the space allocated to the pixel. This requirement is for displays having a pixel density of less than 30 pixels per degree at the viewing distance. A raster modulation greater than 20% interferes with legibility of the displayed image. Minimum raster modulation can be achieved by suitable spacing of adjacent lines, selection of pixel size, or both. Maximum legibility is achieved with a "perceptual flat field," i.e. one approaching zero modulation across adjacent lines or pixels.

Non-VDT matrix displays may not be capable of presenting pixels continuously. For such displays, the percent active area may be used as an index of uniformity. To define the outline of the pixel and determine its area relative to the area allocated to the pixel, the convention is to use the perceptual edge of the pixel, about the 5% luminance contour.

3.5 RESOLUTION

Resolution of a visual display is a measure of its capability to display the smallest discernible detail. That measure, accordingly, is the means by which the sharpness of a display is specified. Resolution is a property of the display device design. It is derived from the width of a line or a spot imaged on the screen. The narrower the line or the smaller the spot, the higher the resolution. From the measured line width, resolution can be specified in a number of ways, such as lines per unit, distance modulation transfer function (MTF), spot size, etc. (Murch & Beaton, 1987).

One aspect of image quality is resolution or image sharpness. People tend to prefer a sharply focused image. This is true even if symbol size and contrast ratios are such that sharp focus might not seem to be important. There may be a physiological explanation for such a preference, since there is a relationship between image resolution and electrical activities generated in the brain (Gomer & Bish, 1978). Stimulation of the visual system produces measurable electrical activity in the brain. The voltage differences between the electrode placed on the scalp can be recorded. These voltage differences for an image of higher resolution were, within limits, stronger and more clearly defined than ones produced by an image of lower resolution but of similar contrast and equal total light output (IBM, 1984). The resolution of VDT characters has been regarded as one of the principal problems in legibility. However, recent studies have shown that many displays produce sharper images than are typically found on some source documents (Cakir, 1978). Nonetheless, the resolution on many VDUs leaves much to be desired and this clearly poses a difficult problem for the image clarifying mechanism of the visual system. The resolution may be degraded by grime on the front surface of the screen or inside the front panel. In fact some VDTs draw their cooling air over the CRT surface and this may lead to dust or nicotine being deposited in a fine layer causing a blurring image (Stewart, 1980).

Any optical system, whether a lens or a display, will degrade the image of the original figure. This degradation, which varies with the size of the image, can be quantified using a display modulation transfer function. Although large features corresponding to low spatial frequencies are reproduced without much degradation, smaller features (corresponding to low spatial frequencies) are most difficult to reproduce, because they are relatively more affected by noise and blur in the system resulting in greater degradation. Figure 3.5.1 shows an MTF curve for a display system. Note that for the low spatial frequencies the reproduction is perfect with contrast C=1, whereas MTF and contrast fall off at higher spatial frequencies.

Blur, resolution and MTF are all related to the sharpness of display characters. There are, however, no standard procedures for measuring these parameters. It is now possible to compare the MTF of a display with the

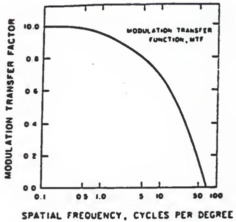


Figure 3.5.1 Modulation Transfer Function (MTF) Curve for a Display System (Snyder, 1980).

contrast threshold function of the eye (see Figure 3.5.2). As the spatial frequency increases beyond a certain value, the MTF curve crosses the contrast threshold function. This crossing point corresponds to the limit of resolution beyond which the human eye cannot perceive finer details of the particular display. Of course the limit of resolution varies, depending upon the luminance of the display and the modulation contrasts.

There have been several different models for quantifying image quality in displays. The most important of these has utilized the MTF or derivatives thereof. In particular, the area enclosed by the MTF and the contrast threshold function called modulation transfer function area (MTFA) has proved to be a good measure of image quality (Snyder, 1980). The main difference between a MTF and the MTFA is that MTFA takes into account the sensitivity of the human eye. It has been shown that MTFA is positively correlated with visual performance (Snyder, 1985). Increasing MTFA increased the viewer's ability to see details, and the relationship between MTFA and visual performance is non-linear (Figure 3.5.3).

Beaton (1984) suggested that the following formula may be used for approximating MTFA for displays with spots that have a luminance profile that is approximately normally distributed.

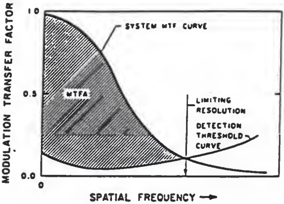


Figure 3.5.2 Modulation Transfer Function Area (MTFA) (Snyder, 1980).

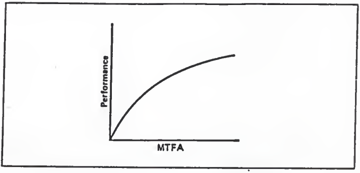


Figure 3.5.3 Typical Relationship Between Visual Performance and MTFA (American National Standard, 1986).

$$\mathrm{MTFA} = 10^{A}$$

where $A = 1.48 + 0.6 \times V_D - 1.07 \times W_D - 1.62 \times A_B - 0.17 \times V_D \times A_B + 0.59 \times W_D + 0.48 \times L_M \times A_B + 0.06 \times V_D \times L_M \times A_B$ where,

V_D = viewing distance in meters, when $0.038 \text{ m} < V_D < 1.02 \text{ m}$;

W_D = full width of Gaussian spot at the half amplitude point in mm, when $0.15 \text{ mm} < W_D < 0.76 \text{ mm}$;

A_B = $\log_{10}$ of reflected luminance in cd/sq.meter from the display screen, when $0 < A_B < 1.7$.

The required value of MTFA depends on whether the display is used for graphics or alphanumerics. Generally, a high resolution display has an MTFA value of 10 or greater whereas a moderately high resolution display has a MTFA value between 7 and 10. For most office applications where the VDTs are used for displaying alphanumeric information, the MTFA should be greater than 5 (Helander, 1987).

4 WORKSTATION

4.1 GLARE

Glare is harsh, uncomfortable bright light which makes reading difficult.

There are several types of glare:

REFLECTED GLARE: Reflected glare results when reflection of a window or an overhead light causes bright spots on the VDT screen. The glare decreases the contrast between the characters and their background resulting in eye strain to the operator reading the screen.

Reflected glare is further categorized into specular reflection and veiling reflections.

SPECULAR REFLECTION: Specular reflections produce mirror like images on the screen (for example, reflection of the operator, luminaires, and other objects in the room).

VEILING REFLECTION: Veiling reflection is a diffuse reflection produced by light falling on the screen surface. Most of the veiling reflection is caused by the phosphor, which has an irregular surface, similar to the surface of paper. The irregularity of the surface causes reflections to be spread in all directions. Veiling reflection increases the luminance of both the screen background and the characters, thereby reducing the contrast ratio of the displayed character.

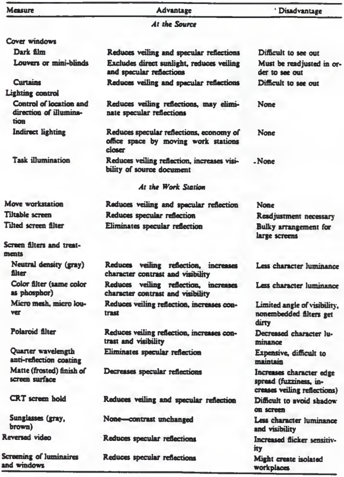
DISABILITY GLARE: Disability glare is produced when intense light shines directly in the operator's eye. When the light enters the eyes, it reduces the amount of contrast the operator can perceive, making it difficult to read the screen.

DISCOMFORT GLARE: Discomfort glare is produced by a light source in the operator's field of view. It usually is caused by light fixtures or by daylight coming through the window, and it makes the screen difficult to see. Glare is reported to be among the most common complaints of the CRT user. It is well accepted that an important aspect of VDT design is the suppression and elimination of glare. The effect of glare on operators may include headaches, fatigue, eyestrain and discomfort (Hopkinson, 1972; Hultgren and Knave, 1974) leading to a decrease in legibility. Screen reflections reduce the legibility of characters and often cause operator discomfort (Helander, 1987). Stammerjohn et al. (1981) observed that bright reflections on the screen was the principal complaint of operators. In a survey by Stammerjohn et al. (1981), potential discomfort glare sources existed at 46 out of 53 workstations. Reflected glare was present in most of the VDT screens surveyed. Of the 53 screens evaluated, 17% had reflected glare levels making reading characters on parts of the screen difficult. A significantly larger proportion of VDT operators (80%)

reported glare from workstation lighting. Approximately 85% of the VDT operators reported that screen glare was occasionally bothersome. Much of the early work on glare dealt with finding the relationship between physical parameters of glare and their effect on vision (Holladay, 1926). This work provided basic information about glare, leading to the discovery that glare that causes discomfort does not necessarily inhibit vision, and glare that inhibits vision does not cause discomfort. Later studies that examined glare approached the issue in two ways. In the first approach, experimenters studied glare and its effect on VDT workers via a questionnaire survey (Hultgren and Knave, 1974). The second approach consisted of having subjects appraise glare by one of two methods. The first method involved studies in which subjects were required to make adjustments between borderline comfort and discomfort glare (Lulla and Bennett, 1981). In the second method, subjects were required to rate the glare sensation on a seven-point scale labelled from pleasant or no glare to intolerable glare (Bodmann and Sollner, 1965).

A known performance study on the effects of VDT glare was that reported by Stone and Groves (1968, cited in Boyce, 1973). Supra-threshold visual performance was studied when various levels of glare were introduced, but no differences among the glare levels were found. A recent study (Garcia and Wierwille, 1985) to determine the effect of glare on performance revealed that glare does affect performance on a VDT reading comprehension task, and that a mild but reliable interaction exists between glare and subjective reading difficulty of text. However, it also revealed that, when faced with glare on a VDT, subjects will choose some method of compensating for or ameliorating its effects.

TECHNIQUES FOR MINIMIZING GLARE: A common suggestion for reducing specular reflection is to use indirect illumination (Carlsson, 1979, Konoschuku and Bodmann, 1980). This can be achieved by positioning luminaires low and directing some of the illumination upward (Helander, 1987). Also see Figure 4.1.1 for measures for reducing screen reflections. Isensee and Bennett (1983) suggested that low to moderate levels of ambient illuminance (approximately 100 to 260 lux) minimize the discomfort due to direct glare and reflected glare. The evidence also suggested that a negative polarity screen was preferable to positive a polarity screen in terms of comfort. To reduce sources of discomfort, video luminance should be reduced without decreasing the legibility of characters on the display. One method may be to use a filter over the face of the VDT screen (Sach, 1970, Kroemer, 1983). Filters improve contrast and reduce glare. A diffuse surface on a filter can cut down on glare by scattering the reflected light.



Measure	Advantage	Disadvantage
	At the Source	
Cover windows		
Dark film	Reduces veiling and specular reflections	Difficult to see out
Louvers or mini-blinds	Excludes direct sunlight, reduces veiling and specular reflections	Must be readjusted in order to see out
Curtains	Reduces veiling and specular reflections	Difficult to see out
Lighting control		
Control of location and direction of illumination	Reduces veiling reflections, may eliminate specular reflections	None
Indirect lighting	Reduces specular reflections, economy of office space by moving work stations closer	None
Task illumination	Reduces veiling reflection, increases visibility of source document	None
	At the Work Station	
Move workstation	Reduces veiling and specular reflection	None
Tiltable screen	Reduces specular reflection	Readjustment necessary
Tilted screen filter	Eliminates specular reflection	Bulky arrangement for large screens
Screen filters and treatments		
Neutral density (gray) filter	Reduces veiling reflection, increases character contrast and visibility	Less character luminance
Color filter (same color as phosphor)	Reduces veiling reflection, increases character contrast and visibility	Less character luminance
Micro mesh, micro louver	Reduces veiling reflection, increases contrast	Limited angle of visibility, nonembedded filters get dirty
Polaroid filter	Reduces veiling reflection, increases contrast and visibility	Decreased character luminance
Quarter wavelength anti-reflection coating	Eliminates specular reflection	Expensive, difficult to maintain
Matte (frosted) finish of screen surface	Decreases specular reflections	Increases character edge spread (fuzziness, increases veiling reflections)
CRT screen hold	Reduces veiling and specular reflection	Difficult to avoid shadow on screen
Sunglasses (gray, brown)	None—contrast unchanged	Less character luminance and visibility
Reversed video	Reduces specular reflections	Increased flicker sensitivity
Screening of luminaires and windows	Reduces specular reflections	Might create isolated workplaces

Figure 4.1.1 Measures for Reducing Screen Reflections (Helander, 1987).

Tinting or lowering the transmisson of the filter can cut down on glare because light emitted by the phosphor of the VDT passes through the filter once, but ambient light passes through the filter twice-- once coming in from the outside and again after it is reflected by the surface of the VDT. Thus, a filter cuts down background luminance more than it cuts down video luminance. This means that, by installing a filter, the user can perceive a lower video luminance and consequently observe less direct glare without altering the contrast ratio. In general, filters are more effective against diffuse (veiling) reflections than specular reflections (Snyder, 1983).

Antireflection coating helps to reduce specular reflections. Matte surface treatment (e.g. etching) reduces specular reflection and reduces the sharpness of the screen symbol.

It is essential to eliminate the source of reflection by relocation of light source or workstation, or using indirect illumination. Other glare-reduction techniques include placing shields over luminaires so that lighting is indirect, using task lighting to illuminate printed material rather than the VDT, placing a hood over the VDT to shade the screen, covering windows with drapes or blinds, or even using dark colors for walls, ceilings and clothing.

4.2 VISUAL ANGLE

The visual angle of a character or a line of characters determines the retinal image size or effective visual size of reading material. In our discussion we will be referring to the horizontal visual angle of an entire line (Figure 4.2.1).

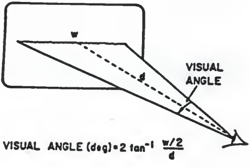


Figure 4.2.1 Schematic Diagram Showing Visual Angle and its Calculation.

Effects of visual angle are discussed here to explain why people read more slowly from VDT displays than from paper (Gould and Grischkowsky, 1984; Kak, 1981; Mills and Weldon, 1984; Muter et al., 1982; Wright and Lickorish, 1983). One possibility is that participants take more time to read from VDT displays because wide lines require more eye fixations.

If people view the two texts from the same distance, their visual angles will differ by about the ratio of screen widths (Gould and Grischkowsky, 1985). Gould and Grischkowsky (1985) studied the effects of visual angle on reading over a wide range of distances. Two different types of fonts were used. One was a font from a frequently used VDT display and the other was a frequently used paper font. This allowed an assessment of possible interactive effects of visual angle and font. The results of the experiment showed that the speed and accuracy of reading remained about the same for each font over an angular range of 16 to 36 degrees. Character lines on most VDT displays fall within this range.

Kurk and Muter (1984) did not find changes in reading rates for character lines subtending 9, 14 and 26 degrees horizontal visual angle on a VDT display.

The viewing angle refers to the horizontal angle, in degrees, between the eye of the viewer and the face of the display (Williams, 1981). Carel et al. (1974), after a review of the literature, reported that legibility remained unchanged for lateral or vertical viewing angle up to 30 degrees (off perpendicular). Shurtleff (1960) reported little change up to 45 degrees. Buckler (1977) recommended the maximum viewing angle to be 30 degrees. The most comfortable vertical angle is 15 degrees (viewing from above) (Ostberg, 1977).

Thus visual angle can be ruled out as an explanation of why people read more slowly from VDT displays. However, after eliminating the visual angle effect, reading was 16 to 20% faster for "Letter Gothic" font than for the "3277 CRT font".

4.3 VIEWING DISTANCE

Proper viewing distance is important in minimizing visual fatigue, and incorrect viewing distance or angle can lead to awkward operator postures. Viewing distance should not be so great that the characters subtend less than the minimum arc required for reading (Lambart and Stammerjohn, 1981). The distance of the viewer from the display and the viewer's visual acuity determine the readability of the display (Williams, 1981). A comfortable viewing distance is a function of not only the size of the displayed characters, but also of a person's ability to maintain focus and align the eye. In most office tasks, the speed of visual accommodation i.e., adjustment of eyes to accommodate changes in focal distance is not important since the luminance is more or less uniform at each workstation and the visual distances involved in most office tasks are much the same. But it is often recommended that, at the viewing distance of 45 to 50 cm, the speed of frequency of accommodation becomes more important. For physiological reasons, it is necessary to keep changes in viewing distance to a minimum to reduce accommodation time. The reason for this lies not only in saving accommodation time but also to protect the individual from reading with non-optimally accommodated eyes. In addition, because the screen and the keyboard usually are not located on the same visual plane, i.e. at desk level, there follows a change of focal point between these elements in the vertical plane. These changes in the focal point stress the eye and neck muscles and should, therefore, be kept to a minimum.

Gould et al. (1987) determined the distance at which people sit when reading from a VDT display and from paper so as to account for differences in reading. Their study showed people would sit further away from a VDT display as compared to paper, though perhaps not far enough to compensate entirely for potential differences in visual angle. In another study (Kurk and Muter, 1984), the distance between the subject and the video monitor was varied. However, distances did not seem to have any effect on reading. This finding is consistent with the finding of constant perceptual span over different distances (Morrison and Rayner, 1981), but contradicts the result of Kak (1981), who reported that reading speed was faster for closer distances. Kak used distances of 35 cm, 73 cm, and 111 cm in a between-subject design with four subjects per distance. She used a 22.9 cm monitor, with an APPLE microcomputer. Therefore the visual angle of her characters were slightly smaller than those in Kurk and Muter's study (1984). The differences cannot be attributed to a lack of sensitivity in the Kak's (1981) experiment, since the use of error mean square from Kurk and Muter's study (1984) with Kak's (1981) results would have shown significant differences in reading speed. Unless there are some special requirements, displays should not be designed to be viewed at distances of less than 30 cm. It is advantageous to locate frequently viewed surfaces at or near the same optical distance. The typical eye-to-keyboard distance when the VDT user is seated in the upright position has been estimated at 45 to 50 cm. However, when the eye position is corrected for comfortable viewing of the keyboard, the viewing distance is reduced by about 10 cm (Farrel and Booth, 1984) to a range of about 35 to 40 cm.

In summary, a viewing distance of 45 to 50 cm, with a maximum of 70 cm is recommended (Cakir et al., 1979).

5 GENERAL

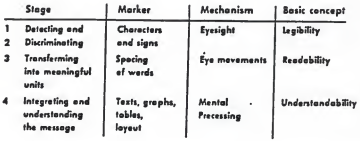
Legibility and readability are different from other terms described in this paper in the sense that they are

(1) integrated measures of merit, and

(2) these measures are based on human performance.

Legibility, according to ISO (Sauter et al., 1984), is defined as the visual ability to recognize the form of a symbol and readability is the quality of text which allows groups of characters to be easily discriminated and recognized as meaningful units. The performance criteria for VDTs are that they should be legible, readable, and comfortable to use. These criteria are complementary rather than interchangeable. Individual characters can have good legibility without having good readability (which may be determined by between-character spacing ,length of lines, layout, etc.), and vice-versa. Another case would be the use of sharp red characters on blue backgound. This may give short term legiblity due to good color contrast, and also long term reading discomfort.

Reading is essentially a four-stage process, which depends on many geometric and photometric characteristics of individual characters (see Figure 5.1.1). Legibility is an essential pre-requisite and as such is a component of readablity. Similarly, reading is necessary in order to comprehend the displayed text. In most types of visual display in addition to minimum character size (which is required to ensure a basic ability to detect and discriminate between similarly-shaped characters), there is also an optimum character size. This effect is clearly seen in the case of a dot matrix generated character. If the characters are increased beyond the optimal value corresponding to the resolution of the matrix and dot size, the separation of the individual dots ceases to present a continuous image to the viewer.



	Stage	Marker	Mechanism	Basic concept
1 2	Detecting and Discriminating	Characters and signs	Eyesight	Legibility
3	Transforming into meaningful units	Spacing of words	Eye movements	Readability
4	Integrating and understanding the message	Texts, graphs, tables, layout	Mental Processing	Understandability

Figure 5.1.1 The Components of Readability (Cakir, 1979).

5.1 READABILITY

Several reports confirmed that people read more slowly from VDT displays than from paper (Kak, 1981; Gould and Grischkowsky, 1982, 1984; Muter et al., 1982; Treuniet and Bean, 1982; Wright and Lickorish, 1983; Kurk and Muter, 1984; Happner et al., 1985; Gould et al., 1987). On the other hand, two studies reported no reading speed differences between paper and VDTs. Cushman (1984) compared two different groups of participants, and Switchenko (1984) had participants read the same material twice. The evidence, on balance, indicated that people read more slowly from VDT displays than from paper.

The study by Gould et al. (1987) attempts to explain the cause of the reading speed difference. Their results showed that no single variable (e.g experience in using VDT display, display orientation, character size, font or polarity) clearly explained the observed difference in reading speed. Reviews of decades of reading research on typeset material by Patterson and Tinker (1940) and Tinker (1963) showed that most physical variables, when studied individually had only a modest effect (10% or less) even when varied over a large range. These physical variables included line width, line spacing, margin size, print size, and font type. By combining several "reasonable" but "non-optimal" print conditions, however, reading rate was reduced by 20%. The effect of these, however, was cumulative. The tentative conclusion is that the difference is due to a combination of variables, probably centering on the image quality of the character themselves. Most of the evidence, including that from the experiment (Gould et al., 1987), suggested that the image quality of characters rather than task or user variables, was the most likely reason producing differences in reading speed. The visual angle experiment (Gould etal., 1987), which rules out visual angle, showed that people read photographs of the 3277 display (an IBM VDT display) significantly more slowly than they read photographs of paper letter gothic characters. This suggested that the associated difference in the image quality, font, color, and polarity contribute to differences in reading speed. Gould et al. (1987) also compared reading from paper and from a VDT display when the display looked similar to paper, i.e. they had the same font, polarity (dark letters on a light background), size, color (almost) and layout on the two media. Their studies showed that the characters shown on the VDT display were anti-aliased (Sholtz, 1982). Most VDT display are raster displays that typically feature dot matrix characters and lines that appear to contain "staircasing" or "jaggies". These phenomena are a result of aliasing, which is caused by an under-sampling of the signal that would be required to produce sharp, continuous characters. Perceptually, anti-aliasing eliminates staircasing or the jaggies in characters. The anti-aliasing technique developed by Sholtz accomplishes this by adding grey level or variations in luminance to each character. This is done without requiring greater addressablity (resolution) of the display. The result identifies a set of conditions that when present on a VDT display leads to significantly faster reading--equivalent to that achieved by reading on paper.

Some conditions that permit faster reading on a VDT display are as follows:

1. Display polarity-the VDT characters must be dark on a light background.
2. Display color-the characters must be dark rather than greenish.
3. Display layout-the layout (i.e. line length, character size and interline spacing) must be exactly the same as on the paper.
4. Display font-the font must be same as paper font rather than dot-matrix font; fonts are based upon anti-aliased characters rather than aliased characters.
5. Display tube characteristics-the contrast must not be as high as compared to other displays (3277 or 3278) but should be sufficient. A particular character will always appear the same regardless of where it appeared on a 3277 or a 3278, but it will

look slightly different depending on where it appeared anti-aliased on the display.

6. Display tube resolution-display addressability (resolution) must be higher for IBM 5080 than for IBM 3277 or 3278.

6.2 LEGIBILITY

Poor legibility can have serious consequences on the individual operator to successfully and reliably carry out the work for which the VDT is intended. Crucial in this respect is the `cost of error'. At the simplest level, and provided that they are not too frequent, errors are a source of inconvenience rather than cost. At higher level, however, (e.g. billing, credit checking), the consequences of error, however infrequent, can become serious and costly. In extreme cases, e.g. in air traffic control and many types of military application, the cost of errors can be disastrous. Display legibility is, therefore, one of the most important criteria by which the merits of a VDT-based system are judged and by which the individual operator of a VDT judges the quality of the VDT.

Studying legibility usually requires that one or more human subjects try to recognize letters or read words that are presented on a VDT. The set of letters or letter characteristics that give the best reading performance (e.g. speed of recognition, freedom from error) are customarily said to be the most legible. The objective in studies of this kind is usually to investigate how reading performance depends upon factors such as character size and style, brightness, spacing and other geometric and photometric properties of the characters on display.

Direct legibility testing requires almost no equipment. But it is costly to administer, execute, analyze and report the results and it causes fatigue and also is boring to the subjects involved in the study. In other words, it takes experimental skills and experience to run legibility tests. Gould et al. (1987) reported great difficulties in obtaining reliable proofreading speed differences between poor and good text, even though, in the real world, people would almost certainly refuse to read poor quality text. Such disheartening experiences are common among VDT researchers; it may take a laboratory specialized in research or fatigue/performance, and repeated measurements for over five days or more with subjects, before differences in display legibility show up as true differences in proof reading performance (Wilkinson and Robinshaw, 1987). It can be argued that proofreading provides a measure of display readability rather than legibility. However, the basic problem is the same. Ostberg (1988) tested the legibility of two VDT screens - one was a positive polarity VDT (Tele Nova Compiss-a Swedish make) and the other a negative polarity VDT (IBM PC color). Twenty subjects took part in 350 legibility test trials. The legibility of the negative polarity (IBM PC color) VDT was significantly lower than that of the positive polarity (Tele Nova Compiss) VDT. Also Ostberg recommended an MTFA (modulation transfer function area) value of at least 7 to promote legibility.

6 CONCLUSION

The readability and legibility of a VDT can be the same as that of printing, if the display is of positive polarity (dark characters on light background). In addition, the VDT should have high resolution (240 pixels/inch), should be anti-aliased, and should have the same font as that of the the text. With respect to the text, the following guidelines should be followed:

1. Horizontal spacing between characters should be 20% to 50% of the character height.
2. Spacing between lines should be 100% to 150% of the character height.
3. Character width-to-height ratio should be between 3/4 to 1/1.
4. The dot-matrix of 5x7 is generally acceptable where only upper case character heights are used. Where upper and lower case character heights are used, then the dot-matrix should be at least 7x9 but not above 9x11.
5. Character size should be more than 16 to 18 minutes of arc, or 0.10 inch (2.6 mm), whichever is less and no less than 22 minutes of arc for general reading purposes.
6. Stroke width should be 12% to 17% of character height.

7. The viewing distance should be between 45 cm to 50 cm with a maximum of 70 cm.
8. Viewing angle (horizontal) should be between 16 to 36 degrees.
9. The contrast reduction should be as low as possible but not more than 15%.
10. Resolution should be high, with a minimum acceptable Modulation Transfer Function Area (MTFA) value of 7. A high resolution display has an MTFA value of 10 or more.
11. Raster modulation should be less then 20%.

Furthermore, problems with glare or flicker present on the displays should also be considered. Use of a filter and refresh rate of over 60 Hz may help in minimizing glare and flicker.

It should be noted that the lower fatigue effects reported by Cushman (1984, 1986) for reading negative polarity could be more important, in the long run, than the small performance advantage favoring the positive polarity VDTs.

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GLOSSARY

Accented Letter. A mark used on a letter to indicate which syllable is stressed.

Accommodation. The adjustment of focal length of the lens of the eye.

Anti-Aliasing. Eliminates staircasing or the jaggies which reduces sharpness of characters by adding variations in luminance to each character.

Ascenders. The portion of the letter that goes above the body of most lower case letters (e.g. b, h, d, f).

Decay constant. The decay of N_0 phosphor particles to N particles after time t is given by the equation $N=N_0\ e^{-kt}$ where k is called the decay constant.

Descenders. The portion of the letter that goes below the body of most lower case letters.

Illuminance. The luminous flux incident on a surface, measured in lumens per square meter (lux) or in lumens per square foot called footcandles (fc).

Luminance. The luminous flux per unit of projected area per unit solid angle reflected from or emitted by a surface. Measured in candelas per square meter (Nits) or footlamberts.

Modulation Transfer Factor. The ratio of output to input luminance modulation at a given spatial or temporal frequency.

Modulation Transfer Function. The function or expression describing the curve generated by a series of modulation transfer factors taken over a range of frequencies.

Modulation Transfer Function Area (MTFA). MTFA is a measure of the ability of the display to present sine wave patterns and the eye's ability to detect the presence of a sine wave pattern. These patterns are considered fundamental building blocks for the formation of symbols and figures.

Negative Polarity. Light characters on a dark background screen.

Phosphor-Persistence. That is how long the phosphor remains illuminated after the electron beam has excited it.

Pixel. The smallest discrete addressable subsection of a visual display.

Point. Printer's unit of measurment, used principally for designating type sizes. There are 72 points to an inch.

Positive Polarity. Dark characters on a light background screen.

Presbyopia. Is normally produced when the lens loses its elasticity due to aging. This prevents the lens from changing shape, or accommodating, thus limiting the range over which objects may be brought into focus.

Refresh Rate. Is the frequency of the electron beam that excites the phosphor.

Videotex. A system which enables reading of continuous text on a television screen.

Visual Angle. The angle subtended by the height of an object.

LEGIBILITY

OF

VISUAL DISPLAY UNITS

by

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AN ABSTRACT OF A REPORT

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ABSTRACT

This report reviews the available literature concerning the legibility of visual display terminals (VDTs). It also analyzes in detail the parameters affecting the legibility and readability of the VDTs. Parameters are divided into categories of character, equipment, workstation, and general factors. Character is subdivided into categories of character spacing, line spacing, character format, width to height ratio, size and stroke width. Equipment is subdivided into flicker, image polarity, luminance contrast, raster modulation and resolution. Workstation is subdivided into glare, visual angle and viewing distance. General parameters are subdivided into legibility and readability.