Objective Image Quality of CRT Displays under Ambient Glare:

Assessing the ISO 9241-7 Ergonomic Technical Standard

By

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(Abstract)

This thesis assessed the readability of CRT displays viewed under ambient lighting conditions and then evaluated the findings with respect to the ISO 9241-7 standard. More specifically, two phases of work were conducted in this thesis. In Phase 1, seven monitors were evaluated photometrically according to the ISO 9241-7 standard to determine whether they were Class I, II, or III in positive and negative polarity. Additionally, six filters were attached to each of the monitors and their ISO Class also was assessed. All monitor/filter combinations yielded either Class I or II in positive polarity and Class II, III or failed in negative polarity.

In Phase 2, fourteen participants were asked to read Tinker passages from seven display/filter combinations (tested in Phase 1) under five lighting conditions and two screen polarities. The purpose of the Phase 2 was to determine if people perform differently for Class I, II, or III monitor/filter combinations. The dependent measures were the time to read the Tinker passage (reading time) and the ability to identify the out of context word in each passage (accuracy). An Analysis of Variance was used to determine the significant effects of reading time and accuracy. The ANOVA results indicate that specular glare interferes significantly more with reading time than does diffuse glare.

Diffuse (200 lux) and Specular reading times also were correlated against two ISO metrics: *screen image luminance ratio* (Diffuse, 200 lux) and *specular reflection luminance ratio*. Reading times did not correlate with the *screen image luminance ratio*, but they did correlate with one of the ISO *specular reflection luminance ratios*.

The results of this thesis indicate that the ISO standard should not equally weight the *screen image* and the *specular reflection luminance ratios*. Additionally, the results indicate that it is not necessary to have separate ISO Classes for positive and negative polarity. Furthermore, people did not read differently for Class I, II, or III monitor/filter combinations. Finally, the data of this investigation provide an initial human factors database for use in assessing the validity of ISO 9241-7.

Preface

Joy Kempic conducted her thesis in conjunction with Gary Olacsi. Both students wanted to work on the same topic area (i.e. evaluating the ISO 9241-7 standard) but from different perspectives. Gary Olacsi wanted to evaluate the ISO 9241-7 using subjective measures of human performance while Joy Kempic wanted to evaluate the standard using objective measures. Thus, much of the background and literature review sections are similar in the two theses since they deal with similar topic areas. Both students took part in researching and writing these sections and have a good understanding of the research process. Additionally, both students worked together to take the 500 measurements on the monitors and filters according to the ISO 9241-7 standard. Thus, the Phase 1 Methods and Results sections are also similar in the two theses. Phase 2 of these theses greatly differ since Gary Olacsi performed a subjective evaluation and Joy Kempic performed an objective evaluation.

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INTRODUCTION AND RATIONALE

In today's society, computer workstations are common tools in homes and offices. Since the beginning of electro-optical visual display terminal (VDT) use in the late 1970’s, people have complained of several problems associated with the use of these devices. The most prevalent class of complaints is visual performance-related (Rancourt and Grenawalt, 1986). In particular, VDT operators complain of blurred vision, redness, burning, dry eyes, and visual fatigue. Investigators have determined that glare is a contributing factor to visual discomfort and eye-strain (Cakir, Hart, Stewart, 1980). One cause of glare in the workplace is that VDTs are prone to reflections of ambient illuminance. In fact, studies by Laubi, Hunting, and Grandjean (1982) and Stammerjohn, Smith, and Cohen (1981) reported that 45 and 85% of computer workstation operators complain of bothersome screen reflections. Therefore, screen reflections are a serious problem for VDT users and efforts should be made to reduce or eliminate them.

U. S. National and international standards have been developed to address reflected glare problems in cathode ray tube (CRT) workstations. Essentially, they measure the ability of a CRT display to sustain usable and satisfactory image quality in luminous work places that produce screen reflections. The American National Standard for Human Factors Engineering of Visual Display Terminal Workstations (ANSI/HFS 100-1988) discusses the problem of glare indirectly by providing display hardware requirements for luminance, contrast, and resolution. Unfortunately, this standard does not directly measure the design attributes of a display (and/or anti-reflection filter) that contribute to disruptive screen reflections. In other words, the tests prescribed in the standard produce results that indicate only the effects that reflected glare has on display luminance, contrast, and resolution output for a specific workplace lighting environment. On the other hand, International Standard Organization 9241 Part 7 of the Ergonomic Requirements for Office Work with Visual Display Terminals (ISO 9241-7) quantitatively characterizes the reflectances of display device surfaces.

ISO 9241-7 directly measures the display hardware design attributes that contribute to screen reflections (i.e., the diffuse and specular reflectances of the display device surfaces). Thus, this standard has the potential to provide display and glare filter manufacturers with the necessary information to assess product performance in work environments susceptible to glare.

The main problem with the ISO 9241-7 standard is that it is loosely based on human performance data. It is entirely unclear how the standard developers arrived at the specific luminance ratio requirements. Therefore, the question of whether the ISO classifications used to rate display devices truly represent perceivable display performance differences remains to be addressed.

With this problem in mind, the present thesis was designed to assess the validity of the ISO standard. Particularly, whether the ISO standard can effectively model CRT viewability under various glare conditions and whether it can also assess potential improvements of glare filter use.

BACKGROUND

In general, glare is defined as a “brightness within the field of vision that is sufficiently greater than the luminance to which the eyes are adapted so as to cause annoyance, discomfort, or loss in visual performance and visibility” (Sanders and McCormick, 1993). Glare can be categorized by its effects on people into either discomfort or disability. Discomfort glare is caused by intense bright light or non-uniform distributions of light that are in the visual field. A person perceives the light as annoying or disturbing but it does not interfere with a person’s ability to perform work. On the other hand, disability glare does interfere with a person’s ability to perform work by superimposing stray light caused by the glare onto the retinal image. Stray light reduces the contrast of an item being viewed and it may be impossible to see it. A good example would be seeing the outline of a person standing in front of a window on a sunny day. People often experience from discomfort glare at a visual display terminal and not disability glare (Cakir et al., 1980).

Glare is further defined by type: direct or reflected. Direct glare occurs when glare sources are in the direct field of view of a person. Reflected glare occurs when the glare sources are reflected from a surface and into the visual field. This thesis focuses on reflected glare since this is what occurs on computer screens and can be reduced by the use of glare filters.

Reflected glare on a display is caused by two types of screen reflections: diffuse and specular. Diffuse reflections create a light or bright haze over some or all of the display and are not well defined images. In contrast, specular reflections produce sharp mirror like images on the first surface of the display. Visual display terminals can have both diffuse and specular reflections at the same time.

Effects of Screen Reflection Types

Specular and diffuse reflections create several problems for the operators of visual display terminals. To understand these problems, it is necessary to explain how and where the reflections are formed on a CRT. An untreated CRT monitor usually consists of a curved glass placed over the phosphor layer of the screen. The glass surface reflects about 4% of the light that falls onto it (Grandjean, 1987; Cakir, 1980). The light that is reflected from the curved glass creates the specular (sharp mirror-like) images. These images appear to the observer to be behind the visual display screen. For some displays, they appear to be as much as 32 cm behind the screen (Sanders and McCormick 1993). Not all of the light is reflected from the glass surface. Some light is transmitted through to the phosphor layer of the screen. The phosphor layer of the screen is responsible for producing the display images that an operator must detect. The light that is reflected from the phosphor layer creates most of the diffuse (light haze) images. However, some of the light that is reflected from the first surface scatters and creates diffuse images as well.

Specular reflections are annoying and distracting to the operator for two reasons. First, people tend to shift their eyes toward bright spots in their visual field. This effect is known as *phototropism* (Sanders and McCormick 1993). The second problem is that the eye has difficulty focusing on the display images, since the characters on the screen and the reflections are in different focal lengths. When the eye is focused on the characters, the reflected image is blurred and out of focus. Because the eye naturally wants to bring the blurred image into focus, it will shift its attention to the specular reflection: thereby blurring the character images. Therefore, the eye’s focus is constantly oscillating between screen characters and the reflected image (Cakir et al., 1980).

The degree to which the operator feels annoyed or distracted by specular reflections is dependent upon two characteristics of the specular image. One characteristic is the intensity or brightness of the image (Cakir et al., 1980; Rancourt and Grenawalt 1986). The brighter the specular image is, the more distracting it becomes. Another characteristic is the sharpness of the image. A more sharply defined image is perceived as more annoying and noticeable than a less sharply defined image of the same intensity (Cakir et al., 1980; Rancourt and Grenawalt, 1986).

One reason that diffuse reflections are annoying to the operator is that they reduce the contrast of the characters on the screen. In order to read text on a display, there must be a certain amount of luminance difference between the characters and the background. Diffuse reflections reduce contrast by illuminating all areas of the screen image, which decreases the luminance difference. The screen is, therefore, more difficult to read. This phenomenon can be mathematically represented by the modulation equation:

$$\mathrm{M} = \frac{\left(L_{\max} + L_{amb}\right) - \left(L_{\min} + L_{amb}\right)}{\left(L_{\max} + L_{amb}\right) + \left(L_{\min} + L_{amb}\right)} = \frac{\left(L_{\max} - L_{\min}\right)}{\left(L_{\max} + L_{\min} + 2L_{amb}\right)} \qquad \text{(Eq. 1)}$$

where L_{max} represents the maximum luminance of the display
L_{min} represents the lowest luminance of the display
L_{amb} represents the ambient luminance reflected from the display

If the minimum luminance (L_{min}) equals the maximum luminance (L_{max}), then the modulation value is zero and the display is unreadable. Therefore, higher modulation values are better. A display with no ambient light will yield a higher modulation value than the same display with ambient light. Thus, the display will be harder to read with ambient light. For example, if the display is viewed in a dark room (L_{amb}=0) and L_{max}=100 cd/m^2 and L_{min}=10 cd/m^2, then the modulation value is 0.82. Suppose now there is ambient light present in the room and L_{amb}=10 cd/m^2, then the modulation value is 0.69; a rather substantial decrease in modulation.

There are U. S. National technical standards that specify proper luminance modulation and contrast ratios (highest luminance to lowest luminance). For example, the *American National Standards for Human Factors Engineering of Visual Display Terminal Workstations* (1988) states that character luminance modulation must be greater than or equal to 0.5, which is equivalent to a contrast ratio of 3:1. It also states that a preferred modulation is 0.75 or 7:1. The Illuminating Engineering Society of North America (IES) also recommends contrast ratios of visual display terminals. The standard (IES RP-24, 1989) states that contrast ratios should range from 3:1 to 15:1, and that the preferred range is 5:1 to 10:1. It is important to note that these documents came out in the late 1980's when most displays used light characters on a dark background (negative polarity). Today, people mainly use dark characters on a light background (positive polarity). The IES has, however, made a recommendation for positive contrast displays. It states that the preferred range is also 1:5 to 1:10.

Methods of Reducing Glare

Although it is always best to reduce glare at its source, such as reducing the ambient illumination or covering windows, this approach is not always practical for all VDT workplaces. Such is the case where there are other tasks that need to be performed in conjunction with VDT work, which require sufficient ambient illumination. These tasks include reading documents, looking at the keyboard, filing, and safely walking around the work area. The following is a discussion of methods that reduce glare at the VDT screen. These methods include etching, quarter-wave thin film coatings, neutral density filters, polarization filters, and micromesh filters.

It is important to note that in order for a CRT anti-reflection treatment or glare reduction method to be effective it must do two things. It must first enhance the display contrast by reducing diffuse reflections from the phosphor surface. Additionally, it must reduce the intensity *and* the sharpness of specular reflections from the glass face-plate of the CRT.

One method of reducing glare is to etch or roughen the screen surface. Etching is a chemical or mechanical treatment applied to the outer layer of the glass surface. An advantage of this method is that it blurs the edges of specular reflections, making them appear diffuse. Etching can reduce the reflectivity of the glass from 4% to 2% (Cakir et al., 1980). There are, however, some disadvantages to etching. Not only does etching blur the reflected image, but it also may blur the image emitted from the phosphor screen. Therefore, legibility of the screen can be reduced. Another disadvantage is that etching does not improve the contrast of the display by reducing diffuse reflections at the phosphor surface.

Quarter-wave thin film coatings are another anti-reflection treatment that reduces specular reflections. It acquired its name because the film thickness is equal to one quarter the wavelength of light. Quarter-wave thin film coatings reduce specular reflections by setting up an interference pattern for light. Because air to coating interface has a different index of refraction then the air to glass interface, the incoming ambient light wave will interfere with a reflected light wave from the glass and cancel each other. The operator will never perceive this light. An advantage of this method is that it does not blur images produced from the phosphor screen. There also are disadvantages in using this method. One disadvantage is that it does not reduce diffuse reflections at the phosphor surface. Another disadvantage is that quarter wave coatings do not reduce the sharpness of the specular reflections. A final disadvantage is that the coating is highly susceptible to fingerprints, dust, and scratches. If the screen becomes soiled, then the phosphor image tends to look smeared.

Another anti-reflection technology is to use a neutral density filter. A perfect neutral density filter works by absorbing equal amounts of light from each wavelength in the visual spectrum. However, neutral density filters are not perfect and they tend to lose some of their absorption properties at either end of the visual spectrum. This can be a problem if an operator needs true color representation. Neutral density filters also improve the contrast of the display by reducing ambient light twice, once by the filter on its way to the phosphor surface and then again when it is reflected back from the surface. The screen luminance, however, is reduced only once through the filter. Since the ambient light is filtered more than the screen luminance, the contrast is improved. Figure 1 depicts the contrast enhancement for a filter. A problem with neutral density filters is that they are made from plastic, glass, or gelatin material and their first surface can be a source of specular reflections.

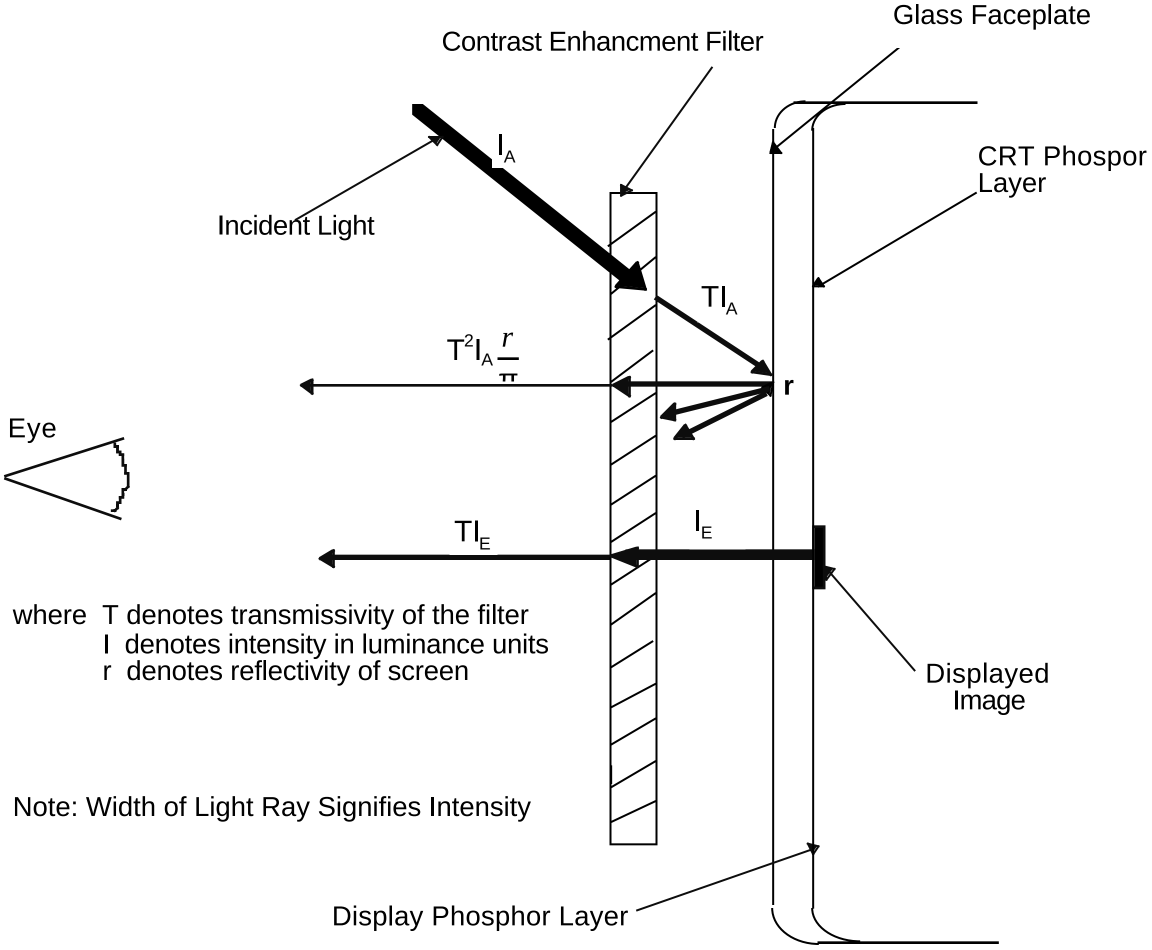


Figure 1. Contrast enhancement for neutral density and polarization filters.

Polarization filters also improve the contrast of the display. To understand how a polarization filter works, a general discussion of light is needed. Light can be considered a wave form that oscillates in any direction such as up/down, left/right, and all directions in between the two. A polarizing filter only allows the waves that are traveling in the polarizing direction of the filter to pass though it. Therefore, a polarization filter improves contrast the same way as a neutral density filter: first by reducing ambient light as it passes through the filter to the phosphor surface and then again, as it passes back through the filter and to the observer. Again, the image luminance is only filtered once so characters appear more distinct on the screen. One problem with polarization filters is that they have highly polished and reflective first surfaces that make them extremely susceptible to specular reflections. One way to remedy the problem is to apply an anti-reflection coating to the first surface.

A final anti-reflection technology is micromesh filters. These filters are made of fine fabrics which resemble black nylon stockings stretched over CRT screens. Micromesh filters only allow light that is perpendicular to the mesh to pass through it and it absorbs or scatters the rest of the light. The ambient light that does pass through the filter is either reflected from the glass surface or the phosphor layer. In either case, the reflected light is further reduced by passing through the filter once again while the screen luminance is only passed though the filter once. Thus, a micromesh filter reduces specular reflections *and* enhances display contrast. However, this filter does have some drawbacks. The overall display luminance is reduced when the screen is viewed from oblique (indirect) angles. Thus, unless the display is viewed head-on, there may not be enough luminance contrast to read the screen. A second drawback is that micromesh filters are difficult to clean and tend to collect dust and dirt, which further reduces luminance from the screen.

Methods of Physically Measuring Screen Reflections

There are several methods to quantitatively evaluate reflections on a visual display. This thesis will focus on two methods. One is the reflectivity transfer function and the other is the ISO 9241 part 7 standard.

Reflectivity transfer function (RTF) (Beaton, 1993) measures both the intensity of the first surface specular image and the sharpness. However, it does not measure the loss in contrast of the display. RTF is determined by a Fourier Transform and either a line spread function or an edge spread function. RTF is defined as “the modulation spectrum of a reflected edge-target [or line-target] image divided by the modulation spectrum of the edge [or line] image measured directly” (Beaton, 1993). Essentially, RTF describes how efficiently the display produces a specular image. Therefore, higher RTF values indicate sharper and more intense images produced on the first surface, an undesirable quality.

Another method of physically measuring reflections on displays or filters is the recently approved ISO 9241 part 7. The purpose of ISO 9241-7 is to determine acceptable VDT image quality when the VDT is subjected to certain glare conditions. The ISO standard classifies or predicts the image quality of VDT monitors based on their usefulness in particular office environments. The ISO standard states that all monitors must comply with one of three classes: Class I, II, or III. Class I monitors have the best image quality under glare conditions and are considered suitable for general office use. Class II monitors are suitable for *most* office environments, but have poorer image quality than Class I under the same glare conditions. Class III monitors have the worst image quality under glare conditions and are only suitable for specially controlled luminous environments.

The ISO standard measures reflections on a VDT screen or filter using luminance ratios. Luminance ratios are similar to contrast ratios but they are not the same. The ISO standard defines a luminance ratio as “the ratio between two luminances, either or both of which may be the composite of two or more other luminances” (ISO 9241-7, 1997). The ISO standard states two types of luminance ratios that *must* be met.

One type is the *screen image luminance ratio* with specular and diffuse reflections. The screen image luminance ratio is the ratio between the higher and lower luminances of an image that has both specular and diffuse reflections on it. In other words, the ratio not only includes the luminances of the image but also the specular and diffuse reflected luminances. The image stated by the ISO standard is either a dark square of pixels surrounded by a bright patch of pixels (positive polarity) or the image is a bright square of pixels surrounded by a dark patch of pixels (negative polarity). Thus, the screen image luminance ratio is dependent on the polarity of the screen. These formulas can be expressed mathematically as:

$$\text{Screen Image Luminance Ratio} = \frac{L_{\text{background}} + L_{\text{diffuse}} + L_{\text{specular}}}{L_{\text{foreground}} + L_{\text{diffuse}} + L_{\text{specular}}} \geq 3 \quad \text{(positive polarity)} \quad \text{(Eq. 2a)}$$

$$\text{Screen Image Luminance Ratio} = \frac{L_{\text{foreground}} + L_{\text{diffuse}} + L_{\text{specular}}}{L_{\text{background}} + L_{\text{diffuse}} + L_{\text{specular}}} \geq 3 \quad \text{(negative polarity)} \quad \text{(Eq. 2b)}$$

where $L_{\text{background}}$ is the luminance of the background of the image
$L_{\text{foreground}}$ is the luminance of the foreground of the image
L_{diffuse} is the diffuse reflected luminance
L_{specular} is the specular reflected luminance

The second type of luminance ratio is the *specular reflection luminance ratio*. It is the ratio between the luminance of the background of an image with specular and diffuse reflections on it to the luminance of the background with only diffuse reflections on it. Therefore, the formula does not change for the different polarities, but the required limit does change. The required limit is different because positive polarity displays do not show specular reflections as well as do negative polarity displays (Sanders and McCormick, 1993). Therefore, if a display has specular reflections, it is better to use positive polarity than negative polarity. The formulas for the specular reflection luminance ratio are as follows:

For positive polarity,

$$\text{Specular Reflection Luminance Ratio} = \frac{L_{background} + L_{diiffuse} + L_{specular}}{L_{background} + L_{diifuse}} \leq 1.25 \qquad \text{(Eq. 3a)}$$

For negative polarity,

$$\text{Specular Reflection Luminance Ratio} = \frac{L_{background} + L_{diiffuse} + L_{specular}}{L_{background} + L_{diffuse}} \leq 1.2 + \frac{\left(\dfrac{L_{foreground} + L_{diffuse}}{L_{background} + L_{diffuse}}\right)}{15}$$

(Eq. 3b)

where $L_{background}$ is the luminance of the background of the image
$L_{foreground}$ is the luminance of the foreground of the image
$L_{diffuse}$ is the diffuse reflected luminance
$L_{specular}$ is the specular reflected luminance

The ISO standard utilizes a combination of luminance ratios, monitor polarities, and glare source aperture sizes to evaluate monitor performance. In particular, the monitor *class* (Class I, II, or III) is determined only according to the luminance ratios acquired at different glare source sizes. And this *Class* must be determined separately for both positive and negative monitor polarities, so that a display might be rated Class I for positive polarity and Class II for negative polarity. The exact determination of a display *Class* involves applying two different glare source test conditions: large and small glare source. These two test conditions use large (15°) and small (1°) aperture integrating spheres as the glare sources, respectively. The screen image and specular reflection luminance ratios then are calculated under both the large and small glare source test conditions. In summary, eight different luminance ratios need to be calculated for each monitor: four ratios each for positive and negative polarity.

To be Class I, the polarity of the monitor must pass the screen image and the specular reflection luminance ratio for both the large *and* the small glare sources. A Class II polarity only has to pass the screen image luminance ratio and the specular reflection luminance ratio for *either* the large or the small sources. In other words, it can pass the screen image luminance ratio and the specular reflection luminance ratio for the large source and fail one or both ratios for the small source. The opposite can also be true. The polarity of the monitor can pass the ratios for the small source and fail one or both for the large source. A Class III polarity of the monitor also only has to pass the screen image and the specular reflection luminance ratio for *either* the large or the small sources, but the calculations for the luminance ratios use different luminance levels for the sources than Class I or II. Table 1 shows the luminance levels used in the calculations of the luminance ratios for the three *classes* and the two sources. These luminance levels are different from those used in taking the luminance measurements. While taking the measurements, the luminance of the sources are set equal to or greater than 2000 cd/m^2.

TABLE 1. Luminance Values Used in the Calculations of the Luminance Ratios

Class	**Requirement**	**Luminance of Large Sources (cd/m^2)**	**Luminance of Small Sources (cd/m^2)**
I	must pass luminance ratios for both sources	200	2000
II	pass luminance ratios for either source but not both	200	2000
III	pass luminance ratios for either source but not both	125	200

The discussion of luminance ratios demonstrates that the ISO standard characterizes specular and diffuse reflections two out of three respects. First, the ISO standard measures the contrast of the display using the screen image luminance ratio. Second, it measures the intensity of the specular image using the specular reflection luminance ratio. However, the ISO standard fails to analyze the sharpness of the specular image. This is a serious drawback.

RELEVANT LITERATURE

Several interesting observations were found during a review of the literature regarding the effects of CRT glare and glare attenuation techniques. Overall, most of the researchers agree that high ambient illumination ultimately is responsible for loss in screen contrast and for formation of specular reflections. However, investigators do not entirely agree upon the most effective methods to achieve contrast enhancement and to reduce specular reflections. A notable downfall of most of the studies reviewed was that they were only meaningful for specific situations and did not allow for generalization to other luminous environments. In other words, because these studies did nothing to characterize the reflectivity of display surfaces, predictions could not be made as to how CRTs perform in other luminous environments. The Reflectance Transfer Function (RTF), however, was found to quantitatively characterize a monitor's ability to diffuse (blur) and attenuate first surface reflections.

The studies could be described as belonging to two types of investigations. The studies either approached the glare problem from a hardware (physical measurement), photometric measurement, and analytical perspective or by way of human subjective and objective performance measures. Unfortunately, only a few studies were able to effectively incorporate both approaches. In other words, only a few studies were able to characterize the reflected light in a quantitative manner, thereby allowing its effect on human performance to be determined. Also, ambient lighting conditions and controls seemed to significantly differ between studies in terms of glare source design and incident angle to either an observer or photometer. These ambient lighting condition inconsistencies made it difficult to compare the results of one study to another because, in general, glare increases with the luminance, size, angle of incidence, and proximity of a glare source to an operator's line of sight (ANSI/HFS 100, 1988).

Physical Measurement Studies

Beaton and Snyder (1984). Beaton and Snyder described a series of experiments in which they measured the capabilities of 10 anti-reflection filters. Specifically, they measured the ability of the filters to suppress specular reflections. Additionally, they measured whether the displayed image quality was degraded by the filters. Finally, they measured the display image luminance lost by adding the filters. The glare filters were placed on polished and etched CRTs and measurements were performed for a number of off-axis glare source angles.

Modulation transfer functions (MTF) were obtained for each of the CRTs while the glare filter was fixed in front of it. In general, the MTF concept is an image quality metric that shows the amount of achievable luminous power at each of the spatial frequencies of interest. In basic terms, display systems that are capable of transmitting sufficient luminous power at high spatial frequencies are perceived by the observer as having sharper edges. Those that are incapable of transmitting high frequencies appear blurred (Hunter, 1988). Therefore, the MTF for glare filters indicates whether a filter tends to degrade the displayed images by scattering or diffusing them. The four off-axis vertical angles used for these measurements were 15, 30, 45, and 60 degrees. In addition, the author reported that the maximum display luminance intensity of 86.68 cd/m^2 for the no-filter condition. Quantitatively documenting display maximum luminance intensity is an important control for determining the effects of glare (contrast loss) on a particular CRT’s performance.

Beaton and Snyder found that the circular polarizer and quarterwave coated neutral density filters produce the least reduction in overall image quality. The micromesh filters, in comparison, produced the greatest reduction. Moreover, because of its diffusing effect, the etched CRT produced lower MTF values than the polished display did overall.

RTFs also were collected for each of the display and filter combinations. The RTF concept is like the MTF in that they are both spatial frequency founded measures. The difference is that the RTF indicates the surface's ability to diffuse or eliminate specular reflection independent from displayed image quality. Moreover, small RTF values describe surfaces that effectively reduce specular reflection by eliminating high spatial frequency information, unlike the MTF test for which larger MTF values are viewed desirable. The three horizontal angles used were 20, 30, and 45 degrees. The luminance of the glare source was 3000 cd/m^2. Beaton and Snyder found that the etched CRT diffused specular reflections more than the polished did, regardless of the glare filter used.

Lastly, Beaton and Snyder produced a signal-to-noise ratio (SNR) by dividing the measure of the displayed image quality (MTF) by the measure of the "noise" (RTF). These ratios describe the relative improvement in display quality that a particular glare filter produces by attenuating glare sources. Beaton and Snyder found that the SNR of the etched CRT proved to be greater than the SNR for the polished CRT due to its capacity for diffusing specular reflections. In addition, the quarterwave coated neutral density filter was found to produce the largest SNR with the etched CRT, whereas the micromesh, green and high neutral density filters performed well with the polished CRT. Notable is that only the reflected image sharpness component of the CRT’s first surface reflectance was quantitatively characterized by the authors (i.e., RTF measurements), while diffuse reflections and display surface diffuse reflectance were not.

Rancourt, Grenawalt, Hunter, and Snyder (1986). Rancourt, Grenawalt, Hunter, and Snyder (1986) studied the effects of several glare reduction techniques including: chemical etching, chemical etching combined with a quarterwave filter, and a polished surface with a quarterwave filter. They compared these three techniques to a polished CRT alone in terms of the ability of each to reduce specular reflections without degrading image quality. Rancourt et al. used the MTF and RTF metrics previously mentioned in the Beaton and Snyder study (1984) and found considerable differences between the treatment conditions. The MTF measurements were conducted with a collimated incandescent light that was varied between 20 and 50 degrees from normal, under overhead fluorescent lighting, and in a dark room conditions.

Rancourt et al. found that the etched surface reduced the MTF by about 30% over the polished surface, with or without a quarterwave filter. In addition, they found that placing the quarterwave filter on either the etched or polished CRT surfaces had no effect on image quality under any of the lighting conditions tested. Moreover, glare angle was found to have no effect. The RTF measurements of specular glare suppression ability suggested that the etched, etched with quarterwave, and polished with quarterwave were all much more effective at reducing reflection than the polished only condition. Also, calculated signal-to-noise ratios (same as in Beaton and Snyder, 1984) indicated that the etched conditions resulted in the highest overall image quality and that adding an anti-reflection coating to either an etched or polished CRT surface increases both of their SNRs. It is important to note that only the reflected image sharpness component of the CRT's first surface reflectance was quantitatively characterized by the authors (i.e., RTF measurements), while diffuse reflections and display surface diffuse reflectance were not.

Stammerjohn, Smith, and Cohen (1981). Stammerjohn et al. (1981) investigated VDT workstation designs at five San Francisco area businesses to determine their consistency with recommended design specifications. Measurements were taken and reported on workplace illumination and glare for each of the workplaces. VDT operators were then surveyed to identify factors which contribute to worker dissatisfaction, annoyance, and health complaints. Stammerjohn et al. found illumination levels ranging from 300 to over 1000 lx, 75% of which had illumination levels of 501-700 lx. In 1984, Snyder recommended workplace illumination levels of about 200 lx for workstation with supplementary lighting. Cakir et al. (1979) suggest that illumination levels between 300 and 500 lx are sufficient for VDT workstations without supplementary lighting. The Human Factors Society (ANSI/HFS-100, 1988), along with Sanders and McCormick (1993) has recommend ambient illumination levels of 200-500 lx. An important finding of the Stammerjohn et al. investigation was that a majority of the workstations had levels above the recommended lighting requirements.

The glare measurements taken in this study are representative of early attempts to quantitatively measure specular and diffuse reflections on VDT screens and relate their effects to a subjective image quality evaluation (glare questionnaire). Results from the questionnaire included the finding that 17% of the VDT screens had reflected glare that could make reading characters on parts of the screen difficult. Of particular interest, were the findings that 85% of the participants complained of screen glare and 70% complained of character brightness (presumably resulting from the loss in contrast from relatively high ambient illumination levels). Glare sources for the workstations included windows and light fixtures, with luminance levels of up to 2100 cd/m^2. Specular and diffuse components of reflections were measured directly together, at one of the sites, with a hand-held photometer. Specifically, the measurements included the maximum reflected luminance levels of reflections on VDT screens with the display turned off. They recorded luminance values between 3 and 50 cd/m^2.

Human Performance Studies

Beaton, Murch, and Knox (1985). Beaton, Murch, and Knox (1985) conducted three studies to determine the effects of various anti-glare filters on perceived image quality under dark, diffuse, and specular lighting conditions. Moreover, a different CRT was used in each of the studies in order to determine if the effects of the filters are consistent for different CRT technologies.

The conditions for the first study consisted of a high resolution monochrome CRT with one of the following placed in front of it: a neutral density spray filter, a rectangular oriented micromesh filter, a mechanically abraded glass filter, a quarterwave coated glass filter, or a quarterwave coated filter with a low neutral density layer. The maximum screen luminance produced by this CRT was 68.5 cd/m^2. A non-filtered, polished CRT display condition served as a baseline for this experiment. This study presented a series of paired comparisons to the participant under both dark and diffuse ambient lighting conditions (900 lx from two glare sources displaced off-axis 0.86m vertically and +/- 1.37m horizontally). Beaton et al. found that the spray and etched filters yielded the lowest perceived image quality ratings when viewed in the dark, whereas the quarterwave with the low neutral density layer was found to produce perceived image quality improvements over the baseline condition. None of the other four filters were found to be significantly different from the baseline condition. For the conditions employing the diffuse glare source, the spray filter was judged to degrade the displayed image. Whereas the quarterwave filter with a neutral density layer was found to enhance a displayed image's quality. The authors believed that the softening or blurring produced by the etch and the luminance nonuniformity associated with the spray filter, were what caused the perceived image degradation.

The second study was conducted using a medium resolution color CRT to investigate the effects of the same six filters used in the first experiment along with a louvered filter, a green density filter, a diagonally oriented mesh filter, a glass circular polarizer, and a quarterwave coated filter with a high neutral density layer. The physical characteristics (maximum display luminance and glare source orientation) of the first study were employed here again in this study.

In this experiment, participants were asked to compare each filter to the no-filter baseline condition using an 11-point rating scale ranging from extreme degradation to extreme improvement. Participants judged the quarterwave with a high density layer to mildly degrade the image, whereas the rectangular mesh, the etch, and the louvered filter moderately degraded display images. As in the first experiment, the spray filter yielded the most degraded images. Also, the spray was again found to reduce image quality in the diffuse glare source condition, whereas the quarterwave coated filter and the diagonal mesh produced moderate improvement. The quarterwave filters with the low and high neutral density layers and the circular polarizer were judged to greatly enhance image quality relative to the no-filter condition. The most important finding of this study was that the differences between the filters could not have been a function of CRT type or bandwidth settings.

A third study was conducted using a high resolution monochrome CRT and the six filters which produced image quality enhancement capability. The purpose of this experiment was to determine the effects of uniform and patterned specular reflection on perceived image quality. These two specular reflection types constitute the two glare levels used. The uniform glare source consisted of a large 48% reflective gray-colored matte board illuminated with 1500 lx of diffuse light which was located 1.52m behind the subject. For the Patterned glare condition, the matte board consisted of alternating white (90% reflective) and black (5% reflective) stripes. This large matte board also was illuminated with 1500 lx of diffuse light and the stripes were 10.16 cm wide, thereby forming a vertical square-wave grating pattern.

Beaton et al. found that the circular polarizer degraded perceived image quality for the uniform glare condition, whereas the quarterwave coating with either low or high neutral density layers were found to enhance the displayed information. According to the authors, one possible reason for this finding was that the quarterwave coating reduced the first surface reflectance and the neutral density layer provided contrast enhancement. In the case of the circular polarizer, contrast enhancement was achieved but specular reflection reduction was not. The patterned specular reflection condition yielded similar results for all of the filters but the diagonal micromesh filter, which received a slightly higher image quality rating than the no-filter baseline condition. The authors believe that this finding suggests that the mesh was able to attenuate the high spatial frequency information of the patterned reflection. Another important conclusion on the part of Beaton et al. is that contrast enhancement and anti-reflection treatments are both needed to improve image quality in the presence of a specular glare source. This fact was demonstrated by the subpar performance of the circular polarizer and quarterwave filter with no density layer.

In summary, there were three findings from this study that had far-reaching implications for future research. First, glare filter investigations must have a dark or low ambient lighting condition for a baseline. Secondly, both diffuse and specular glare sources must be used to test whether the filter can both enhance contrast and cut specular (patterned) reflections effectively. Third, the validity of the human performance measures used was found to be high. In other words, VDT operators can discriminate and detect even small differences between lighting filter conditions regardless of the psychophysical data collection procedure employed.

Garcia and Wierwille (1985). Garcia and Wierwille (1985) investigated the effects of ‘no-glare’ and ‘glare’ lighting conditions on reading response time and proportion of correct responses. It is important to note that diffuse reflections were actually present in their ‘no-glare’ condition while specular reflections were present in their ‘glare’ condition. The same glare sources were used for both the ‘no-glare’ (diffuse) and ‘glare’ (specular) experimental conditions. They included two sets of fluorescent tube lights recessed in the ceiling (located above the VDT) and several fluorescent tubes suspended from the ceiling behind the operator. However, a shield was used for the ‘no-glare’ (diffuse) condition to redirect the light in order to prevent direct light from striking the CRT surface. Unfortunately, glare source illuminance and luminance levels as well as incident angles were not reported. Only one CRT was employed in this experiment and no anti-reflection or contrast enhancement treatments were implemented. The difficulty of the reading passages also was varied by the authors for the ‘no-glare’ (diffuse) and ‘glare’ (specular) lighting treatments.

For the human performance measurement procedure, the participants were asked to read each of the passages very carefully because their reading comprehension was going to be tested. The specular lighting conditions yielded the most interesting results of the study. There was more time required to read ‘easy’ passages under specular conditions than diffuse. However, the time required to read ‘difficult’ passages surprisingly decreased. This finding is inconsistent with prior research that would expect an intense specular reflection to have either no effect or an increased reading time. Garcia and Wierwille rationalize this finding by saying that the participants may have been so annoyed by the intensity of the glare source that they rushed through the reading task in an effort to end their contact with the experimental condition quickly. If their explanation had been accurate, than more incorrect responses would have been recorded for the more difficult passages. However, there was no increase in incorrect responses for the more difficult passages.

Isensee and Bennett (1983). Isensee and Bennett investigate the effects of diffuse reflected glare on subjective discomfort ratings under two video polarities, three video luminance, and three ambient illumination conditions. The polarities of video were negative (light characters on a dark background) and positive (dark characters on a light background). The levels of video luminance (photometrically measured) were 120.1, 65.2, and 10.3 cd/m2. The levels of ambient illuminance, measure at the keyboard, were 420, 260, and 100 lx. Isensee and Bennett (1983) did, however, note that ambient illumination levels measured at the center of and parallel to the front surface of the CRT produced readings that were around 20% smaller than those at the keyboard. Also, the illumination was emitted by a single four-lamp fluorescent ceiling source located directly above the CRT. Finally, the authors ensured the absence of specular reflections from light colored clothing by having the participants wear a black cape. This eliminates a confounding variable.

Isensee and Bennett found that reflected glare was judged to be less uncomfortable at lower levels of ambient illuminance and higher levels of video luminance, overall. Also, they found a significant interaction between video luminance and ambient illumination. Specifically, as video luminance increased, the average discomfort rating for the levels of ambient illuminance were more similar. In other words, the average discomfort ratings for the illuminance levels was less variable as video luminance amounts were increased. At that time, Isensee and Bennett believed this finding was an artifact caused by the ratings approaching the low end of the discomfort scale (floor effect). However, this finding can be explained by the fact that higher video luminance usually means higher contrast capability. Further, higher video luminance output (modulation) can help lessen the effects of diffuse reflections that act to reduce the contrast of displayed images. Another important finding was that positive polarity video was preferred to negative polarity in terms of comfort for all the combinations of video luminance and ambient illumination.

Habinek, Jacobson, Miller, and Suther (1982). Habinek et al. (1982) studied the effects of three anti-reflection treatments, two display polarities (positive and negative), and two lighting conditions (‘no-glare’ and ‘glare’) on correct reading rates (CRR) and subjective preference ratings. Just as in the Garcia and Wierwille study, diffuse reflections were actually present in their ‘no-glare’ condition while specular reflections were present in their ‘glare’ condition. Three identical Sylvania CRTs were fitted, respectively, with a micromesh filter, a quarterwave coated filter, and a no-filter. The no-filter polished CRT served as the baseline condition. A fourth condition of a Clinton CRT with an etched front surface was also employed. The ‘no-glare’ (diffuse) condition employed fluorescent lighting located directly over the VDT, while the ‘glare’ (specular) condition used a bank of bare fluorescent tubes suspended from the ceiling behind the participant. Both sources provided 1450 lx of ambient illumination. In addition, glare source incident angle, operator line of sight, and maximum screen luminances were not recorded.

For the ‘no-glare’ (diffuse) lighting condition, no CRR differences were found among the three anti-reflection treatments and the baseline condition. However, significant differences were realized for the preference data. Specifically, the polished baseline treatment was judged to have ‘sharper’ characters. For the ‘glare’ (specular) lighting condition, the micromesh filter produced the highest CRR, while the polished baseline produced the lowest CRR. Subjective preference results indicated that participants found the micromesh filter display to be the easiest to read under ‘glare’ (specular) lighting, whereas the polished CRT was significantly more difficult to read than the others.

In summary, the authors could not recommend one anti-reflection treatment over another treatment, but they were all rated as superior to an unpolished CRT when specular glare is present. However, there is one main problem with the methodology the authors employed. They may have confounded the CRT anti-reflection treatments with the recorded contrast ratios because the subjects were allowed to adjust the brightness controls of the CRTs for the each of the conditions.

Morse (1985). Morse (1985) studied the effects of six anti-glare filters on subjective evaluations of the brightness, sharpness, contrast, color, glare and preference for each filter. In addition, photometric measurements of luminance, MTF, contrast, and glare were made in order to identify the optical characteristics of the filters that are responsible for particular subjective preferences. A quarterwave filter with a neutral density layer, a micromesh filter , a circular polarizing filter, a quarterwave filter with a blue density layer, an etched filter, and a no-filter polished CRT surface were included in the investigation. The specular glare source used consisted of fluorescent light fixture with two 48 inch tubes reflected from a piece of white fome-cor (48 X 18 inches) suspended above and behind the displays. Overhead fluorescent lights provided additional ambient lighting. Unfortunately, no low ambient or dark condition was administered. For each pair of filter-CRT combinations, participants were instructed to make a comparison as to the brightness, sharpness, contrast, color, glare, and overall preference.

Morse did not directly measure the MTF of the display the way that Beaton and Snyder (1984) and Hunter et al. (1987) did. Instead, he calculated the MTF using a prediction equation that takes viewing distance, spot luminance, and average ambient illuminance into account. Therefore, the calculated MTF values could not account for the reflected glare differences or changes in resolution and luminance that resulted from the participants adjusting the brightness controls.

Morse found that, for the preference results, the quarterwave filter with a neutral density layer, the quarterwave filter with a blue density layer, the micromesh filter, and the circular polarizing filter were all rated moderately high for all six criteria. However, the etched filter and no-filter conditions were rated significantly lower for most of the criteria. Calculated estimates indicated that the quarterwave filters produced the highest MTF values, whereas the etched surface produced the lowest MTF. Also, the quarterwave filters, circular polarizer, and micromesh filters were all much more effective in reducing reflected luminance levels than were the etched and polished conditions. Calculated correlations between the subjective and objective measures yielded moderately high r values.

Physical (Photometric) and Human Performance Measurement Studies

Hunter (1988). Hunter's dissertation was composed of two experimental phases. One objective of the first phase was to investigate the effects of 16 glare filters with different surface treatments and transmissivity ratings. This group of filters included three polished with 31-92%, six etched with 31-92%, one polished AR coated with 62%, one etched AR coated with 62%, and two mesh with 50 & 37% transmissivity. The polished glass filter with a 92% transmissivity rating served as a baseline for all the measurements in this phase. Three ambient lighting conditions and two monochrome CRT resolution conditions were also investigated for the filters. The second objective of Hunter's first phase was to quantitatively model the relationship between the measured image quality of the display/filter combinations and the recorded human performance data. His models were based on signal to noise measurements similar to the SNRs used by Beaton and Snyder (1984).

The glare sources employed in the phase one experiments consisted of two, fluorescent light fixtures. One was located directly above the CRT and provided an approximately 650 lx source of diffuse illumination. The other fixture was placed directly behind and above the participant producing a specular image in their line-of-sight. This specular glare source produced a reflection of sufficient luminance to simulate an environment with a poorly located lighting fixture or window.

One of Hunter's general findings was that none of the treated filters significantly improved readability and legibility performance more than the polished glass filter that served as the baseline. However, he did identify various filter treatments that severely degraded performance. Specifically, the etched and low transmission filters degraded human performance over the baseline. Another finding was that the mesh and quarterwave filters improved perceived image quality for the specular glare condition. Hunter's modeling efforts produced mixed results. Although good fit models were produced for perceived image quality, the models Hunter developed for the reading and legibility tasks proved to have little utility.

Hunter's second experimental phase examined the separate and combined effects that filter transmission and diffuse illumination have on readability, legibility, and perceived image quality. Specifically, five contrast enhancement filters with transmissivity rating between 11% to 92% were measured under five ambient illumination experimental conditions. The diffuse glare source used in his second phase consisted of a four-lamp, fluorescent light fixture placed above the CRT. The five discrete levels of illumination used were 0 lx, 320 lx, 1200 lx, 2000 lx, and 2800 lx.

This experimental phase indicated that even during occurrences of extreme contrast loss, the participants were able to maintain good reading and legibility performance. In addition, an inverse correlation was found between illuminance level and perceived image quality. It is important to note that Hunter did not control for specular reflections from light clothing in this diffuse glare experiment, as Isensee and Bennett (1983) did by placing a black cape over their participants. Also, Hunter makes no attempt to quantitatively characterize CRT phosphor surface diffuse reflectance.

Lloyd, Mizukami, and Boyce (1996). Lloyd et al. propose an ambient lighting-display parameter interaction model. It has the potential to provide display and glare filter manufactures with the necessary tools for predicting and assessing the improvements of their product's performance in work environments susceptible to reflected glare. The authors developed an equation that, in theory, predicts the subjective image quality of displays with reflections.

Predicted conspicuity or disturbance ratings (R_p) are calculated as follows:

$$R_p = b_1 * M_s + b_2 / M_{da} + b_3 * W_b / M_{da} + b_4 * M_s * W_b \qquad \text{(Eq. 4)}$$

where M_s is the modulation of the reflected image
M_{da} is the modulation of displayed image when reflections are present
W_b is the width of blur of the specular image
the regression coefficients for b_1 through b_4 are 16.31, 0.7575, -0.003726, and -0.06572, respectively.

The authors identified three display parameters that are needed for the equation. The authors took measurements of six different displays so that they could calculate the three display parameters. They used three CRT displays and three Liquid Crystal Displays. One of the display parameters is the modulation (contrast) of the reflected image (M_s). This indicates the intensity of the reflected image. For example, if a display is used in a dark room, the Ms would equal 0. The M_s value is similar to the specular reflection luminance ratio used in the ISO-9241-7. Another display parameter is the modulation (contrast) of displayed image when diffuse and/or specular reflections are present (M_{da}). This parameter is similar to the screen image luminance ratio used in the ISO 9241-7. The only difference is that this study uses a modulation value and ISO standard uses a ratio. The last display parameter is the width of the blur of the specular image (W_b). A small W_b value indicates that the display or filter does not blur specular images very well. As can be seen, there are a lot of parallels between the physical measures described in this study and those in the ISO standard. The largest difference is that this study addresses the component of specular reflections that the ISO standard does not: reflected image sharpness (edge sharpness).

Lloyd et al. also conducted a human performance study. The purpose was to relate the 3 parameters to subjective analysis of specular glare for the same 6 monitors. Participants were asked to rate the conspicuity or the disturbance of the specular glare under two display polarities for each of the six monitors. The glare source used was an integrating sphere and the words ‘Lighting Research Center’ appeared on each of the displays. The specular glare source was positioned with respect to the participant and the display so that the center of its reflected image appeared about 10 cm from the center of the display’s active area. Also, the mean illuminance on the display was 120 lx, provided primarily by overhead fluorescent luminaries fitted with parabolic louvers. Lloyd et al. found that ratings improved (decrease) as the modulation of the reflected image decreases, the modulation of the displayed image in ambient lighting environment increases, and the width of blur function increases. Additionally, the modulation of the reflected images has a stronger affect on the ratings when the specular reflection is sharper.

There are several problems with this study. One problem is that it uses unrealistic specular glare sources (integrating spheres) which are hardly representative of ambient lighting fixtures in office work environments. Also, a section of the results suggest that the displays may have been given anti-reflection treatments even though the authors don’t address whether they had been treated or not. Another problem is that they used both CRTs and LCDs to build their model. The reflective properties of CRTs and LCDs vary greatly. Therefore, they should have built separate models for the two types of displays. A final problem with the study is that the authors did not hold certain variables constant on the displays for the human performance study. These variables included display resolution, line spacing, and character size.

Conclusions

There are several important themes that can be identified from the literature review of photometric measurement, analytic, and human performance research. These themes are directly relevant to present research and dictate the design of the experimental investigation.

1. Photometric and human performance measure should both be incorporated in order to characterize reflected light in a quantitative manner, thereby allowing its effect on human performance to be determined.

2. Glare filters performance must be measured under a number of different ambient lighting conditions. In other words, both specular and diffuse glare sources can be used to determine a filter’s strengths and weaknesses (many environments contain both). Additionally, a dark or low ambient lighting condition that serves as a baseline must be implemented so that the glare filter can be evaluated under an optimal viewing condition.

3. A range of filter technology should be evaluated. For example, the review of the literature to date showed the need for investigations into the effects of various levels of filter transmission. One advantage of this approach is that it allows for increased generalization to other using environments.

4. Another important consideration is that glare filter evaluations should be carried out on a range of CRTs. The luminance, contrast, uniformity, and resolution characteristics are all capable of affecting the results of the study and are found to vary between monitors. Also, many monitors today have anti-reflection coatings applied to the front of their glass

face-plates. Investigating a cross-section of contemporary CRTs with various anti-reflection treatments applied to them directly, yields increased generalization to other using environments.

5. The reflected image sharpness (edge sharpness) component of specular reflections must be quantitatively analyzed in order to assess a filter or monitor's ability to diffuse and attenuate first surface reflections. Researchers have noted that a more sharply defined reflected image is perceived as more annoying and noticeable than a less sharply defined image of the same intensity.

6. Finally, some standardization is needed in glare investigations for ambient lighting conditions and controls in terms of glare source design and incident angle to either an observer or photometer. Ambient lighting condition inconsistencies make it difficult to compare the results of one study to another because, in general, glare increases with the luminance, size, angle of incidence, and proximity of a glare source to an operator's line of sight.

Objective of Present Work

The objective of this research was to assess the readability of CRT displays viewed under ambient lighting conditions and then to evaluate the findings with respect to the ISO 9241-7 standard. In Phase 1 of this work, seven monitors were evaluated according to the ISO 9241-7 standard to determine whether they were Class I, II, or III. Additionally, anti-reflection filters were attached to monitors to see if they changed the class of the monitor. In Phase 2, human performance measurements were taken to determine if people perform differently for Class I, II, or III displays or display/filter combinations under different lighting conditions and different screen polarities. Finally, correlation models were developed to see if there was a linear relationship between the ISO measurements and the human performance measurements.

PHASE 1

Methods for Physical Measurements

Seven monitors were classified according to the ISO 9241-7 standard. For each of these seven monitors, six filters were attached and evaluated according to the ISO 9241-7. There were a grand total of 49 different monitor/filter combinations that were classified according to the ISO 9241-7 standard. The specifications for the monitors and the filters are shown in Tables 2 and 3, respectively.

TABLE 2. Monitor Specifications

Monitor	Coating
SamSung Model # CSN5987	uncoated
Packard Bell Model # 1020	1-layer spin coat
Sony Trinitron 100	1-layer spin coat
Nokia	2-layer spin coat
Sony Trinitron 200	4-layer PET/AR laminate
Mitsubishi Model# TF870	4-layer direct coat
Panasonic Pana Flat PF 70	AR Bonded Panel

TABLE 3. Filter Specifications

Filter Brand Name	Coating	Transmissivity
3M Anti-Glare Filter Model BF 10	1-sided Anti-Reflection coating, Neutral Density	45%
3M Anti-Glare Filter Model AF 150	2-sided Anti-Reflection coating, Neutral Density	45%
3M Anti-Glare Filter Model AF 100 or AF 200 *	2-sided Anti-Reflection coating, Neutral Density	31%
3M Anti-Glare Filter Model 400	1-sided Anti-Reflection coating, Neutral Density	44%
3M Anti-Glare Filter Model 450	2 sided Anti-Reflection coating, Neutral Density	53%
3M Circular Polarizing Filter Model HF 300	Circular polarizer, 1 sided Anti-Reflection coating	42%

* Note: AF 100 and AF 200 are the same filter but the names are different for different filter sizes.

Equipment

The photometric measurement facility at the Displays and Controls Laboratory, Virginia Tech was employed to make all ISO measurements. The photometric equipment consisted of a two-dimensional CCD detector (model: Photometrics, Inc., AF 200), mounted on a large-area XYZ translation stage (Aerotech, model: 101SMB2-HM). The translation stage and photometer were coupled to a pneumatically-mounted optical bench, which also contained a jig for the CRT displays under test. All measurements were performed under the conditions stated in the ISO 9241-7 standard. Moreover, all measurement equipment was calibrated to NIST-traceable standards. Figure 2 depicts the equipment configuration for the ISO measurements.

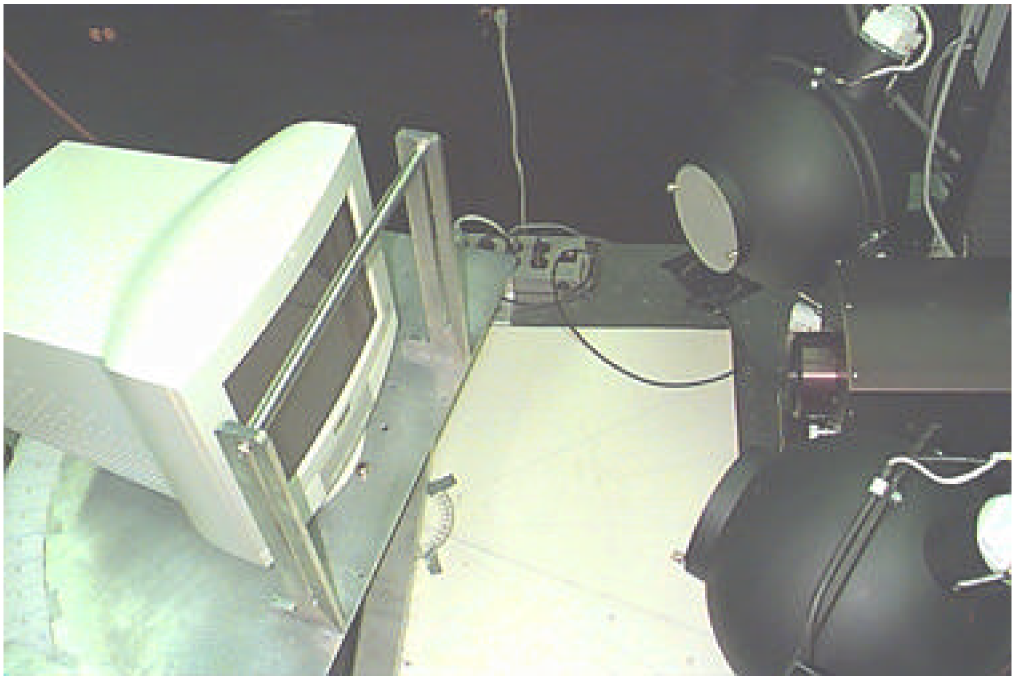


Figure 2. Picture depicts the equipment configuration for the ISO measurements.

Test Procedures for ISO 9241-7

According to the ISO 9241-7 standard, 10 measurements are needed from each monitor/filter combination. These 10 measurements were used to calculate the four luminance ratios. The 10 measurements can be grouped into 5 categories. The categories and measurements are listed in Table 4.

TABLE 4. Categories and Measurements used in the ISO 9241-7

Category	**Measurement**	**Abbreviation**
Diffuse Measurements Taken Perpendicular to Center of Screen	the diffuse reflected luminance of the display	$L_{D(0)}$
	luminance of reflectance standard at diffuse location	$L_{D(STD,0^\circ)}$
Display Luminance Measurements in *Negative Polarity*	luminance of foreground	$L_{F(15^\circ)}$
	luminance of background	$L_{B(15^\circ)}$
Display Luminance Measurements in *Positive Polarity*	luminance of background	$L_{B(15^\circ)}$
	luminance of foreground	$L_{F(15^\circ)}$
Extended-Source Reflection Measurements @ 15 Degrees	luminance of specular + diffuse extended source reflection	$L_{DS(EXT,15^\circ)}$
	luminance of reflectance standard at extended L_{DS} location	$L_{DS(STD,15^\circ)}$
Small-Source Reflection Measurements @ 15 Degrees	luminance of specular + diffuse small source reflection	$L_{DS(SML,15^\circ)}$
	luminance of reflectance standard at small L_{DS} location	$L_{DS(STD,15^\circ)}$

The following paragraphs describe the procedures used to take the 10 measurements. A full description of the measurements is in the *Measurements and Calculations* section of the ISO 9241-7 standard. (Note: For all measurements, the faceplate of the screen was positioned at 90 degrees or vertical to the floor. In other words, the screen was not tilted at an angle.)

Diffuse Measurements Taken Perpendicular to Center of Screen. The layout for the first two measurements is shown is Figure 3. Both luminance sources (15-degree apertures) were turned on and set to 2000 cd/m^2. The monitor was powered off for these measurements. First, the photometer was focused on the phosphor layer of the screen and at the center of the display. Screen grid coordinates were used to ensure that all photometric measurements were taken at the center of the CRT. A scan was taken of the diffusely reflected luminance ($L_{D(0)}$) of the monitor/filter combination. The diffuse reflectance standard then was placed directly over the center of the CRT screen or filter and a second measurement was made. This was the diffuse reflectance standard measurement $L_{D(STD,\ 0^\circ)}$.

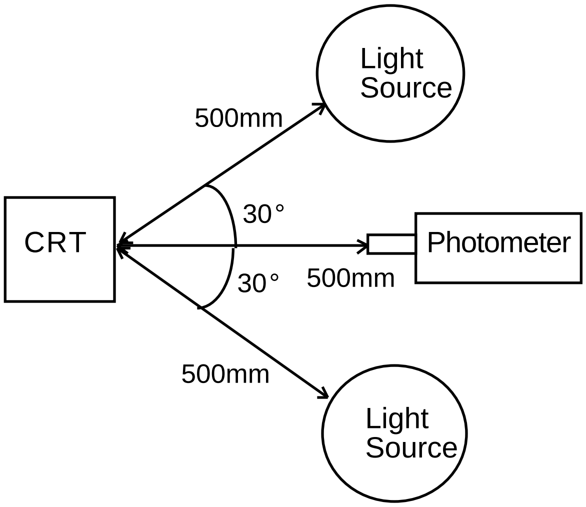


Figure 3. Top view of the layout for the diffuse measurements.

Display Luminance Measurements. The monitor was required to be activated for 20 minutes prior to *any* display luminance measurements to ensure that the monitor luminance output was stable. The following brightness and contrast procedure was implemented after the 20 minute warm-up. First, both the contrast and brightness controls were turned off. Then, the luminance was increased until the outer edges of the raster lines were just perceivable in a dark room. Finally, the contrast was increased until the luminance output for a full white screen reached 75 cd/m^2. The contrast level of 75 cd/m^2 was chosen because it was the highest output for all seven monitors.

Display Luminance Measurements in Negative Polarity. For these next two measurements, the power to the luminance sources remained off and the monitor was rotated 15 degrees from the center of the faceplate (Figure 4). After the monitor was turned on and allowed to warm up for 20 minutes, a 50 mm white box was displayed at the center of the screen. A single 512 x 512 pixel scan was taken. Half of the scan consisted of the top portion of the white box and the other half consisted of the adjacent black background. Using IPLab Spectrum software, the luminance foreground $L_{F(15)}$ was measured by selecting the white (foreground) area and calculating an average area luminance for it. The luminance background $L_{B(15)}$ then was measured by selecting the black (background) area and calculating an average area luminance for it.

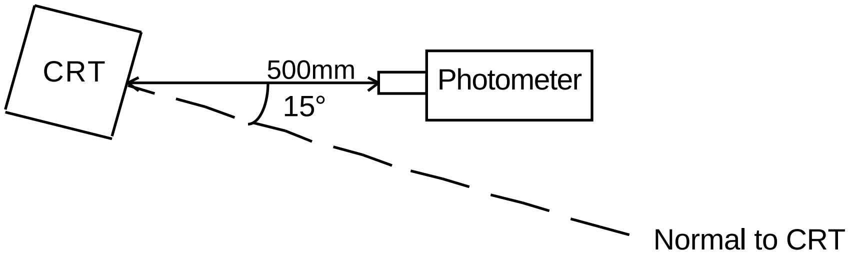


Figure 4. Top view of the layout for the display luminance measurements.

Display Luminance Measurements in Positive Polarity. A five minute waiting period was observed after the monitor was switched to positive polarity. The positive polarity had the same setup as the negative polarity except that the screen displayed a 50 mm black box (foreground) with a white background. Again, the luminance measurements were taken exactly like the negative polarity. Half of the scan taken was the top of the black box and half of the scan was the white background. The luminance of the black foreground $L_{F(15)}$ was selected and calculated using the software. Finally, the luminance of the white background $L_{B(15)}$ was selected and calculated.

Extended-Source Reflection Measurements @ 15 Degrees The extended-source specular measurements were performed with the monitor off. The monitor was again turned 15 degrees from the center of the faceplate (Figure 5). Additionally, only one light source at a 15-degree aperture was activated for these measurements. The light source was set to 2000 cd/m^2. For the $L_{DS(EXT,\ 15°)}$ measurement, the photometer was focused on the monitor's first surface for measurements taken without a filter. For the monitor-filter combinations, the photometer was focused on the first surface of the filter. It should be noted that the filters were positioned on the monitor such that all three reflections (filter glass, monitor glass and phosphor plane reflections) were superimposed at the center of the screen where the measurement was taken. After the $L_{DS(EXT,\ 15°)}$ was taken, the diffuse reflectance standard then was placed in front of the monitor or filter and the $L_{DS(STD,\ 15)}$ measurement was taken.

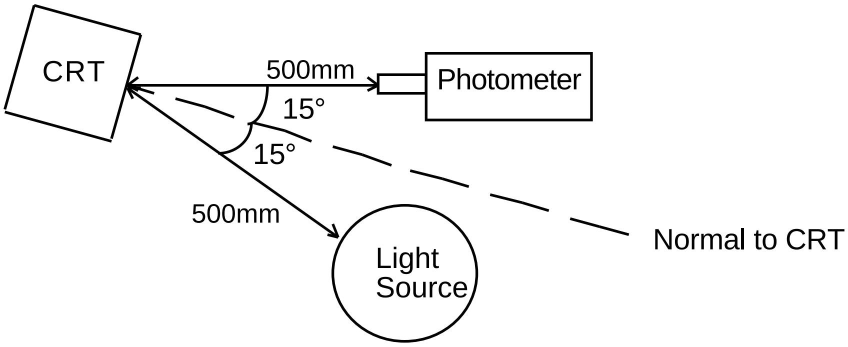


Figure 5. Top view of the layout for the extended and small source reflections.

Small-Source Reflection Measurements @ 15 Degrees. The last two measurements had the same layout (refer to Figure 5) as the Extended-Source Reflection Measurements with one exception. The luminance source had a 1 degree aperture instead of a 15 degree aperture. Again, the one light source was set to 2000 cd/m^2. For the $L_{DS(SML,\ 15°)}$ measurement, the photometer again was focused on the monitor's first surface for the measurements taken without a filter. For monitor-filter combinations, the photometer was again focused on the first surface of the filter. The standard states that the three reflections(filter glass, monitor glass and phosphor plane reflections) should superimpose for the small source measurements. The filter was placed carefully so that the reflections from the first surface of the filter and the display overlapped, but the reflection from the phosphor layer of the display would not superimpose. Thus, two measurements were needed: one for the filter and display first surfaces and one for the phosphor plane. These two measurements then were added together since these are additive photometric quantities. After the $L_{DS(SML,\ 15°)}$ measurements were taken, the diffuse reflectance standard was placed in front of the monitor or filter and the $L_{DS(STD,\ 15)}$ measurement was taken.

Results and Discussion

After the ten measurements were taken for each monitor/filter combination, the luminance ratio equations were calculated for both sources and both polarities. The ISO Classes were then determined for each polarity. Table 5 shows the results of the ISO standard measurements. Table 6 shows whether adding the a filter improved, degraded, or kept the same Class as the display by itself.

TABLE 5. Monitor and Filter Classifications

	Monitor	AF 150	BF 10	PF 400	PF 450	HF 300	AF 100 or AF 200
SamSung	II	I	II	II	II	II	II
	FAILED	III	FAILED	II	III	II	III
Packard Bell	I	I	II	I	II	II	II
	III	II	III	II	III	II	III
Sony Trinitron 100	I	I	II	II	II	II	II
	III	II	FAILED	II	III	II	III
Nokia	II	I	II	II	II	I	II
	III	III	FAILED	II	II	II	III
Sony Tinitron 200	I	I	II	II	II	I	II
	II	II	III	II	II	II	III
Mitsubishi	I	I	II	II	II	I	II
	II	II	III	II	II	II	III
Panasonic Pana Flat	I	II	II	I	II	I	II
	II	II	III	II	II	II	II

* Positive polarity in white and negative polarity in gray

TABLE 6. Filter Effect on ISO 9241-7 Monitor Classification

	Monitor	AF 150	BF 10	PF 400	PF 450	HF 300	AF 100 or AF 200
SamSung	II	+	0	0	0	0	0
	FAILED	+	0	++	+	++	+
Packard Bell	I	0	-	0	-	-	-
	III	+	0	+	0	+	0
Sony Trinitron 100	I	0	-	-	-	-	-
	III	+	-	+	0	+	0
Nokia	II	+	0	0	0	+	0
	III	0	-	+	+	+	0
Sony Tinitron 200	I	0	-	-	-	0	-
	II	0	-	0	0	0	-
Mitsubishi	I	0	-	-	-	0	-
	II	0	-	0	0	0	-
Panasonic Pana Flat	I	-	-	0	-	0	-
	II	0	-	0	0	0	0

Note: Positive polarity in white and negative polarity in gray
‘-’ means filter degraded one class
‘0’ means filter kept the same class as the monitor alone
‘+’ means filter improved one class
‘++’ means filter improved two classes

Monitor-Filter Combinations

As shown in Table 5, certain glare filters work better on some monitors than other monitors. The following paragraphs describe which filters work best and worst on the different CRT displays examined.

- *SamSung.* The AF 150 is the only filter that improved the positive polarity classifications on the SamSung monitor. All of the filters improved the negative polarity class except the BF 10.

- *Packard Bell*. Only the AF 150 and PF 400 kept the Packard Bell a Class I in positive polarity. All other filters degraded the Class. The only filters to improve the negative polarity class were the AF 150 and PF 400.

- *Sony 100*. The AF 150 was the only filter that kept the Sony 100 a Class I in positive polarity. In negative polarity, the AF 150, PF 400, and HF 300 improved the class to Class II.

- *Nokia*. The AF 150 and HF 300 improved the Nokia to a Class I in positive polarity. In contrast, the HF 300, PF 400, PF 450 were the only filters to improve the negative polarity class to a Class II.

- *Sony 200.* Only AF 150 and HF 300 kept the Sony 200 a Class I in positive polarity. All other filters degraded the Class. All filters kept the same negative polarity class as the Sony 200 with the exception of the BF 10 and AF 100, which degraded it to a Class III.

- *Mitsubishi.* Only the AF 150 and HF 300 kept the Mitsubishi a Class I in positive polarity. All other filters degraded the Class. All filters kept the same negative polarity class as the Mitsubishi with the exception of the BF 10 and AF 100, which degraded it to a Class III.

- *Panasonic.* Only the PF 400 and HF 300 kept the Panasonic a Class I in positive polarity. All other filters degraded the Class. All filters kept the same negative polarity class as the Panasonic except BF 10 which degraded it to a Class III.

Filters

There are also a number of important points that can be made about the filters themselves.

- *AF 150.* In general, AF 150 always improved or remained the same as the monitor alone with one exception: Panasonic Positive polarity.

- *BF 10.* In general, this filter degraded the polarity Class. It even failed a Class III for the negative polarity on the SamSung, Sony 100, and Nokia.

- *PF 400.* In negative polarity, the PF 400 improved the smaller, lower end monitors and kept the same class for the bigger, higher end monitors. In positive polarity, the PF 400 either kept the same class or it degraded the class. Because the standard explicitly states that measurements should not be performed on displays that have significant luminance fall off when viewed at oblique angles, it is difficult to determine the validity of these findings.

- *PF 450.* Regardless of the monitor, this filter was always a Class II in positive polarity. In negative polarity, the PF 450 seemed to keep the same class as the monitor with two exceptions: it improved the SamSung and Nokia monitors. Because the standard explicitly states that measurements should not be performed on displays that have significant luminance fall off when viewed at oblique angles, it is difficult to determine the validity of these findings.

- *HF 300.* In general, the HF 300 either kept the polarity Class the same as the monitor alone or it improved the polarity Class. It especially improved the SamSung negative polarity and the Nokia positive polarity classes.

- *AF 100 or AF 200.* Regardless of the monitor, the AF 100 or AF 200 filter was always a Class II in positive polarity. Additionally, this filter was always a Class III in negative polarity with one exception: Panasonic.

General Findings

One general finding was that positive polarity always yielded either Class I or Class II because the Large Source, *Screen Image Luminance Ratio* (LR $_{BDS/FDS}$) and the *Specular Reflection Luminance Ratio* (LR $_{BDS/BD}$) always passed. Conversely, negative polarity always produced Class II, III, or Failed because the Small Source, *Specular Reflection Luminance Ratio* (LR $_{BDS/BD}$) failed every time (note: it would occasionally pass when the calculations were performed for a Class III monitor). Additionally, the negative polarity, large source, *specular reflection luminance ratio* (LR $_{FDS/BDS}$) always passed. Additional observations of the ISO standard are described in Appendix A.

Overall, the AF 150 and HF 300 were the best filters for reducing glare on monitors. The BF 10 and AF 100 (or AF 200) seem to be the worst filters because they increased the Class of the monitor. Thus, these filters can intensify screen reflections because the first surface of the filter can be a source of specular reflections. Tables 7 and 8 depict the overall results for the filter effects.

TABLE 7. Tabulation of Filter Effects on Monitor Class in Positive Polarity

Monitor Class	AF 150	BF 10	PF 400	PF 450	HF 300	AF 100 or AF 200
I	0	-	-[1]	-	0[2]	-
II	+	0	0	0	[3]	0

TABLE 8. Tabulation of Filter Effects on Monitor Class in Negative Polarity

Monitor Class	AF 150	BF 10	PF 400	PF 450	HF 300	AF 100 or AF 200
II	0	-	0	0	0	-[4]
III	+[5]	-[6]	+	0[7]	+	0
FAILED	+	0	++	+	++	+

Note: The symbols mean the following:

‘-’ means filter degraded one class
‘0’ means filter kept the same class as the monitor alone
‘+’ means filter improved one class
‘++’ means filter improved two classes

The superscripts mean the following:

[1] = filter degraded the class 3 times but kept the same class twice
[2] = filter kept the same class 3 times but degraded twice
[3] = filter improved the class once and kept the same class once
[4] = filter degraded twice and kept the same class once
[5] = filter improved the class twice and kept same class once
[6] = filter degraded the class twice and kept same class once
[7] = filter kept the same class twice and improved class once

PHASE 2

Methods

Phase 2 of this thesis was a human performance experiment. It was a three factor (7 x 5 x 2) within-subjects design. The three independent variables were monitor/filter combination, ambient illumination, and polarity of the CRT monitor.

The monitor/filter combination had seven levels. Three monitors and four monitor/filter combinations were selected for the human performance study. The monitors and monitor/filter combinations were chosen based on their ISO classifications. There is at least one display from each of the classes plus filters that improved, degraded, and kept the same Class as the display alone. Table 7 shows the monitor/filter combinations used in the study.

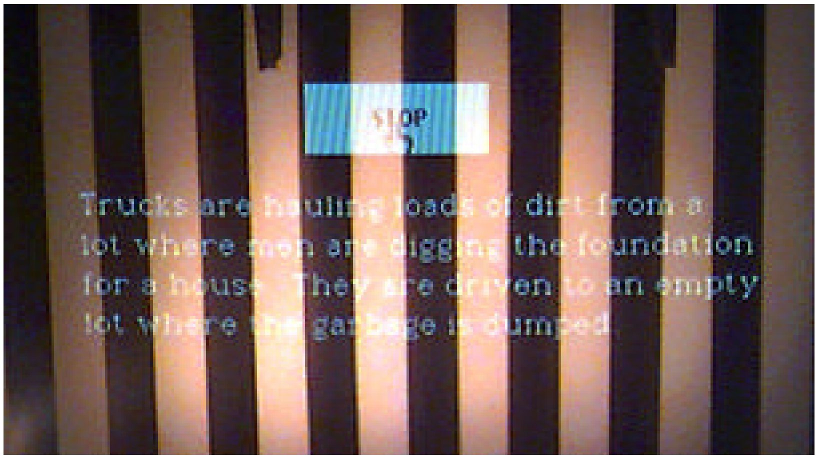
TABLE 9. Monitors and filters Used in the Human Performance

Monitor	Positive Polarity	Negative Polarity
SamSung	Class II	Failed
SamSung plus AF 150	Class I	Class III
SamSung plus HF 300	Class II	Class II
Sony	Class I	Class III
Sony plus BF 10	Class II	Failed
Mitsubishi	Class I	Class II
Mitsubishi plus AF 150	Class I	Class II

Ambient illumination consisted of five levels: one for a dark condition, three for diffuse light, and one for specular light. For the dark condition, the only light sources were the monitor under test and an incandescent lamp. The lamp had a 15 watt light bulb and had orange filters placed over it so that it did not interfere with dark adaptation. The lamp was necessary so that the participants could use the keyboard to type the out of context word in the dark.

For the diffuse light conditions, fluorescent light sources were positioned so that they did not create any specular (sharp, mirror like) images on the screen. Additionally, the participants sat behind a viewing booth so that their clothing did not create any specular images on the screen. The three levels of diffuse lighting were 200, 500, and 800 lux. The 200 lux condition was chosen since it was the same amount of light used in the diffuse measurements for the ISO standard. Additionally, the ANSI/HFS 100 standard (1988) indicates that office lighting levels should be between 200 and 500 lux. Thus, 500 lux was chosen because it was the upper range suggested by ANSI. Since most office environments are illuminated much brighter than 500 lux (Stammerjohn et al., 1981), 800 lux was chosen as the last level.

For the specular condition, a white and black vertical bar pattern was positioned to reflect in the display. The width of each bar was 19 millimeters. Two incandescent lights shined on the bar pattern so that the luminance emitted from the center white vertical bar was 2000 cd/m^2. This is equivalent to the lighting level used for the specular condition in the ISO standard. The specular bar pattern was positioned so that it overlapped the information that the subject needed to read from the screen. Figure 6 shows the specular pattern overlapping the text passage.



Trucks are hauling loads of dirt from a lot where men are digging the foundation for a house. They are driven to an empty lot where the garbage is dumped.

Figure 6. Pictures shows the specular pattern overlapping the text passage.

The last independent variable is the polarity of the screen and it has two levels: positive and negative. The positive polarity screen had dark characters on a bright background and the negative polarity screen had bright characters on a dark background.

The dependent measures were the accuracy and the time to read the Tinker Speed of Reading Test passages. The Tinker Speed of Reading Test was developed by Miles A. Tinker and it consists of about 450 paragraphs (Feldt, 1955). All of the paragraphs are kept at the same comprehension level so that accuracy and reading time are the only factors under test. Each paragraph consists of about 3 sentences. To make sure that participants are actually reading and understanding the paragraphs, they are asked to identify the one word that is out of context within each paragraph. The word is usually located in the last sentence of each paragraph. The following is an example of a Tinker reading passage. The word out of context is ‘car’.

> Marge was on the lake when the lightning started flashing, and she rowed back home as fast as she could because she was frightened that the car would hit her.

The independent variables were blocked according to monitor-filter combination. In other words, participants received all levels of ambient illumination and polarity of the screen for one monitor at a time. A Balanced Latin Square was used to order the way in which the participants received the monitor-filter combination. The other independent variables (ambient illumination and polarity of the screen) were randomized for each monitor with one exception. The dark ambient light condition was always given first to the subjects so that they would have time to dark adapt.

Equipment

The experiment was conducted in the Displays and Controls Laboratory. A Power Macintosh 8500/120 was used with three cathode ray tube (CRT) monitors: SamSung, Mitsubishi, and Sony Trinitron 100. The following filters were attached to some of the monitors: 3M Anti-Glare Filter Model BF 10, 3M Circular Polarizing Filter Model HF 300, and 3M Anti-Glare Filter Model AF 150. The three monitors were positioned on a sliding table so that each monitor could be positioned in front of the participant. A chin rest was also used to position participants heads while viewing the screens.

The five levels of ambient illumination were created in a specially configured laboratory testing room. In the testing room, the displays were viewed through a porthole in a wall (or viewing booth) that lead into a light chamber. Figure 7 shows the viewing booth. The chamber contained a mixture of high intensity incandescent and bright-white florescent bulbs that were calibrated for diffuse and specular illumination. There were two purposes of the viewing booth. The first purpose was to eliminate specular reflections caused by the participants clothing. The second purpose was to keep the participants from knowing how many monitors they were viewing. The active area of each of the CRTs were masked by foam core bezels to reveal a fixed viewable area of 14” diagonal. Figure 8 shows the foam core bezels attached to the three monitors.

Figure 7. Participant sitting in the viewing booth looking at text on a computer screen.

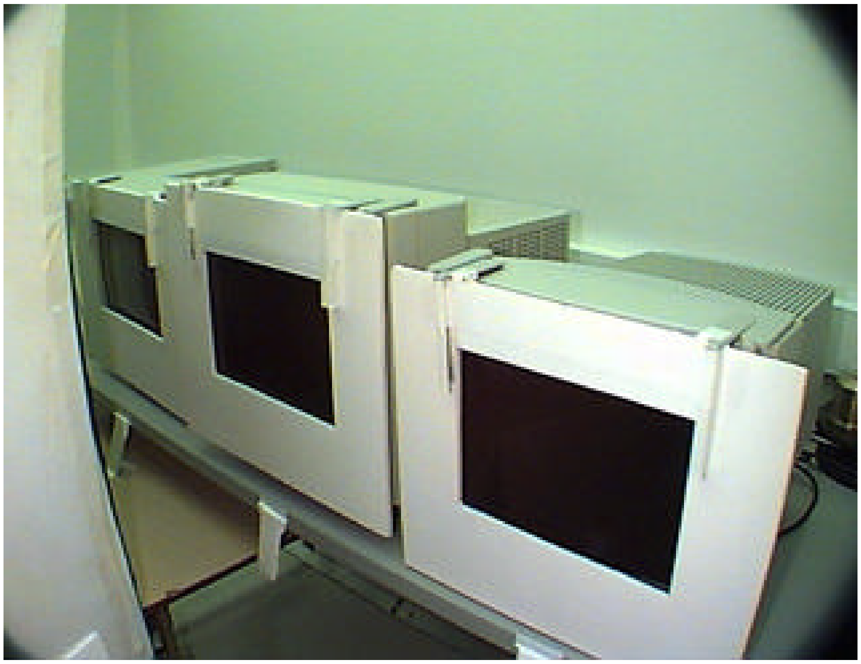


Figure 8. Picture taken from the other side of the viewing booth. The picture also shows the foam core bezels on the monitors.

Participants

Fourteen participants (seven female; average age 24) were used in this experiment and were paid for their time. These participants were from the Virginia Polytechnic Institute and State University. Participants had 20/20 or 20/20 corrected near vision and were screened using an Ortho-Rater test. Those participants who wore contact lenses and glasses were allowed to participate but had to meet the vision requirements. People who wore tinted lenses were not allowed to participate. Additionally, each participant spoke English as a native language.

Experimental Conditions

There are a number of experimental conditions that needed to be controlled before the experiment began. These conditions included: setting the monitor's contrast and brightness levels; setting the computer's addressability and font; placing the chin rest; and measuring the lighting levels.

The contrast and brightness levels were set on each monitor by following a specific procedure. First, the brightness and contrast levels were turned completely down. Then, the brightness level was raised until the raster lines were just perceivable in a dark room. Finally, the contrast level was raised until it reached 75 cd/m^2.

The pixel addressability used was 832 by 624. This was the highest addressability that all three monitors could display. The font used for the passages was New York. Characters were set to same heights and same widths on each monitor. Characters subtended 0.67 degrees of visual angle. The chin rest was placed 40.64 cm (16 inches) from the screen.

The illuminometer was not used to measure the lighting levels during the experiment for a number of reasons. Using the illuminometer would lengthen the experiment time because it and the lighting controls would be separately located. Another reason is that the participants would have to relocate for each change in lighting level so that the experimenters could read the illuminometer from inside the booth. The illuminometer could not be read from outside the booth because the experimenter would lower the actual lighting level by absorbing light. Therefore, a calibration procedure was necessary. The following equipment was used in the calibration procedure: a Minolta illuminometer, a 18% Kodak gray card, and a hand-held photometer (Minolta CS-100). The illuminometer was taped to the front of each monitor (i.e. lighting levels were set separately for each monitor). The gray card was placed on a wall next to the monitors.

The photometer was aimed at the gray card and located behind the light chamber next to the lighting controls. For each monitor and each lighting level, the corresponding luminance readings were made. For example, 200 lux on the Sony was equivalent to 26.4 cd/m^2 read from the photometer. Thus, during the experiment, the lighting levels were changed using only the hand held photometer rather than the illuminometer.

Task Procedure

The participants were first asked to read and sign an informed consent form (Appendix B). Then, the participants' near binocular acuity was tested using the Ortho-Rater Device. After the participants passed the visual acuity test, they were seated in the viewing booth and the experimenter read the instructions to them. A copy of the instructions is listed in Appendix C. Next, the participants were allowed to practice reading passages from the Tinker reading task. The practice session allowed the participants to become familiar with the passages and the computer program. After completing 6 practice trials, the actual experiment began.

First, the participants were asked to sit in the dark for three minutes to allow them time to dark adapt. They were then asked to read one of the Tinker reading passages displayed on the screen in the dark. The participants were asked to indicate the word out of context and the participants' reading speeds were timed. The participants repeated this process for all of the ambient lighting levels and polarities of the screen.

After the participants received all levels for one monitor, they were asked to sit in the dark for another three minutes. Meanwhile, the experimenter changed the monitor-filter combination. Once the next monitor was in place, the participants received all of the levels for lighting and polarity once again. This procedure was repeated until all of the monitors or monitor filter combinations were given to the participants. Upon completion of the last level, the participants were paid and thanked for their time.

Results and Discussion

The two dependent variables (reading time and accuracy) were analyzed using separate analysis of variance (ANOVA) procedures. Additionally, diffuse (200 lux) and specular reading times were correlated with two ISO metrics: screen image luminance ratio and specular reflection luminance ratio.

Reading Time. ANOVA results for reading time are shown in Table 10. The main effects of Lighting and Polarity were significant. Figures 9 illustrates the main effects of Lighting on reading time. A Newman-Keuls post hoc analysis was performed to determine which Lighting levels were significantly different and the results are shown in Table 11.

TABLE 10. Analysis of Variance Reading Time

Source	**df**	**SS**	**MS**	**F**	**p**
Between					
Subject	13	6135.278	471.944		
Within					
Monitor	6	41.662	6.944	1.18	0.328
Monitor*Subject	78	460.349	5.902		
Lighting	4	74.381	18.595	6.35	0.000
Lighting* Subject	52	152.359	2.93		
Polarity	1	21.251	21.251	7.49	0.017
Polarity* Subject	13	36.877	2.837		
Monitor*Lighting	24	34.217	1.426	0.50	0.978
Monitor*Lighting* Subject	312	888.312	2.847		
Monitor*Polarity	6	8.279	1.380	0.45	0.846
Monitor*Polarity* Subject	78	241.175	3.092		
Lighting*Polarity	4	17.217	4.304	1.35	0.263
Lighting*Polarity* Subject	52	165.552	3.184		
Monitor*Lighting*Polarity	24	55.518	2.313	0.72	0.831
Monitor*lighting*Polarity*Subject	312	1002.325	3.213		
Total	**979**	**9334.752**			

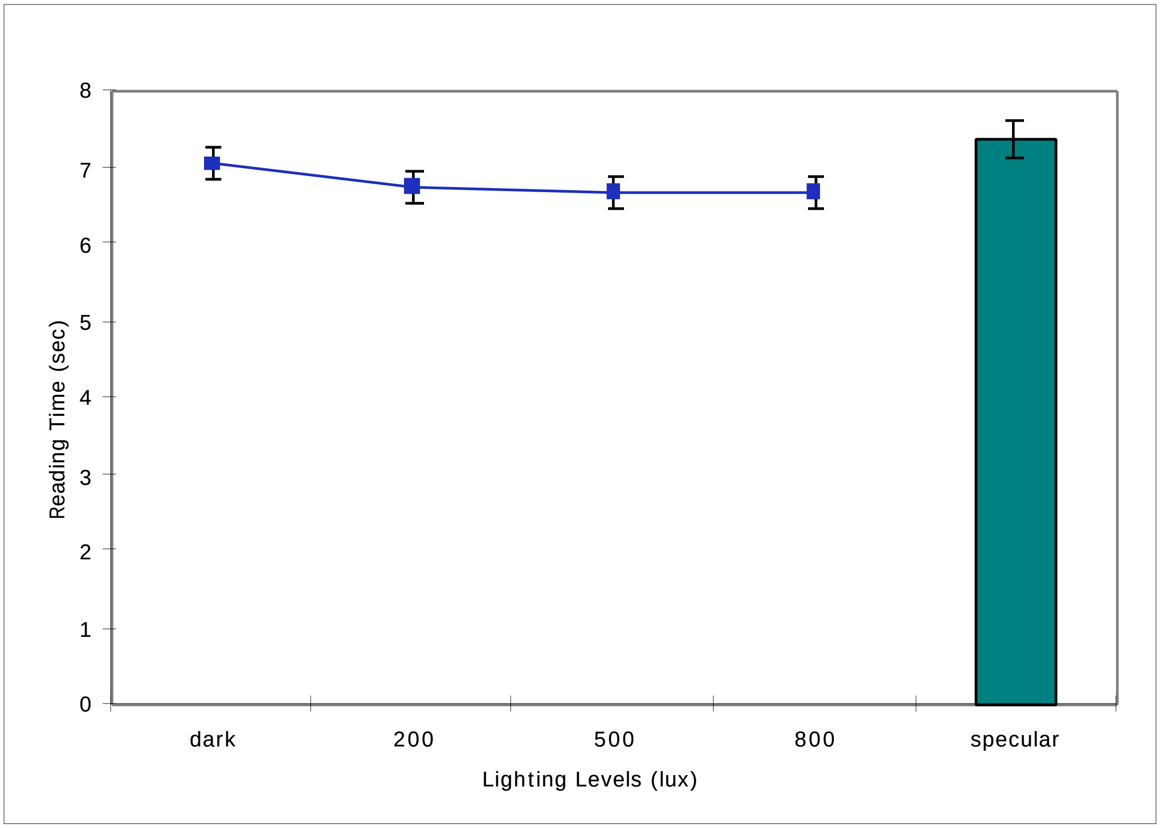


Figure 9. Main effect of lighting on reading time.

TABLE 11. Newman-Keuls Results for the Main Effect of Lighting on Reading Time

LIGHTING	Mean	N	SNK Grouping	
Specular	7.3719	196	A	
Dark	7.0614	196	A	B
200	6.7379	196		B
800	6.6722	196		B
500	6.6707	196		B

(Note: Means with the same letter are not significantly different.)

There are three points that can be concluded from the *post hoc* analysis. First, reading times were significantly longer for the specular condition as compared to the three diffuse conditions. This result is expected because of effects caused by specular reflections. People naturally want to shift their eyes towards bright spots in their visual field. Additionally, the text passage and the vertical bar pattern are at different focal lengths. When the eye is focused on the characters, the reflected image is blurred and out of focus. The eye naturally wants to bring the blurred image into focus and it will shift its attention to the specular reflection, thereby, blurring the character images. Therefore, the visual focus is constantly oscillating between screen characters and the reflected image. Thus, it should take participants longer to read the text passages when a structured image (specular) is present as opposed to diffuse images that have no structure.

Second, there were no differences in reading times between the dark condition and the three diffuse conditions. This result is consistent with other researchers findings. Legge, Rubin, and Luebker (1987) found that reading rate varies little for contrast modulations between 0.1 and 1 and for character sizes between 0.2 and 2 degrees of visual angle. The modulation contrast levels used in this experiment are shown in Tables 12 and 13 for positive and negative polarity, respectively. The lowest modulation contrast value was for the SamSung, positive polarity, 800 lux condition. This yielded a modulation contrast of 0.614. This is well above the 0.1 constraint that Legge et. al found. Additionally, the text passages were set to 0.67 degrees of visual angle. Again, this falls within the range that Legge et. al. stated. Therefore, reading time must be incredibly tolerant to changes in contrast caused by diffuse glare.

TABLE 12. Positive Polarity Modulation Values

	dark	**200 lux**	**500 lux**	**800 lux**
SamSung	0.928	0.815	0.699	0.614
SamSung + AF 150	0.922	0.871	0.813	0.754
SamSung + HF 300	0.926	0.872	0.825	0.776
Sony 100	0.932	0.853	0.769	0.701
Sony 100 + BF 10	0.958	0.919	0.880	0.847
Mitsubishi	0.934	0.874	0.808	0.749
Mitsubishi + AF 150	0.932	0.894	0.872	0.845

TABLE 13. Negative Polarity Modulation Values

	dark	200 lux	500 lux	800 lux
SamSung	0.957	0.836	0.712	0.623
SamSung + AF 150	0.956	0.902	0.840	0.779
SamSung + HF 300	0.957	0.900	0.851	0.800
Sony 100	0.959	0.874	0.785	0.714
Sony 100 + BF 10	0.965	0.923	0.882	0.847
Mitsubishi	0.956	0.898	0.833	0.776
Mitsubishi + AF 150	0.959	0.922	0.900	0.874

A final point that can be drawn from the Lighting *post hoc* analysis is that there was no difference in reading times between the dark condition and the specular condition. This is a little unusual because one would expect that reading times in the dark would be shorter than in the specular condition. However, Hunter (1988) conducted two experiments which contradicted the expected results. In his first experiment, he investigated the effects of 16 glare filters, 3 lighting levels, and 2 resolution levels had on reading time. The three lighting levels were dark, 650 lux diffuse, and specular. He found that the dark condition yielded significantly longer reading times than both the specular and diffuse conditions. In Hunter's second experiment, he examined the effects that filter transmission and diffuse illumination have on readability. The ambient lighting levels ranged from 320 to 2800 lux and included a dark condition. He found that reading times were significantly longer for the dark condition than the 320 lux level, but no significant difference existed for the dark condition and any other levels of diffuse. Additionally, no significant differences were exhibited between the levels of diffuse illumination. Hunter had several theories to explain the unusual results but they were mainly based on the fact that he used negative contrast. One reason why present results differ from Hunter might be because this experiment had both positive and negative polarity. Thus, dark reading times were equivalent to the specular reading times rather than being greater than specular. Therefore, the dark condition results of this thesis may not be as unusual as originally thought.

Figure 10 illustrates the main effect of Polarity on reading time. The results indicate that reading times for positive polarity (dark characters on a light background) were significantly faster than for negative polarity (light characters on a dark background), but the difference is small in practical terms. The difference in reading times is only about 4 percent. This finding is consistent with other researchers results such as Snyder, Decker, Lloyd and Dye (1990). They performed two different reading experiments and found a significant main effect of polarity for both experiments. In the first experiment, they found a 2% increase in reading times for dark characters on a light background. In the second experiment, they found a 7% increase. Thus, a 4% increase is consistent with their results.

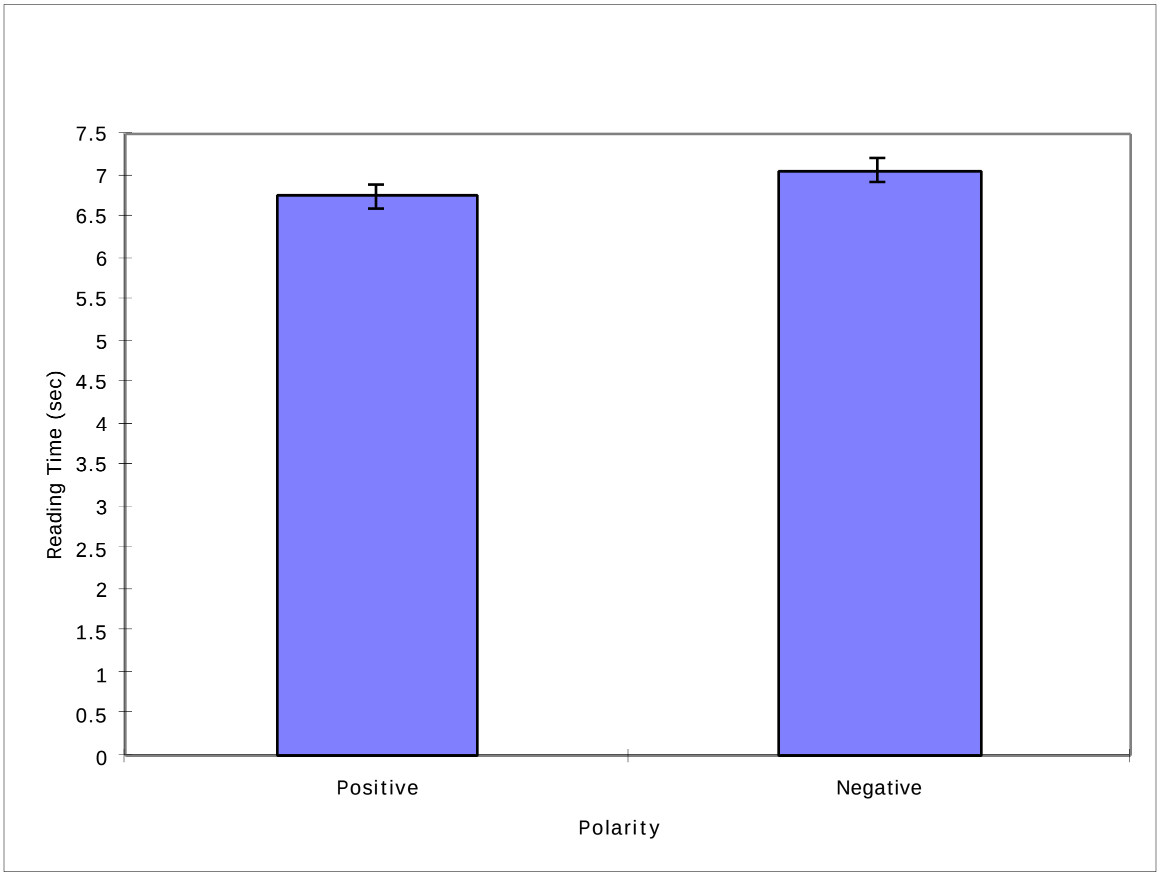


Figure 10. Main effect of polarity on reading time.

Accuracy. The ANOVA results for Accuracy are shown in Table 14. There were no main effects or interactions significant for accuracy, because people were able to identify the word out of context most of the time. Overall, participants identified the correct word out of context 99.5% of the time.

TABLE 14. Analysis of Variance for Accuracy

Source	**df**	**SS**	**MS**	**F**	**p**
Between					
Subject	13	0.040816	0.00314		
Within					
Monitor	6	0.012245	0.002041	0.48	0.82
Monitor* Subject	78	0.330612	0.004239		
Lighting	4	0.014286	0.003571	0.87	0.49
Lighting* Subject	52	0.214286	0.004121		
Polarity	1	0	0	0	1
Polarity* Subject	13	0.057143	0.004396		
Monitor*Lighting	24	0.1	0.004167	1.02	0.436
Monitor*Lighting* Subject	312	1.271429	0.004075		
Monitor*Polarity	6	0.028571	0.004762	1.18	0.325
Monitor*Polarity* Subject	78	0.314286	0.004029		
Lighting*Polarity	4	0.030612	0.007653	2.01	0.107
Lighting*Polarity* Subject	52	0.197959	0.003807		
Monitor*Lighting*Polarity	24	0.083673	0.003486	0.84	0.678
Monitor*Light*Polarity*Subject	312	1.287755	0.004127		
Total	**979**	**3.983673**			

Luminance Ratio Correlation. In addition to the ANOVA results, reading times were correlated with the ISO metrics for screen image luminance ratio (Diffuse, 200 lux) and specular reflection image luminance ratio. Specifically, the reading times were compared with ISO metrics obtained from each monitor/filter combination under each of the polarity test conditions. Pearson Product-Moment Correlation coefficients are reported in Table 15.

TABLE 15. Correlations Between Tinker Reading Times and the ISO 9241-7 Image Quality Metrics

	Screen Image Luminance Ratio	**Specular Reflection Luminance Ratio**
	r , p	*r* , p
Positive Polarity, Large Source	0.516, p = 0.457	-0.089, p = 0.850
Positive Polarity, Small Source	0.030, p = 0.949	0.100, p = 0.831
Negative Polarity, Large Source	-0.311, p = 0.497	0.789, p = 0.035
Negative Polarity, Small Source	-0.508, p = 0.245	0.635, p = 0.125

The correlation coefficients above show that the *Screen Image Luminance Ratio* (Diffuse) did not significantly correlate with reading times, while the *Specular Reflection Ratio* metric did for one of the four specular metrics (positive polarity, large source, specular reflection luminance ratio). The data suggest that reading times did not systematically increase as screen contrast was reduced (i.e., *Screen Image Luminance Ratio* was reduced). However, the reading times did increase as the reflectivity of the monitor-filter combinations increased for the *Negative Polarity Large Source Specular Luminance Ratio.*

The correlations indicate that the participants were less affected by the reduction in contrast of the text on the screen than by the specular glare condition. In fact, the ANOVA results for the main effect of Lighting demonstrate this effect. Specifically, reading times were affected about the same for the no glare condition (dark) as all three of the diffuse glare conditions (200, 500, and 800 lux). But, reading times were significantly higher for the specular condition as compared to the diffuse conditions. In other words, moderate to large changes in character to background contrast (reduction in screen image luminance ratio metric for ISO standard) did not interfere with an operators ability to read from CRT screens. However, specular reflections did interfere and significantly increased participants reading times.

Class Correlation. In addition to the luminance ratio correlation, reading times in positive and negative polarity also were correlated with positive and negative polarity ISO classifications. A spearman rank correlation was used. Reading times in positive polarity had a correlation coefficient of 0.4330 (p=0.332) and in negative polarity the correlation coefficient was 0.3969 (p=0.378).

These results indicate that reading times were not significantly faster for a Class I monitor than a Class II in positive polarity. Additionally, reading times did not systematically increase as the Class of the monitor increased in negative polarity. Thus, reading times do not seem to be affected by the Class of monitor/filter combination used. The ANOVA results also support this conclusion since no main effect or interactions of the *monitor* variable were significantly different.

Conclusions

The analysis of variance of reading time and the correlation data have several important implications for the ISO procedure. First, the standard currently weighs the contributions of the *specular reflection luminance ratio* and the *screen image luminance ratio* equally. The author contends that giving each of these two ratios equal weight is problematic for two reasons. First, reading times were not significantly different in the three diffuse lighting conditions (200, 500, 800 lux) but were significantly higher in the specular condition. Second, reading times were correlated better with the *specular reflection luminance ratio* than the *screen image luminance ratio*.

Another important implication is that the standard currently classifies monitors separately for positive and negative polarities. While the main effect of Polarity was significant for reading time, the interaction between Lighting and Polarity was not significant. This means that people read slightly faster in positive than in negative polarity. But when diffuse or specular reflections are present, people do not read differently in positive and negative polarity. Thus, it is not necessary to have separate Classes for positive and negative polarity.

A third implication is that the standard currently states that all monitors must fall into one of three Classes in positive and negative polarity. Class I is considered the best and Class III is considered the worst. However, this classification scheme has some flaws. First, none of the monitor/filter combinations yielded a Class III in positive polarity. Second, none of the monitor/filter combinations yielded a Class I in negative polarity and some even failed a Class III. Thus, the ISO standard seems rather lenient in positive polarity classifications and too stringent in negative polarity. Furthermore, reading times in positive and negative polarity did not correlate with the ISO Classes. In other words, reading times did not systematically increase as the as the ISO Class increased. Thus, separating monitors into three classes does not convey any meaningful information with respect to objective measures, because the supposed “best” monitor does not yield the “fastest” reading times.

Finally, the findings of this thesis provide an initial human factors database for use in assessing the validity of ISO 9241-7. Specifically, the data have great utility for display designers, filter manufacturers, and ergonomic practitioners.

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Appendix A

ISO Measurement Procedure Observations

Diffuse measurements

- The ISO standard does not specify which optical surface to focus the photometer for the diffuse measurements: the glass face plate or the phosphor surface. The author of this paper focused on the phosphor surface because that is where the diffuse reflections act to reduce contrast.

Small-Source Specular Measurements @ 15 degrees

- For these measurements, the standard states that the reflections from the glass surface and the reflections from the phosphor layer should be superimposed. Additionally, the photometer should be focused on the virtual image. Unfortunately, the reflections could not be superimposed in this study. In order to superimpose the reflections, the display needed to be rotated out of position: 15 degrees from normal. The author believes that this is a flaw in the design of the standard because this measurement is nearly impossible to make. Thus, the author decided to take one scan of the phosphor reflection and then add it to a scan of the glass surface reflection, as these luminance values are additive quantities.
- When a filter is placed over the monitor, it creates a third reflection that should be superimposed with the two from the display. Again, at a 15 degree angle, these images could not be superimposed. However, a concerted effort was made to superimpose the reflections as best as possible. The author, thus, decided to change the angle of the filter slightly so that these two images would superimpose. Therefore, only two scans were required for these measurements: one for the phosphor layer of the screen and one for the superimposed first surface reflections.

Extended-Source Specular Measurements at 15 degrees

- Unlike the small source measurements, the ISO standard does not specify whether the photometer should be focused on the virtual image or the phosphor layer, nor does it state that the images should be superimposed for the extended-source measurements. The author did, however, focus on the virtual image. In this case, the reflections from the phosphor layer and the first surface did superimpose because of the aperture of the sphere was so large. Thus, only one scan was needed.
- Adding a filter to a display introduced yet another optical surface reflection which need to be superimposed for these measurements. Thus, the filter was

moved until the images superimposed, but again the problem was that the filter was not rotated at a 15 degree angle.

Points of Confusion

Determining Class

- The notion that a monitor can have two separate and different classifications, one for positive polarity and one for negative polarity, is confusing. For example, a monitor can be Class I for positive polarity and Class II for negative polarity. This means that the monitor is suitable for general office use in positive polarity but only suitable for "most" office environments in negative polarity. If the monitor only had one classification, then the standard would be much easier to understand and interpret. Furthermore, the author never found a monitor that had the same *Class* for both positive and negative polarity. However, some monitor/filter combinations had the same Class in both polarities.
- The requirements to determine classification seem arbitrary and confounding. The author has already described the requirements in the section titled "Methods of Physically Measuring Glare" of this report. Table 16 lists some examples of which luminance ratios need to pass to be a Class I, II, or III. Examples 3 and 5 clearly show the confusion. The standard can't say if only one or two ratios fail, then it is a Class II, because classification depends on which ratios fail.
- Table 16 also shows that knowing a monitor is Class II in a polarity does not give much information about the monitor. For example, one monitor could be Class II in positive polarity because it failed the Screen Image Luminance Ratio for a small source, but another monitor may fail at both the Screen Image and the Specular Reflection Luminance Ratios for the small source.

TABLE 16. Examples of Luminance Ratios that need to pass for Class I, II, or III

	Example 1	**Example 2**	**Example 3**	**Example 4**	**Example 5**	**Example 6**
Large Source						
Screen Image Luminance Ratio	pass	pass	pass	pass	pass	pass
Specular Reflection Luminance Ratio	pass	pass	pass	fail	fail	fail
Small Source						
Screen Image Luminance Ratio	pass	pass	fail	pass	pass	fail
Specular Reflection Luminance Ratio	pass	fail	fail	pass	fail	fail
	Class I	**Class II**	**Class II**	**Class II**	**Need to do calculation to see if a Class III**	**Need to do calculation to see if a Class III**

Calculating the Equations

- When calculating the reflectivity equations and the luminance ratio equations, it is difficult to understand what numbers should be used for the L_A. For example, the reflectivity equations use the luminance level used for the integrating spheres (i.e. 2000 cd/m2). However, the luminance ratio equations use the luminance levels found in Table 1 of this report. These are the same luminance levels that are used to determine classification.
- Furthermore, the standard does not explain why these luminance levels were chosen and intuitively they do not make much sense. For example, the screen image luminance ratio equation is shown below.

$$\text{Screen Image Luminance Ratio} = \frac{L_{background} + L_{diffuse} + L_{specular}}{L_{foreground} + L_{diffuse} + L_{specular}} \geq 3 \qquad \text{(positive polarity)}$$

The $L_{specular}$ component is calculated by the formula $L_{specular} = L_{A(Table\ 1)} * \text{Specular Reflectivity}$. For the large source, the L_A would be 200 cd/m^2 but for the small source the L_A would be 2000 cd/m^2. The standard does not clarify why the different sources use the different lighting levels in the equations. Remember that the large and small aperture integrating spheres are set to the same level (2000 cd/m^2) in the measurement procedure.

ISO 9241-7 Recommendations

The first time a person tries to classify a monitor they notice an exorbitant number of measurements and subsequent calculations are needed. Specifically, there are ten photometric measurements to take and 12 algebraic equations to calculate to determine the class of a monitor. Two sets of measurements that appear to be redundant are the two small source specular ($L_{DS(SML,15)}$) for negative/positive polarity and the two large source specular ($L_{DS(EXT,15)}$) for positive/negative polarity. The only difference between these two measurements is the exit port size of the specular light source used (1 degree for small-area source and 15 degrees for large-area source at 500 mm). "Optically, the large-area and small-area reflection characteristics will be equivalent for specular reflections" (Cone, 1997). In other words, measured reflected luminances values will be the same for these two sets of measurements. When John Cone, one of the creators of the document, was contacted he described the rational behind the small source specular measurements.

Cone claims that the main reason for the small-area source measurement is that the large-area source measurement is not "fair" to mechanically or chemically etched (surface-textured) screens. In fact, "these treatments do not, in general, actually reduce the total number of quanta reflected... they may actually add some diffuse reflection to the first optical surface" (Cone, 1997). The ISO standard should not lower its requirements just so mechanically and chemically etched screens can pass the standard. In fact, researchers have noted that mechanically etched or chemically abraded screens can actually reduce the quality of the displayed information, regardless of ambient lighting conditions. Beaton and Snyder found that average MTF values for an etched CRT were lower than average MTF values for a polished CRT (1984). Therefore, the author believes that these two small source measurements should be eliminated from the standard.

A more fundamental problem with the specular measurements of the standard is they do not address an important component of specular reflections: the reflected image sharpness or structure. This is unfortunate because researchers have noted that a more sharply defined or structured image is perceived as more annoying and noticeable than a less structured image of the same intensity (Rancourt and Grenawalt, 1986). Moreover, specular reflections are annoying and distracting to the operator because the eye will have difficulty focusing on the display images, since the characters on the screen and the reflections are in different focal lengths. When the eye is focused on the characters, the reflected image is blurred and out of focus. Because the eye naturally wants to bring the blurred image into focus, it will shift its attention to the specular reflection: thereby blurring the character images. Therefore, the visual focus is constantly oscillating between screen characters and the reflected image (Cakir et al., 1980). This oversight may be due to the inability of the investigators and researchers in the field to agree upon a single quantitative physical measurement method for characterizing display specular reflectance. The RTF, however, has shown promise in this arena. Hunter (1988) found that good fit models were produced for perceived image quality and the RTF physical image quality metric. Therefore, the author recommends that the standard committee considers implementing the RTF metric instead of the four specular measurements outlined in the standard. The benefits of implementing the RTF would not be restricted to an accurate indexing of perceived image quality, but would also provide substantial time savings (one measurement as opposed to four).

Additionally, affixing an after-market stand-alone filter to a monitor will increase the number of specular images. This is due to light rays reflecting from the first surface of the monitor and the first surface of the filter. Additionally, these reflections will be at different focal lengths because there is a gap between the front surface of the monitor and the front surface of the filter. The additional specular image presents yet another image on the screen that the eye will naturally try to pull into focus: compete with the character images on the screen for attention. This problem has a significant implication for the ISO standard. First, the ISO standard requires that all images be superimposed so it does not account for this problem. Furthermore, the limited human performance data from which the ISO standard is based did not test monitors coupled with stand alone filters (Kubota 1994. This increase in the number of specular reflections represents another reason why investigators and researchers in the field should work together to develop an improved quantitative physical measurement method for characterizing display specular reflectance.

Appendix B

EXPERIMENTAL PROTOCOL

Title of Project: **An Assessment of the Validity of the International Standard, ISO 9241-7**

Investigators: **Joy Kempic, Industrial and Systems Engineering Graduate Student**
Gary Olacsi, Industrial and Systems Engineering Graduate Student
Dr. Robert Beaton, Industrial and Systems Engineering Professor and Director of the Displays and Controls Laboratory

1. Justification of the Research Project

The purpose of this research is to critically assess the validity of the international standard, ISO 9241-7. This standard specifies ergonomic display requirements with reflections for office work with VDTs. In particular, it measures display hardware design attributes that produce screen reflections and stipulates the type of office ambient lighting environment for which a display is suitable.

Although the authors of this standard claim to have based it upon human performance data, it is entirely unclear how they arrived at specific ergonomic display requirements. Therefore, this experiment will collect objective and subjective human performance data and correlate it with ISO 9241-7 measurement results in order to determine whether the standard truly captures perceivable display performance differences.

2. Procedures

Description of Subjects

Participants will be from the Virginia Polytechnic Institute and State University population. A total of 16 people will participate and they will be at least 18 years of age. Participants will have 20/20 near vision and will be screened using an Ortho-Rater visual acuity test. Those participants who wear contact lenses and glasses will be allowed to participate but must meet the vision requirements. People who wear tinted lenses will not be allowed to participate. Finally, each participant must speak English as a native language.

Equipment Used for the Experiment

The experiment will be conducted in the Displays and Controls Laboratory. A Power Macintosh 8500/120 will be used with three different cathode ray tube (CRT) monitors: SamSung, Mitsubishi, and Sony Trinitron 100. The following filters may be attached to the monitors: 3M Anti-Glare Filter Model BF 10, 3M Circular Polarizing Filter Model HF 300, and 3M Anti-Glare Filter Model AF 150. A chin rest will be used to position participants heads while viewing the screens. Additionally, they will look through a viewing booth. The viewing booth is made from foam core pieces and has a whole in the center so that the participants can view the screen. The purpose of the viewing booth is that the participants will not know which monitor they are viewing. The participants will also use a keyboard and a mouse to interact with the computer.

Experimental Procedure

After the participant has passed the visual acuity tests using the Ortho-Rater device, he or she will be seated in the viewing booth and asked to place his/her head on a chin rest. Next, the participants will be allowed to practice reading passages from the Tinker reading task. The Tinker Speed of Reading Test was developed by Miles A. Tinker and it consists of 500 paragraphs (Feldt 1955). All of the paragraphs are kept at the same comprehension level so that accuracy and speed are the only factors under test. Each paragraph consists of about 3 sentences. To make sure that participants are actually reading and understanding the paragraphs, they are asked to identify the one word that is out of context within the paragraph. The word is usually located in the last sentence of each paragraph. The following is an example of a Tinker reading passage. The word out of context is ‘car’.

> Marge was on the lake when the lightning started flashing, and she rowed back home as fast as she could because she was frightened that the car would hit her.

Upon completion of 6 practice trials, the participant will be asked to sit in the dark for three minutes to allow them time to dark adapt. They will then be asked to read one of the Tinker reading passages displayed on the screen in the dark. The participant will be asked to indicate the word out of context and the participant’s reading speed will be timed. He or she will also be asked to rate the image quality of the text passage on a nine point scale ranging from worst imaginable to best imaginable. The participants will repeat this process for different ambient lighting levels and different polarities of the screen. (Note: Polarities can be of two types: positive or negative. Positive polarity refers to dark characters on a light background and negative polarity refers to light characters on a dark background.)

After the participants receive all levels for one monitor, they will be asked to sit in the dark for another three minutes. Meanwhile, the experimenters will change the monitor or monitor-filter combination. Once the monitor is in place, the participants will receive all of the levels for lighting and polarity once again. This procedure will be repeated until all of the monitors or monitor filter combinations have been given to the participants. Upon completion of the last level, the participants will be paid and thanked for their time.

The total time commitment for each participant is one session with a maximum length of 2 and 1/2 hours.

3. Risks and Benefits

There is minimal risk to the participants (i.e. risks that are no greater than those encountered in everyday life.) The task is very similar to reading documents on a computer.

There are no benefits promised or implied to the participants of the experiment.

4. Confidentiality/ Anonymity

Confidentiality of the experimental results will be maintained by assigning each participant a number known only to the investigators. The participant numbers will be used for any analyses of the research.

5. Informed Consent

Please see attached sheets labeled VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY: Informed Consent for Participants of Investigative Projects.

6. Biographical Sketch

Joy Kempic

Joy received a B.S. degree in Industrial and Systems Engineering from Virginia Tech in 1995. She is currently working towards an M.S. degree in Industrial and Systems Engineering (human factors option) at Virginia Tech. She has worked two summer interns that were more involved with classical industrial engineering: one with Roadway Package System and another with Union Camp Corporation Fine Paper Division. While at Roadway Package System, she performed productivity studies and provided recommendations to improve efficiency. While at Union Camp Corporation, she performed studies to increase operating efficiency and improve employee health and safety. She also performed an ergonomic evaluation on a workstation and provided recommendations to improve the layout. More recently, she has researched and ran a study about team performance in her Macroergonomics class last semester. She is also an active member in the Human Factors and Ergonomics Society.

Gary Olacsi

Gary received a B.A. degree in Psychology from California State University Northridge in 1994. Currently, he is a Graduate Research Assistant in the Displays and Control Laboratory working towards an M.S. degree in Industrial and Systems Engineering (human factors option) at Virginia Tech. He is also an intern in the Human Research and Engineering Directorate of the Army Research Laboratory where he is working to support the Visual and Auditory Processes Branch on a project concerning the psychophysical aspects of target acquisition. Last December he completed an internship for the Image Quality Group of the Human Factors Lab at Eastman Kodak, Rochester N.Y. While an intern for Kodak, he conducted display reflectance measurement studies on a contemporary flat panel display technology under various ambient illumination conditions. He is currently an active member of the Human Factors and Ergonomics Society student chapter at Virginia.

ROBERT JOHN BEATON

Bob Beaton received his M.S. degree in Experimental Psychology (visual psychophysics) in 1980 from Villanova University, Villanova, PA., and his Ph.D. degree in Industrial Engineering and Operations Research (human factors engineering) in 1984 from Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, VA. His dissertation work involved the development of image quality metrics for digital imaging systems, and it won the George E. Briggs Award from the Engineering Psychology Division of the American Psychological Association.

Dr. Beaton's career has included industrial, academic, and consulting positions. From 1983 to 1988, Dr. Beaton was a scientist at Tektronix Laboratories in Beaverton, Oregon where he managed research activities in visual psychophysics and image quality evaluations of flat-panels, high-resolution CRTs, projection devices, ink-jet printers, field-sequential 3-D displays, and interactive instrument interfaces. During this time period, Dr. Beaton also served as adjunct faculty in the Department of Psychology at Portland State University where he lectured and supervised graduate student research in the human factors engineering of visual display systems. Currently, Dr. Beaton is an Associate Professor of Industrial and Systems Engineering at Virginia Tech and Chief Scientist at Keystone Engineering Limited. He teaches graduate courses in visual display ergonomics, human performance, and human-computer interaction, as well as undergraduate courses in human factors engineering and work methods engineering.

Dr. Beaton is the Director of the Displays and Controls Laboratory at Virginia Tech, which is a leading facility for human factors research on visual display and manual control systems. Dr. Beaton's laboratory provides engineering development and compliance evaluation services for visual displays, manual controls, and interactive systems to industrial, military, and governmental groups.

Dr. Beaton is the Director of the ErgoNorms Compliance Center at Virginia Tech, which is a service unit of the Displays and Controls Laboratory in the Human Factors Engineering Center. While the Displays and Controls Laboratory primarily is an academic unit for sponsored research work in the area of electro-optical display systems and manual control systems design, the ErgoNorms Compliance Center is available for non-research related work.

Dr. Beaton is an active educator, researcher, and practitioner; he has developed several graduate level courses in human factors engineering and has published over 120 technical papers and presentations, as well as two patents, in the area of visual display ergonomics. Dr. Beaton is a member of the Human Factors and Ergonomics Society (HFES), Society for Information Display, Optical Society of America, Society for Photographic Scientists and Engineers, Society for Photographic Instrumentation Engineers, and he holds a voting membership in the Electronic Industries Association. Additionally, Dr. Beaton is the chairperson of the HFES Technical Standards Committee, the American National Standards Institute/HFES-100 Standard Committee, and the U.S. Technical Advisory Group to the International Standards Organization Technical Committee No. 159 for Ergonomics.

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants of Investigative Projects

Title of Project: An Assessment of the Validity of the International Standard, ISO 9241-7

Investigators: Joy Kempic, Industrial and Systems Engineering Graduate Student
Gary Olacsi, Industrial and Systems Engineering Graduate Student
Dr. Robert Beaton, Industrial and Systems Engineering Professor and Director of the Displays and Controls Laboratory

I. The Purpose of this Research

The purpose of this research is to critically assess the validity of the international standard, ISO 9241-7. This standard specifies ergonomic display requirements with reflections for office work with VDTs. In particular, it measures display hardware design attributes that produce screen reflections and stipulates the type of office ambient lighting environment for which a display is suitable.

Although the authors of this standard claim to have based it upon human performance data, it is entirely unclear how they arrived at specific ergonomic display requirements. Therefore, this experiment will collect objective and subjective human performance data and correlate it with ISO 9241-7 measurement results in order to determine whether the standard truly captures perceivable display performance differences.

II. Procedures

After you have passed the visual acuity tests using the Ortho-Rater device, you will be seated in the viewing booth and asked to place your head on a chin rest. Next, you will be allowed to practice reading passages from the Tinker reading task. The Tinker Speed of Reading Test was developed by Miles A. Tinker and it consists of 500 paragraphs (Feldt 1955). All of the paragraphs are kept at the same comprehension level so that accuracy and speed are the only factors under test. Each paragraph consists of about 3 sentences. Within each paragraph, one word is out of context and you will be asked to identify this word. The word is usually located in the last sentence of each paragraph. The following is an example of a Tinker reading passage. The word out of context is ‘car’.

> Marge was on the lake when the lightning started flashing, and she rowed back home as fast as she could because she was frightened that the car would hit her.

Upon completion of 6 practice trials, you will be asked to sit in the dark for three minutes to allow time for your eyes to dark adapt. You will then be asked to read one of the Tinker reading passages displayed on the screen in the dark. You will be asked to type the word out of context and your reading speed will be timed. You will also be asked to rate the image quality of the text passage on a nine point scale ranging from worst imaginable to best imaginable. You will repeat this process for different ambient lighting levels and different polarities of the screen. (Note: Polarities can be of two types: positive or negative. Positive polarity refers to dark characters on a light background and negative polarity refers to light characters on a dark background.)

After you receive all levels for one monitor, you will be asked to sit in the dark for another three minutes. Meanwhile, the experimenters will change the monitor or monitor-filter combination. Once the monitor is in place, you will receive all of the levels for lighting and polarity once again. This procedure will be repeated until you have received all of the monitors or monitor filter combinations. Upon completion of the last level, you will be paid and thanked for your time.

The total time commitment is one session with a maximum length of 2 and 1/2 hours.

III. Risks

There is minimal risk involved in participating in this experiment. In simplified terms, minimal risk means that the risks involved in participating are no greater than those encountered in everyday life.

IV. Benefits of this Research

You will receive no benefits from participating in this experiment, other than whatever satisfaction you may derive from contributing to the knowledge of glare on computer screens. No promise or guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity and Confidentiality

The results of this study will be kept strictly confidential. The information that you provide will have your name removed and only a participant number will identify you during analysis of the research.

VI. Compensation

Upon completing the experiment, you will receive five dollars per hour for a maximum of $12.50 (for 2 1/2 hours) and a $25 gift certificate to a local restaurant for your participation.

VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty. If you choose to withdraw, then you will be compensated for the portion of the time you participated in the study.

VIII. Approval of Research

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Participants at Virginia Polytechnic Institute and State University.

IX. Participant's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:

1.) I should not volunteer for participation in this research if I am younger than 18 years of age, wear tinted lenses, or can not speak English as a Native language

2.) I will not discuss this experiment with anyone for at least 30 days after participating in the experiment.

X. Participant's Permission

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in the project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

______________________________ ______________________________
Signature Date

Should I have any questions about this research or its conduct, I may contact:

Joy Kempic Investigator	951-4276
Gary Olacsi Investigator	552-3470
Dr. Robert Beaton Faculty Advisor	231-5986
H.T. Hurd Chair, IRB Research Division	231-5281

Appendix C

INSTRUCTIONS

Task Overviews

For this experiment, there are two tasks which you will be asked to perform. The first task requires that you to read text passages which are 4 lines in length and contain one out of context word. The out of context word will usually be found in the last line of these text passages. For this task, your reading speed (time) and accuracy (ability to identifying the correct word out of context) will be recorded. The second task of this experiment requires that you rate the overall image quality of the display using a nine point subjective image quality scale. Prior to the experiment, you will be asked to complete a demo of the experimental control computer program. This demo will allow you to gain familiarity with performing these tasks. Specifically, it provide you with valuable practice in identifying the out of context word and the range of ambient lighting conditions you can expect to encounter in the experiment.

Procedure

For both the demo and the experiment, we ask that you place your head on the chin rest before the start of each trial. To start the demo or the experiment, use the mouse to click on either the demo or experiment button. The next screen will you see is the ‘ready’ screen. Clicking the mouse at this time will start the timer and display the first text passage. Once you have finished reading the passage and identifying the word out of context, you will press the mouse button again to stop the timer. **Note***: please do not move the mouse around the screen while you are reading the passage***, as this may affect your reading time. If you happen to move the pointer down to the passage, then you do not have to move the mouse back to the word ‘stop’ located above the passage to advance to the next screen. We will demonstrate this in the practice trials.

The next screen will ask you to type the word that was out of context and to indicate the image quality of the display. **Note: you will most likely have to take your head out of the chin rest to type the word out of context. We ask that you place your head back on the chin rest once you have finished typing. After you have typed the out of context word, you will be asked to rate the general image quality of the entire screen. To aid you in using this subjective image quality scale, the experimenters will show a range of screens you will encounter during the demo. Your accurate opinion of the image quality of each trial and your ability to use all the categories of the scale are essential to the success of this experiment. If you have any questions regarding the subjective image quality rating scale, please feel free to ask them at this time.

Once you’ve ‘clicked’ on the appropriate number of the scale, the ‘ready’ screen will appear on the monitor again. At the end of every two trials, a message asking you to wait for the experimenters okay before continuing will appear. At this time, the experimenters will change the lighting level in the room. This process will continue until you have received all of the lighting and polarity levels.

Please note: There will be times during the experiment that we will ask you to sit in the dark for 3 minutes. This allows your eyes a chance to adapt to the dark.

Appendix D

X-Sender: bobb@mail.vt.edu
Mime-Version: 1.0
Date: Tue, 26 Aug 1997 18:39:30 -0400
To: golacsi (Gary Olacsi), jkempic (Joy Kempic) From: john cone
<jcone@dante.nmsu.edu> (by way of Bob Beaton) Subject: Re: Are you still there?

Hi, Gary & Joy.

I received the following from John Cone today.

Thx,
Bob

Bob -

The root of the issue was a desire to make part 7 a performance standard rather than a product standard. Actual methods of controlling specular reflections (at the time the standard was under development) were pretty much surface etch (mechanical and chemical), surface silica coating, and single-and multi-layer anti-reflection coating. On flat panels, molded texture on the cover plastic was (and is) standard. Most of the surface textures can be combined with simple anti-reflection coating for extremely effective reflection-control. The Europeans (especially Swedes and Germans) wanted to make multilayer coating a requirement. Other countries did not want to exclude surface texturing, as it had (and has) a much lower production cost. And, of course, under controlled environmental conditions, no treatment might be required.

The solution was to propose some image quality measures, to be met under specified surrogates of reasonably valid workplace conditions. The requirement could be met with any combination of high image luminance (my favorite), and/or one or more means of diffuse and direct reflection control.

The next problem arises in the "fair" measurement of reflections from screens treated to diffuse the direct reflection. These treatments do not, in general, actually reduce the total number of quanta reflected. In fact, they may actually increase the total, by adding some diffuse reflection to the first optical surface.

The problem is complicated by the existence of multiple optical surfaces (up to 7 in an LCD) and by curved, non-parallel reflecting surfaces (in CRTs). In the case of specular surfaces, the solution is simple: Use a large luminous source. Then all the multiple reflections can be superimposed over most of the reflected virtual image of the source, and measurement can proceed routinely.

But a large source penalizes the surface-textured screens, and overstates their reflectance for small sources. So we were back to institutionalizing multilayer coatings.

Surface texture can be thought of as applying a point-spread function to the first reflective surface (and the second, in the case of a CRT: The rear glass surface is usually "orange-peeled."). The total amount of light reflected stays about the same, or may actually increase with an increase in diffuse reflectance. However, from a point-source, the intensity of reflection is reduced in any given direction.

The actual luminous intensity of the reflected ray(s) in one direction is the sum (actually, the convolution) of the point spread function(s) and the spatial distribution of luminances about the specular angle - plus any purely diffuse reflected components.

I say point spread functions, rather than function, because - At the first optical surface, some methods of surface texturing, such as chemical etching, often leave some of the original smooth glass surface intact.
- There are usually subsequent optical surfaces or interfaces that also can support specular reflection, and whose reflections are diffused, if at all, by transmission through the surface texture. This will impose a different point-spread function.
- Surface textures are often combined with other coatings, for anti-reflection, anti-static, emission control, etc.

The optical effects of each of these factors is usually dependent on the angle of incidence, and is not fixed. On CRTs, the faceplate glass surfaces are not parallel. Specular reflections from the first and second surfaces do not superimpose, for any given angle of incidence, at more than one point, tending to be near the center of the screen. Therefore, it is (in my opinion) not practical to attempt complete or physical characterization of the optical reflection transfer functions of the display.

As an alternative, the committee decided to try simple characterizations at two points, each having some face validity in the use of displays: - A large-area source, emulating the walls of the office, or papers on the desk. ISO 9241 part 6 (as I recall) specifies the maximum wall luminance at 200 cd/m2. Simple analysis shows that papers on the desk, under 500 lux, have a diffuse reflected luminance of somewhere around 125 cd/m2. - A near-point source, emulating an unavoidable high luminance located nearly behind the user. Examples would be distant windows, luminaires in adjoining offices, etc.
- To avoid the specular reflection of the high luminance, the screen would have to be angled such that a specular reflection would be formed of walls, papers on the table, etc. Therefore, compliance with the standard would be an either/or thing. The screen has to be able to stand up to either small, high-luminance sources, or large, moderate luminance ones (or both).

Optically, the large-area and small-area reflection characteristics will be equivalent for specular reflections. If, however, there is a significant point-spread function, the small-area source will produce a smaller refllection coefficient, in proportion to the amount of the reflection that falls outside the field of view of the photometer. That light is lost from the measurement.

Initially, the geometry of the small-source measurement was set up with a CRT in mind. Assuming a convex sphere, the specular reflection forms a virtual image of the source somewhat behind the faceplate, with a magnification of less than one. We looked at current CRT practice, and found a radius of curvature of arount 600 mm was the smallest in common use.

The measurement geometry and photometer field were selected so that the photometer field would fit comfortably within the reflected virtual image of the small source. Therefore, for a purely specular surface, having a radius of curvature of 600 mm or more, the total specular reflection coefficient would be measured accurately, provided the measurement was taken at the point on the screen where the first and second surface specular rays (and therefore the virtual images) coincided.

The photometer should be focused on the center of the virtual image of the source. The correct aim and focus distance can be difficult to establish if the virtual image is not clearly visible. It can be made visible on a textured surface by moistening the surface. Soapy water, alcohol, glycerin, even light (non-silicone) oil might be used, followed by the cleaning spray of your choice.

In the limiting case, where a true point source is measured by a photometer with an infinitessimal angle of acceptance, what would be measured is the maximum amplitude of the reflection point-spread function. This is impractical. The photometer has a finite aperture*. Since the luminance of the diffused reflection of a point source has no central area of constant luminance, the measured reflected luminance depends critically on the photometer measurement aperture. Different instruments, and different measuring distances, will produce different results. This is unacceptable in a standard, so finite source and aperture angles are specified. The Japanese standard spot photometer has a minimum aperture of 20' (1/3 degree). That was the largest found, so that was taken as the maximum measuring aperture angle.

* Actually, several apertures are potentially significant. Using the Pritchard photometer as a reference, the lens diameter and focal length determine to some extent how much reflected light is accepted for measurement. The focal plane aperture determines the extent of the virtual (specular) reflection measured. The problem is that the scattered light does not come from the same plane as the virtual image. The virtual image is behind the screen surface; the diffused light is redirected from the screen surface. One or the other must always be out of focus in the measurement. By choosing the first-surface specular reflection (virtual image of the source) for focus, the lens aperture (both physical and numerical) exerts an effect on how much out-of-focus light from the screen surface will enter the measurement. Extended discussion of this issue finally came down to weariness and a consensus that most spot photometers out there use about a 50 mm diameter lens and about a 100 mm focal length, so initially the problem would be ignored. It may be revisited if labs get really divergent results on highly textured screens. A contrary view of this may be obtained from at least one of the Dutch members.

Initially, the small-source size was the smallest possible. Practically, this was simply the size which, when massaged through the reflection optics of the source-screen-photometer lens location (magnification, distance, etc) gave a virtual image whose apparent diameter (visual angle) was 30' (= 1.5 times the 20' photometer aperture).

Later, the Japanese did some psychophysics, relating reported acceptability of screen reflections to specular reflections measured with different source sizes. They found best correlation with source sizes of 1 and 3 degrees diameter, as measured from the screen surface. They preferred the 3 degree source, at least in part because measurements are easier. I liked the 1 degree, because interpretation is easier, and it measures moderate diffusion with more sensitivity. I think the consensus swung to 1 degree, but it is possible that this may be revisited in the future.

Optically, the bottom lines are that each method measures the convolution of the spatial distribution of a luminous source of finite size with the reflection point-spread function of the screen: - The large-area source is large enough that further increases in its size do not result in further increases in the luminance of its virtual image, measured in the center. This, in effect, measures total direct (specular plus partially diffuse) reflection coefficient. - The small-area source measures a different point on the convolution. Its size is a compromise between a true point source, which would make practical measurement totally photometer-dependent, and a practical source having validity in the workplace. It is small enough that, for most screen textures, a significant part of the direct reflection falls outside the virtual (specular) image. Therefore, the luminous intensity of the specular rays is reduced relative to a purely specular reflection. In measurement (and view by the user) the luminance of the center of the reflection is reduced relative to the equivalent specular reflection. (Of course, the area or visual solid angle over which the reflection is perceptible increases in proportion.)

As to practical measurements, I would point out that most CRTs today seem to use either silica coating or chemical etch. Both leave substantial areas of flat (or little-changed) glass. (This is a technical way of saying that they often don't do much.) (Silica coating, when it is heavy enough to be effective, often causes "sparkle." Ask me about "sparkle" some day.) The reduction in the coefficient of specular reflection may be hard to measure, relative to the large source.

Some LCDs have a fairly heavy texture on the cover sheet, and may be easier to use for demonstration measurements.

Good luck. Hope this wasn't too much more than you wanted to know about reflections.

- John

At 08:54 AM 8/26/97 -0400, you wrote:
>At 10:45 PM -0400 8/25/97, John Cone wrote:
>>Bob -

>>Yep - I still keep this account active, although I don't check it every da Best bet is email to jcone@nmsu.edu.

>>- John

>Hi, John.

>I'm very glad to find you. I hope all is going well for you. When you get
a moment, I'd be interested in knowing what you are up to at NMSU.

>My main reason for trying to contact you was to ask a question or two
about the ISO 9241-7 standard. Specifically, I'd like to understand the rationale underlying the use of the two sizes of specular luminaires. I understand the effect reported by Kubota (i.e., increasing specular reflection with increasing luminaire diameter). However, Kubota's data seem to be dependent on his measurement system--that is, a detector field of view larger than the luminaire diameter.

>If been making the ISO 9241-7 measurements with a 2-D CCD detector system. When I setup the 30 deg off-axis condition, the small- and large-area luminaire readings are equivalent. This occurs since the required detector FOV are smaller than the projected image of the luminaires.

>Can you help me understand the intention of the ISO requirements?

>Many thanks,
>Bob

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VITA

Joy Kempic

Joy received a B.S. degree in Industrial and Systems Engineering from Virginia Tech in 1995. She has worked two summer interns that were more involved with classical industrial engineering: one with Roadway Package System and another with Union Camp Corporation Fine Paper Division. While at Roadway Package System, she performed productivity studies and provided recommendations to improve efficiency. While at Union Camp Corporation, she performed studies to increase operating efficiency and improve employee health and safety. She also performed an ergonomic evaluation on a workstation and provided recommendations to improve the layout. More recently, she has researched and ran a study about team performance in her Macroergonomics class last semester. She is also an active member in the Human Factors and Ergonomics Society. Joy is also a member of two honor societies: Phi Kappa Phi and Alpha Pi Mu. She will graduate in May of 1998 with an M.S. degree in Industrial and Systems Engineering (human factors option) at Virginia Tech. After graduation, she will work for General Motors.