# The Effects of Age, Illumination, and Anti-glare Treatments on Visual Task Performance and Perceived Image Quality with VDTs

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(ABSTRACT)

This dissertation investigated the effects of age on performance and image quality rating while varying screen surface treatment, ambient lighting, and character resolution. Five age groups were included, ranging from 18 to 69 years of age. The study used a factorial design to vary seven surface treatments which either reduced glare, enhanced contrast, or both; three lighting conditions, dark, diffuse, and specular; and two character resolutions, high and low, subtending visual angles of 16.1 arcmin. and 32.2 arcmin. respectively. Performance was measured using both a speed of reading task and a search task. In addition, subjects rated the image quality of displayed characters within each filter, lighting, resolution condition using a list of nine adjectives.

Results showed performance times to increase with age. The older age groups (40-49, 50-59, 60-69) performed better with the quarterwave filter, which enhanced contrast and reduced glare, and most poorly with the filters with the harshest etch (Gloss25) and the lowest transmission (31%).

Performance was significantly slower for specular and dark lighting. A finding consistent with previous research indicated that extremely high luminance contrast degrades performance with low room illumination. Finally, for all conditions in which resolution was a factor performance was fastest and ratings were highest with the low resolution characters.

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# INTRODUCTION

It is estimated that by the year 2000 over 30,600,000 Americans will exceed the age of 65. The rapid increase in this segment of the population has implications for all members of the population and should affect the design of home and work environments with which large segments of the population interact. In 1987, almost 75% of the workers over age 65 were in white collar occupations (National Research Council, 1987). As the population ages a large number of people will be staying in the workforce to a later age and performing jobs which require the use of visual display terminals (VDTs). Consequently, it will be necessary to understand the aging process as it relates to workforce needs to provide environments which are not only safe and comfortable, but also foster continuing productivity.

It is apparent from casual observations of people that there is wide variability in appearance and behavior during the aging process. Description of this population by chronological age alone is not always a satisfactory method. There are several approaches to describing the aging population, each reflecting the goals of the group who is doing the describing. These approaches include biological aging, functional aging, and chronological aging, to name a few. Although the most commonly used method is chronological age, when the goal of the description has to do with abilities, chronological aging may be inadequate. Nuttall (1972) has explained differences in the way people age in terms of "functional aging." In his scheme a person is placed on a continuum from birth to death, with functional age determined by how close that person is from death, regardless of chronological age. With respect to particular variables, such as mobility or vision, a person may be placed at a different location on each of these continua. Using this scheme, only one continuum might be used to determine "functional age", or more than one combined to determine a composite "functional age."

Although some work is being done to determine factors which help to define aging in other than chronological terms (Bell, Wolf, and Bernholz, 1972; Kahn, Leibowitz, Ganley, Kini, Colton, Nickerson, and Dawber, 1977; Nuttal, 1972), this work is of a longitudinal nature; thus, it may be many years before results are available. While chronological age may not be optimal for describing groups of people, it seems to be most widely used and accepted at the present time. The remainder of this dissertation uses chronological age to describe groups of people but, whenever possible, this will be supported by empirical data describing functional abilities.

## Aging and Vision

Visual functioning affects the way humans perceive their environment and, to a large extent, the way they function within that environment. As a result of the aging process, vision declines to varying degrees with respect to a number of aspects of the visual system and to varying degrees among individuals. "Some people experience severe deterioration of vision with age, and virtually everyone must adjust to some reduction in visual function as he or she gets older." (Sekuler, Kline, and Dismukes, 1982, p. 3).

General physiology of the eye. The human eye responds to light or electromagnetic energy in the wavelength range from approximately 380 to 720 nm. Light enters the eye through the outermost shell called the cornea, a transparent protective covering to the eye which performs a principal part of the refraction of light occurring in the eye. Light then passes through the pupil opening to the lens. The amount of light entering the eye is controlled almost totally by the pupil whose size is determined by the muscles of the iris. The lens focuses light through the vitreous humor onto the retina, which contains the photoreceptors for the eye. The retina is called a duplex retina because it contains two different types of photoreceptors, cones and rods, each used for different types of vision. Cones are used for viewing both achromatic stimuli (black, white, and shades of gray) and chromatic stimuli and for viewing fine detail. The majority of the eye's six to seven million cones are located in the center of the retina called the macula, within which is the small depression called the fovea, containing mostly cones. This area of the retina is used for high illumination (photopic) viewing conditions.

The approximately 130 million rods are located primarily off-axis, with the highest density 15-20 deg from the fovea and used for low light (scotopic) visual conditions. The rods contain no mechanisms for retaining information about the wavelengths of incident light and thus can be considered color-blind (Cornsweet, 1970). Located nasal and proximal to the fovea is the point where the optic nerve leaves the eye. This location, called the optic disc (also called the blind spot), has no receptors and, consequently, no vision.

Effects of age. In general, visual sensitivity is reduced with age. The following discussion presents the perceptual changes which occur as a result of changes in the physical structures of the aging eye. Where possible these effects are discussed quantitatively.

One of the major sources of reduction in vision resulting from aging occurs in the lens. The lens itself is an entirely encapsulated structure and, as such, allows no cells to be lost during its lifetime (Spector, 1982). As new cells are introduced, the old cells are displaced to the center of the lens, resulting in a developmental enlarging of the lens and some packing of cells within its center. These changes observed in the lens generally lead to the progressive accumulation of aggregate materials, membrane breakdown, light scatter, and finally opacity. The packing of cells, along with changes in protein synthesis and a decrease in metabolic activity, while not believed to be directly responsible for the formation of cataract (loss of lens transparency), may increase the possibility of oxidative insult, resulting in the formation of cataract (Spector, 1982). The formation of cataract and other diseases associated with aging are discussed in more detail below.

Changes in the optical media of the eye, particularly the crystalline lens, affect the amount and wavelength of the light admitted to the eye. The human lens becomes progressively more yellow and opaque with age. The effect of this yellowing has been compared to the vision of a younger person looking through a yellow filter. The yellowing and reduced transmissivity of the lens also result in less light being focused on the retina. Weale (1982a) has estimated that about one-third of the light available to the eye of a person in his or her twenties reaches the retina of a 60 year old.

Another aspect of the lens which affects vision is the ability of the lens to change shape. The shape of the lens, which determines its focal length, is controlled by the ciliary muscles. Any reduction in the pliability of the lens or in reduction in muscle strength will affect the focusing of images on the retina. Bell, Wolf, and Bernholz (1972) have reported that "substantial physical changes of the dioptric media (lens turbidity, glare sensitivity) begin at 40-45 years, whereas retinal (metabolic) changes begin after age 60." (pp. 77).

The reduction in the maximum size of pupil diameter is responsible for a large amount of decreased retinal illuminance. This decrease seems to approach asymptote at approximately 75 years of age (Birren, 1964). This reduction in the amount of light incident upon the retina can affect acuity, contrast sensitivity, color vision, critical flicker fusion, and dark adaptation. Although the reduced transmissivity of the lens and the reduced maximum size of the pupil decrease the amount of light entering the eye, Weale (1982b) does not feel that optics alone account for the drop in acuity experienced by older adults. He suggests that an additional factor which may account for some of the loss in acuity may be explained by the reduced number of cells found in the retinas of older people due to cell death.

Acuity. When discussing vision loss due to the normal aging process, visual acuity is probably the most quoted measure. Visual acuity is usually measured in terms of the smallest visual angle subtended at the eye for which detail can be recognized. This reduction in the ability to resolve fine detail which occurs with age appears to be the result of several factors involved with degeneration of the macula. Since the retina is structurally related to the central nervous system, it does not regenerate lost cells. Although it has been calculated that as many as 50% of the visual cortex neurons drop out by age 70, Marmor (1982) has concluded that the retina is composed of more cells than are needed in a lifetime. In addition to the loss of cells, there is some evidence that the retina is adversely affected by light, although the effects of lifelong exposure are as yet unsubstantiated (Marmor, 1982).

In general, while visual acuity declines with advancing age, it appears to remain fairly consistent between the two eyes (Pitts, 1982). The causes attributed to extensive loss of acuity due to aging are, in order of importance, cataract, senile macular degeneration, retinal pathology, glaucoma, and various other unknown causes (Pitts, 1982). A compilation of acuity data by age presented by Pitts (1982) indicated a slight improvement for acuity up to approximately 20 to 30 years of age, leveling off until about age 40, then showing a decline to about age 80.

The Framingham Eye Study (Kahn, Leibowitz, Ganley, Kini, Colton, Nickerson, and Dawber, 1977) compared visual acuity in the better eye by age and gender. Their results indicated a slightly higher percentage of women than men with acuity of 20/30 or worse for most age groups. Milne (1979) reported longitudinal data for male and female subjects (ages 63 to 90 years) investigating acuity changes with age. He tested subjects initially, after a one-year interval, and after a five-year interval. His results showed that 11.6% of the men and 14.4% of the women showed degraded visual acuity after five years, although the gender difference was not statistically significant. His results also showed improvement in 15.2% of the men and 9.6% of the women. He reported significantly more visual impairment at the five-year test interval for the subjects who were older at the initial testing.

He also noted a significant difference in the increased prevalence of cataract at the five-year interval for both men and women, with a slightly more rapid decrease in vision for men due to cataract.

The major functional change to the retina which may affect acuity is reportedly due to senile macular degeneration (SMD), which includes loss of photoreceptors, loss of reflexes, drusen (yellow spots appearing on the pigment layer of the retina), pigment epithelial damage, and generalized ischemia (obstruction of blood flow) (Marmor, 1982). These changes result in the loss of acuity (ranging from 20/50 to 20/100) which can make reading difficult, but does not affect peripheral vision or general mobility.

Miosis. Miosis, the reduction in pupil size, is also experienced with advancing age. The maximum pupil diameter of the eye decreases from approximately 5.2 mm (age 20-29) to approximately 3.2 mm (age 80-89) at 3.2 $cd/m^2$ luminance. For dark measurements these values increase to approximately 7.5 mm for the younger subjects and 4.5 mm for the older subjects (Birren, 1959). The data appear to approach an asymptote after approximately 85 years of age, indicating little appreciable decrease in maximum pupil diameter after that age, although further research on appropriate age groups would be required to validate this trend.

Illumination. Since changes in the lens and the size of the pupil opening result in less light entering the eye, research has been performed to determine if increased illumination facilitates performance for older subjects. Guth, Eastman, and McNelis (1956) varied the amount of illumination to determine its effect on a reading task and found that older subjects (age 61-65) benefited by increased illumination; however, their mean performance never equaled the mean performance of the younger subjects (age 17-60).

Hopkinson and Collins (1970) also performed research to determine the effects of varying levels of illumination on task performance as a function of age. They found that older subjects (50-65 years of age) benefited more from high levels of illumination (1000 lx) for tasks with high contrast, black letters on white background. Both younger (20-30 years of age) and older groups found this level of illumination to be "good" for this high contrast task, but the older group required an increase in illumination to 5000 lx when the task required reading black letters on a gray background.

Reported results on the effects of illumination and age on task performance vary with respect to the amount of illumination recommended. Some show improvements in performance with illumination at about 10,000 lx, while others show improvement with 4880 lx (Boyce, 1981). An important variable in this research seems to be the task used. Tasks which require the worker to resolve fine detail require greater illumination. Any specification of illumination thus should require consideration of the task to be performed in that environment, especially for older persons.

Contrast sensitivity. The luminance contrast threshold is the ability of the eye to detect differences in luminance between an object and its background. Contrast sensitivity is the reciprocal of this value. Birren (1959) cited research which reported contrast sensitivity (for a luminance of 0.3 $cd/m^2$) at a value of about 24 (age 20-30), dropping to approximately 17 (at age 50) without added glare (see below for a discussion of glare). With glare the contrast sensitivity fell from about 3.3 (age 18) to about 1.8 (age 50). Blackwell and Blackwell (1971) have presented multipliers for increasing the contrast of object and background for different age groups. For subjects over the age of 60, these multipliers range from 1.5 to over 5 depending upon background luminance. Of note in this research was the large increase in variability as age increased above the age of 50. A review of the contrast sensitivity literature (Pitts, 1982) showed that more luminance is needed by persons 70 and above than by those in their twenties. He presented recommendations for increased contrast by a factor of 1.17 to 2.51 to compensate for the loss in visual perception experienced by persons after the age of 60.

Sekuler and Owsley (1982) tested the contrast sensitivity of subjects as a function of age. All subjects were refracted to the required viewing distance of 3 m. The mean luminance of the CRT was 103 $cd/m^2$. The best corrected distance acuity for the eye whose contrast sensitivity function (CSF) was measured ranged from 0.68 arcmin for 20 year olds to 1.27 arcmin for 60 year olds. Sekuler and Owsley (1982) found that older subjects had lower sensitivity at 4 c/deg with greater losses as age progressed. Approximately at age 60 the peak CSF was at a lower frequency, 2 c/deg, compared to the younger subjects, who peaked at 4 c/deg. These researchers concluded that the older observers showed reduced sensitivity predominantly at intermediate and high spatial frequencies.

Owsley, Sekuler, and Boldt (1981) reported contrast sensitivity research in which they presented subjects with faces at different contrast levels and asked them to perform two different tasks involving the recognition of a particular face or to discriminate between pairs of faces. They found that the older subjects required an average of about three times more contrast for both detection and discrimination than the younger observers. There was little variability reported within each group, although slightly more for the younger group.

Accommodation. Accommodation is the ability of the lens to change its focal length for objects at various distances from the eye. This is accomplished through changes in the curvature of the lens. Maximum accommodation decreases with age from approximately 20 diopters at age 5 (at a rate of 0.3 diopter per year) until it reaches a value of approximately 0.50 diopter at about age 60, after which no appreciable decrease is observed (Birren, 1959).

Presbyopia, associated with the aging process, is a failure of the lens to accommodate for near vision. Birren (1959) has presented three different theories which have been proposed to explain the presbyopic changes which occur with aging:

- Helmholtz's theory that the reduction in elasticity of the lens produces these accommodative changes.
- Tscherning's theory that the normal forces acting on the lens to modify its shape, as well as the lens itself, change with age.
- Duane's theory that the lens and the muscular forces acting upon it change with age.

Further research is needed either to support one of these theories or to develop a consolidated theory. Regardless of the underlying theory, the near point recedes between the ages of 50 and 60, from about 11.5 diopters at age 17 to 1 diopter or less at age 60 (Simonelli, 1980). Weale (1982b) has stated that the presbyopic changes which occur with age, however, do not occur uniformly within or between individuals. Simonelli's (1980) research on dark focus (discussed below) supports this variability, although he used a fairly small sample size (N = 11).

An important function of the pupil which has implications for VDT studies is that pupillary constriction increases depth of focus. This increase in depth of focus can reduce the need for the eye to accommodate to as large an extent as would be required for the same observer without a reduction in the maximum pupillary size. For a presbyopic subject the reduction in pupil size may offset some of the loss in accommodative power.

Dark focus. Dark focus (the accommodative state to which the eye tends to automatically move in darkness when there is no object on which to focus) appears to move out as a function of age (Simonelli, 1980). He found that both far point and dark focus receded at an accelerating rate after about 40 years of age, with a slight tendency for older people to have a relative dark focus (the difference between the measured dark focus and the far point) of approximately -2.5D at age 60, which is smaller than for younger subjects (approximately 2.0D at age 17). Simonelli (1980) attributes this to the "faster rate of recession of the measured dark focus over that of the far point."(pp. 312). The relationship between near point and relative dark focus found with age (i.e., the near point recedes at a faster rate than the dark focus) results in a relatively large reduction in the accommodative amplitude and a small reduction in relative dark focus.

Dark adaptation. Dark adaptation is the process by which the eye shifts from photopic or cone vision (in a lighted environment) to scotopic or rod vision (in a dark environment). This process is typically presented in terms of the time required to shift from cone vision to rod vision as a function of the amount of illumination present. For young healthy subjects this process usually requires approximately eight minutes for the cones to adapt and approximately 40 minutes for the rods. Birren (1964) reported that the minimum dark adaptive light threshold was fairly stable with respect to age from 10 to 40 years of age. After 40 the curve increased steeply, from approximately 2.7 to 4.0 log units. The slope for older subjects (83 years of age) was still extremely steep, indicating that this effect may increase for older age groups; however, further research using older subjects would be required to determine this.

The transition point between the asymptote of cone adaptation (photopic vision) and the initiation of rod adaptation (scotopic vision) is called mesopic adaptation. In the reduction of luminance, older subjects enter mesopic visual levels at higher luminance levels than do younger subjects, approximately one logarithmic unit at the point of asymptote of the photopic curve. The reduced maximum pupil opening has been reported to be responsible for much of this shift due to decreased amounts of light entering the eye. Weale (1982b) has stated that the pupil of the dark adapted eye reaches its maximum diameter in the teens and then progressively decreases, reducing the total amount of light admitted. This reduced light raises the threshold of the retina nearly one logarithmic unit (at 430 nm) across the age range from 20 to 89 years (Weale, 1982b). A review of the dark adaptation literature indicated that the dark adaptation curve for illumination for older subjects is elevated from approximately 1.2 log units (age 60-69) to 2.2 log units (age 80-89) from that of a 20 year old (Pitts, 1982). This elevation results in the rate of change of dark adaptation with age being approximately 0.3 log unit for every 13 years of age and indicates that the target luminance should be doubled for every 13 years of age above 20, just to be detected. The yellowing of the lens, as well as senile miosis, are reported to be the predominant factors in this dark adaptation shift. The pupillary variations contribute approximately 0.5 log unit for 50-59 year olds and 0.6 log unit for 70-79 year olds to the raised threshold values observed (Pitts, 1982). These data were collected using an age range from 16 to 80 years. The plotted threshold functions were increased for every decade after 20 years of age, including the 80-89 year old range. Although their results indicated that subjects over the age of 89 may also have increased dark adaptation thresholds, no data were available to support this.

Depth perception. Depth perception is another aspect of vision which is reported to degrade with age. Bell, Wolf, and Bernholz (1972) found that between the ages of 40 and 50 years there is a critical change in depth perception. Hill and Mershon (1985) also studied depth perception as a function of age by testing the equidistance tendency on subjects of various age groups. In a task in which subjects were required to indicate when two targets were perceived as being equidistant from the subject, results indicated that, on the average, the older subjects underestimated the distance of the target (4 m) by 0.9 m, when lateral separation between the targets was at the maximum level of 0.06 rad, as opposed to an average underestimation of 0.5 m for the 18-20 year old group. The difference between age groups was significant ($p < 0.0005$).

Field of view. The total instantaneous field of view (FOV) of an eye is the area over which the eye can see when it gazes straight ahead. Carter (1982) found the total lateral FOV to be maximum at about age 35 and then decline with progressing age. He also noted that females have a slightly larger total FOV. He attributed some of the loss of FOV to occlusion from sagging of the eye lid, eye brow, and nose; however, the rapid change he observed after age 60 may be due to retinal factors, miosis, and yellowing of the lens. Carter (1982) cited research which indicates that there is an increase in the size of the blind spot as a function of age.

Critical flicker fusion. Critical flicker fusion (CFF) refers to the perception of a flashing light becoming fused and appearing to be constant. Kline and Schieber (1982) have reported a decline in the CFF threshold with age. They attribute most of the loss in temporal resolution to neural components in the retina. Birren (1959) has attributed much, though not all, of the reduction in the CFF threshold found with age to reduced pupil size. McFarland, Warren, and Karis (1958) concluded from their study of CFF using two levels of illumination (2.03 and 0.004 lx) that the age difference cannot be attributed entirely to reduced retinal illumination found in older subjects.

Color vision. Color vision also shows some effects of the aging process. Due to the yellowing of the lens, the pigmentary absorption by the lens is not consistent across the spectrum, with more of the shorter wavelengths (blues and greens) absorbed, resulting in a shift from white to yellow (Carter, 1982). There is also a relative darkening of blues and a bias toward colors of longer wavelengths (oranges and reds) (Carter, 1982). Carter (1982) has stated that senile miosis, lenticular absorption, and light scatter in the aging eye combine to reduce retinal illumination, resulting in raising the detection threshold and impairing color recognition. Heinsius (1972) noted that longitudinal color testing of railroad workers in England showed an increase in the number of errors produced with increasing age, especially noticeable in the sixth decade. As stated previously, it has been shown that for older subjects the mesopic threshold is reached at significantly higher ambient light thresholds than for younger individuals, thus indicating that more light is required for photopic vision, and that older subjects shift to scotopic vision at higher illumination levels. Maione and Carla (1972) tested different age groups with green, red, and blue targets and concluded that the achromatic isopters for colored targets decrease with age, but the decrease is larger for blue (39.8%) than for red (18.7%).

Although the change in color perception is probably strongly affected by the yellowing of the lens, changes in the retina may also be involved. Kilbride, Hutman, Fishman, and Read (1986) used fundus reflectometry to determine the effects of age on cone pigment density. They found a significant decrease in the density of foveal cone visual pigments with increasing age. They found no significant differences between red and blue wavelength decreases, although their data did suggest a trend ($p$ = 0.06) for the over-forty age group to have less blue wavelength density and more red wavelength density compared to the younger group (under 40 years).

In terms of temporal color resolution, Kline, Ikeda, and Schieber (1982) found that integration of green and red to produce reports of yellow were significantly more frequent among older subjects (mean age 68.4) than younger ones (mean age 19.1). They found, though, that an increase in the intensity of the lights did not seem to affect discrimination and that changing the luminance level had no effect on stimulus persistence for either age group. A study reported by Boyce (1981) showed a general developmental decline in the ability to match colors, especially blue-green and red hues. He also noted that the older subjects needed higher levels of illumination to perform at the same level as the younger subjects.

Glare. An important consequence of aging is the reduction in the eye's ability to resist glare. Glare has been defined by the Subcommittee on Glare of the Research Committee of the Illuminating Engineering Society (Bell, Troland, Verhoeff, 1922) as "the sensation produced by light so invading the eye as to inhibit distinct vision" (p. 743). Sanders and McCormick (1987) have added that the luminance of the glare source must be sufficiently greater than the luminance to which the eye is adapted to cause annoyance, discomfort, or reduction in visual performance. Glare has generally been classified by the way in which it affects the observer. Discomfort glare, resulting from direct sources (e.g., lights within the visual field) or indirect sources (reflections) can cause annoyance or discomfort due to the high levels of illumination in the visual field, but not enough to interfere with performance. Disability glare directly interferes with the visual task, consequently reducing performance, and is likely to cause discomfort.

Another classification of glare, presented by Carter (1982), separates glare into dazzling, veiling, and scotomatic glare. He defined dazzling glare as "aberrations, scattering, and optical imperfections resulting in numerous rays falling outside the geometric image on the retina" (p.122). Veiling glare results from stray light distributed more or less uniformly across the retinal image, reducing the contrast of the object and its background. Finally, scotomatic glare involves the overloading of the retinal photoreceptors for a short period of time, as when a flash bulb is fired, resulting in reduced sensitivity of the photoreceptors for some time afterward. Factors which can contribute to glare include light entering the eye from sources other than the pupil, light scattered by the optic media, especially the lens, light reflected back to the retina a second time from reflective surfaces within the eye, and light resulting from fluorescence (reported to increase with age) of ocular structures (Carter, 1982).

Pulling, Wolf, Sturgis, Vaillancourt, and Dolliver (1978) performed driving research in which they isolated the effects of age on resistance to glare from oncoming headlights. They concluded that glare resistance diminishes in later years, showing an average deterioration of 0.1 log unit every four years, which is equivalent to 50% every 12 years.

Another factor which may affect susceptibility to glare is the Stiles-Crawford effect (directionality of the photoreceptors toward the pupil or light source). This effect may be reduced in the eyes of older adults, making them more sensitive to stray light and, therefore, glare (Sekuler, Kline, and Dismukes, 1982). They reported that, since this effect is primarily, though not exclusively, associated with the cones, older persons may have difficulty when resolving fine detail in the presence of stray light sources. These stray light sources may be external or internal to the eye itself.

Glare can often result in a loss of contrast between an object and its background. The loss of contrast can occur at the retina or at the display. Light entering the eye can be scattered by the lens, interocular fluid, and other structures within the eye, effectively reducing the contrast of the target at the retina. Reduction in contrast at the display can occur as a result of specular reflections from glossy surfaces. The magnitude of these effects depends on factors such as the size, position, and luminance of the source or reflecting surface and the luminance to which the eye has been adapted (Sanders and McCormick, 1987), as well as a function of the age of the observer (Hopkinson and Collins, 1970).

Pathologies. There are several visual diseases associated with the aging process. These can range in severity from slight visual distortion to total blindness. Although these diseases are not restricted to the elderly, they occur more frequently in the older population.

Vitreous detachment results in varying degrees of visual distortion. In a review of the literature on the occurrence of posterior vitreous detachment, Balazs and Denlinger (1982) reported frequencies from 20% to 65% for people over the age of 50, with 94% of the individuals with senile opacities of the lens reported to have posterior vitreous detachment as a result of fundamental structural changes within the vitreous. This detachment can be partial or complete, depending on the area involved, and can produce varying degrees of perceptual changes such as photopsia (the observation of spontaneous light flashes), metamorphopsia (the distortion of the visual image and blurred vision), and floaters (shadows cast on the fovea). The seriousness of the visual disturbance is a result of (1) the amount of traction that is asserted on the retina which, in turn, causes functional and structural changes in the tissue, and (2) the extent of the optical heterogeneities which are present in the vitreous that interfere with image formation (Balazs and Denlinger, 1982).

In addition to vitreous detachment, there are other visual pathologies which occur with higher frequency in older people. Cataracts involve the separation of lens fibers by aqueous fluid, resulting in opaque regions forming in the lens, blocking parts of the visual field. Cataracts may appear at any location of the lens, but central cataracts produce the most disruption to vision and can eventually result in blindness (Verrillo and Verrillo, 1985).

Senile macular degeneration (SMD) is the systematic degeneration of the portion of the retina which contains most of the receptors (macula) used for fine detail and color vision. The effects of SMD can reduce Snellen acuity to a range of 20/50 to 20/100, making such tasks as reading and television watching extremely difficult. Since peripheral vision is not affected by SMD, the ability to negotiate the environment may be relatively unaffected.

Glaucoma, reported to increase with age between the ages of 50 and 85, is a condition characterized by an increase in pressure inside the eyeball which results in pressure being exerted on the optic nerve (Verrillo and Verrillo, 1985). This condition produces distortion in the visual field (blurring or halos) and can eventually result in blindness.

## Summary

It is apparent that many aspects of vision degrade with age. This reduction in visual capabilities can result from deterioration of one, or several, aspects of vision. An interesting point to note is that many of these reductions begin to be noticeable at about 40 years of age, 20 to 30 years before most people begin retirement. Table 1 summarizes reduction infunctions or diseases which affect vision and gives the age at which they generally start to degrade. The visual functions on the chart fall into two groups, those affected by the optics of the eye (cornea, lens, pupil) and those affected by retinal metabolic changes. The table is set up so that the functions affected by the optics are listed in the upper part and those affected by the metabolic processes of the retina are listed on the lower part of the chart. Interestingly, it can be seen in the chart that the functions at the top of the chart (optical) start to degrade about age 35 while those at the bottom do not show signs of degradation until about age 50.

An important result of this literature review was the finding that very few of the reports presented results or discussed variability within the specified age groups. These studies almost totally neglected gender differences. It is apparent that little is known of the effects of aging on vision with respect to gender differences.

The current state of the data base for the visual effects of aging indicates a particular need for applied research. Sekuler et al. (1982) have compiled an impressive amount of literature regarding the effects of aging on vision; however, there is very little information on how to apply these data to the design of products and environments for the population whose visual capabilities are in varying states of reduction. It is often difficult to translate the results of basic research to the requirements of specific applications.

TABLE 1

Visual Function Deterioration

| Visual Function | Age |
|---|---|
| Yellowing of Lens | After 35-40 |
| Miosis | Decrease after 20<br>Asymptotes after 85 |
| Susceptibility to Glare | Increases after 40 |
| Presbyopia | Increases after 40<br>Asymptotes after 60 |
| Far Point | Recedes after 40 |
| Dark Focus | After 40 |
| Depth Perception | Reduced after 40 |
| Color Vision<br>Change in cone pigment density | After 40 |
| Instantaneous Field of View | Reduced after 35 |
| Retinal Metabolic Changes | Degrades after 60 years |
| Acuity | Reduced--Slowly After 40<br>More pronounced after 55 |
| Contrast Sensitivity | Reduced after 50 |
| Critical Flicker Fusion threshold | Reduced after 60 |
| Dark Adaptation threshold | Large Increase after 60 |
| Vitreous Detachment | Increased occurrence after 50 |
| Glaucoma | Increased occurrence after 50 |
| Senile Macular Degeneration (SMD) | Increased occurrence after 50 |
| Cataract | Increased occurrence after 50 |
| Visual cortex Neuron loss (50%) | About 70 years |

This review of the literature indicates, in essence, that with age the particular parts of the visual system degrade to varying degrees. For some aspects of the system data exist which indicate how degradation affects performance as measured using specific tasks. The question becomes one of how effectively these data can be applied to actual tasks performed in the work environment. Further research is needed to determine how these separate parts interact in a typical work environment, for example, performing typical VDT tasks. These results would help to determine recommendations for VDT workstation design that accommodates a large segment of the population in terms of user age and physical environmental characteristics (e.g., lighting intensity, character resolution). Thus, the remainder of this dissertation will concentrate on determining the effects of aging on visual performance using VDTs and translating the findings into design recommendations.

## VISUAL DISPLAY TERMINALS

Although little research has been reported that specifically addresses the problems the elderly encounter when using, visual display terminals (VDT), surveys have indicated that older users with bifocals or trifocals have some difficulty because of the postural contortions involved in viewing the information displayed on the screen through the intended lens. In addition, a major complaint of the general VDT user population is the reduction in contrast due in large part to glare. As discussed earlier, the elderly are particularly susceptible to glare; therefore, when dealing with workstation design for the general population (which includes a wide age range of users), reduction in glare should be an important consideration.

A major difference between VDT work and non-VDT work is that the display in the VDT is in a vertical plane and typically has a curved and highly specular surface. These VDT attributes make the display susceptible to reflection from lights and other surfaces in the environment. Reflections from the VDT are either diffuse or specular. Specular reflections are seen as bright spots on the screen from sources such as lighting fixtures and windows. Reflections from the mirror-like front surface of the screen form images which appear to be in back of the front surface. For example, objects which are at a large distance from the CRT (e.g., more than 70 cm) appear to be approximately 32 cm behind the screen, assuming a radius of curvature of 63.5 cm (National Research Council, 1983; Sanders and McCormick, 1987).

These reflections can be annoying and distracting to someone trying to obtain information from the VDT. When an object is reflected by the surface of the VDT, the plane on which the character images are displayed is interposed between the observer and the reflected image. For example, when "X" is displayed on the screen the two eyes accommodate according to the display distance from the eyes, intersecting at the X to avoid perceiving a double image. When a reflection is present and focused upon, the eyes each perceive the character at a different location; thus, the observer perceives a double image. The eyes then try to accommodate to remove this double image. What may result is an oscillation by the eyes between the plane of the character and the reflected image. Cakir, Hart, and Stewart (1980) have stated that many of the complaints of visual discomfort in the work environment can be traced back to the effects of screen reflections.

An additional consideration for VDT users is the Stiles-Crawford effect which describes the phototropic nature of the retinal receptors, previously discussed. Since the Stiles-Crawford effect is reported to diminish in the older eye, as discussed earlier, the loss in receptor directionality may result in an increased perception of light scatter within the eye due to these reflections (Sekuler et al., 1982).

Another category of reflection that can interfere with viewing information on the CRT is diffuse reflection. This type of reflection produces a veiling effect at the screen which can significantly reduce the contrast between the image and its background. Thus, although diffuse reflections do not cause competitive focusing problems, they nonetheless can interfere with VDT viewing.

There are two principal ways to control the glare reflected from the surface of the VDT. One is to control the environmental lighting and use local light sources for hard copy. The other is to vary the room lighting to control the reflection at the screen through the use of CRT surface treatments. Due to the wide variability in illumination throughout environments in which VDTs are placed, the present research was designed to evaluate the latter approach.

The use of CRT surface treatments which reduce glare regardless of the ambient lighting situation seems to be a viable approach to the VDT glare problem. The effects of the surface treatments are varied, being capable not only of reducing glare, but in some cases of enhancing contrast at the screen. These treatments may have advantages for the general population, but may especially aid older users in the work environment.

## Antireflection Treatments

The purpose of antireflection treatments is to reduce the specular and diffuse reflections from the front surface of the VDT. A reduction in reflections from the display would probably reduce annoyance and possible discomfort for the general population, but it should be especially helpful for the segment of the population that is less resistant to glare as a result of developmental changes in the visual system. Several of these treatments are discussed below.

Chemical etching. Direct reflections can be reduced by making the screen surface rough, or by adding a roughened glass panel to the front of the screen. Etching can reduce the direct reflectance from about 4% to about 2% (Hunter, 1988). Although this method may be effective, it has some drawbacks.

Since the phosphor side of the glass cannot be etched, the treatment on the outer surface can reduce image quality by scattering light. The greater the distance between the displayed image and the etched surface, the greater this scattering effect will be (Cakir et al., 1980). The amount of scatter also depends on how coarse or fine the surface etch is. A fine surface etch will have a small effect on the displayed characters, while a coarse etch will have a larger scattering effect, thus reducing the sharpness of the characters more.

While the etched surface can be effective in eliminating the specular content of the reflected image, it does this by redistributing the incident light. This redistribution can be a problem when high levels of incident light are scattered or spread over the surface of the CRT, creating a "veil" through which the displayed information must be viewed.

Mechanical abrasion. Mechanical abrasion produces a surface which acts essentially in the same manner as the chemically etched surface. The difference lies in the method used to roughen the surface; in this case the surface is mechanically roughened. Although this process can be more controlled than the chemical etch, the same advantages and disadvantages are present with both types of surfaces. As with chemical etching, mechanical abrasion can be used to attain varying degrees of harshness or antireflection. As the roughness of the surface increases, the luminance and resolution of the displayed characters decrease. The abrasion method also diffuses or scatters the incident light, resulting in the same "veil" effect found with the etched surface.

Micromesh filters. Mesh filters reduce specular reflections through the same means as they enhance contrast. The mesh is composed of black tubes arranged at a particular spatial frequency, depending upon the amount of light absorption required. The tubes are oriented vertically, horizontally, or diagonally. Transmission is varied by changing the density or spatial frequency of the mesh (i.e., the higher the spatial frequency, the more effective the filter will be in reducing off-axis specular reflection). A large proportion of the incident light that passes through the mesh and is reflected from the front surface of the CRT will be absorbed or scattered by the black tubes as it passes through the mesh a second time.

Although these filters effectively reduce glare and enhance contrast, there are some disadvantages to their use. First, because the mesh filters are composed of elements of fixed spatial frequency, it is entirely possible that interference or Moiré patterns will be created when the filter is attached to the CRT display. Second, depending on the coarseness of the mesh, the display may be obscured by the mesh when viewed at oblique angles. Third, up to 70% of the light emitted from the displayed characters is absorbed, causing the characters to appear less bright (Cakir et al., 1980).

Quarterwave coatings. This method involves applying a thin-film quarterwave coating on a glass panel which can be bonded to the CRT. The coating consists of a film composed of a single layer (one-quarter wavelength thick) or multiple layers of transparent materials that have indices of refraction making the step from air to glass more gradual. As the incident light travels through the thin-film filter and is reflected by the glass substrate, the quarterwave filter layer sets up an interference pattern at the air-to-filter interface. The reflected light wave and the incoming incident light wave cancel each other, rendering them imperceptible to the observer.

The deposition of this layer on the panel is time consuming and expensive due to the process and sophisticated equipment required. Since the processed panel must be permanently bonded to the CRT, the entire display would require replacement should the panel become damaged. A final consideration is that the filter surface must be cleaned frequently because it is very susceptible to fingerprints and smudges that cause the thin film to lose its antireflection properties (Hunter, 1988).

## Summary of Research

There have been a number of studies which have considered the physical characteristics of the display and the effects of adding anti-glare filters in the presence of glare sources (Beaton and Snyder, 1984; Brauninger and Grandjean, 1983; Kuo and Kalmanash, 1986; Rancourt, Grenawalt, Hunter, and Snyder, 1986; Stevenson, Fendly, and Wallner, 1986). These studies were primarily concerned with the effects of glare on physical image quality and did not use any type of performance measures. The objective measures used were modulation transfer function (MTF), which measures the contrast (modulation) expressed as a function of the size of the bars on a sine-wave grating, with increasing spatial frequency indicating reduced bar size (Snyder, 1984); a measure of the reflectance of the screen (e.g., reflectance transfer function); luminance measures; and luminance contrast measures. Although important information was obtained regarding objective screen characteristics, no performance data were collected.

There is a high degree of variability in the research on the effects of anti-glare filters on screen resolution in the presence of glare sources. Although a few of the studies were well conceived and performed (Beaton, Murch, and Knox, 1985; Hunter, Pigion, Bowers, and Snyder, 1987), most of the others had serious equipment or methodological problems.

Methodological problems with this research include the use of multiple cathode ray tubes (CRTs), thus not controlling for individual differences between CRTs; insufficient sample size (Sach, 1970); no use of a baseline or control filter level (Habinek, Jacobsen, Miller, and Suther, 1982; Morse, 1985); confounding contrast ratio, resolution, and luminance by letting subjects adjust the character luminance (Habinek et al., 1982; McVey, Clauer, and Taylor, 1984; Morse, 1985; Paci, 1984); and the use of inappropriate statistical methods (Paci, 1984). Another problem with this research in general is that the filters were not bonded to the CRT front surface, thereby adding two additional surfaces by which light could be refracted (i.e., the back surface of the filter and the front surface of the CRT).

Although a fairly wide age range was specified for two of the studies (Habinek et al., 1982; Morse, 1985), 21 to 54 years and 23 to 51 years, respectively, the Age variable was not included in any analyses or discussed further. Therefore, any filter types in these studies shown to produce the best performance and highest subject preference may not be appropriate for an aging population with reduced visual capabilities.

Almost without exception, the reported research tested the visual performance and preference of young healthy subjects. The performance tasks used were primarily reading or search tasks. The subjective tasks included ranking a number of conditions, paired comparisons, and rating scales. The current research attempted to eliminate the deficiencies specified above.

Age and Visual Performance

After a review of the age-related visual processing literature, Walsh (1982) concluded that "older adults are slower than younger adults in all stages of visual information processing" (p. 229). He also concluded that there is little support in the literature to specify one causal factor for this slowing. Moraal (1982) has suggested that this slowing may be a result of a change in the strength of the signal from the sense organ to the brain and between processing stages rather than within these stages. Another explanation for the slowing in sensory processing may be caused by cellular loss in the sensory organ itself and in the central nervous system (Ordy, Brizzee, and Johnson, 1982). Kline and Schieber (1982) have discussed the stimulus-persistence hypothesis in relation to slowing of stimulus processing causing a type of "smearing" of the stimulus information. This hypothesis was also discussed by Kline, Ikeda, and Schieber (1982) with respect to the study on temporal resolution of color presented earlier in this dissertation. This hypothesis may be further supported by the data on critical flicker fusion discussed previously.

In an embedded figures test (Rackoff, 1975) older subjects averaged almost seven times longer to identify the simple figure within the confusing background. The older subjects took an average of 1.497 min while the younger subjects took an average of 0.215 min. The performance for the older group was more variable ($s = 0.56$) than that of the younger group's ($s = 0.09$).

Using color vision tests which required the subjects to identify an object from its background, Stanford and Pollack (1984) investigated the age effects of complexity of figure-ground segregation. Their subjects were all female with a mean age for each of six groups ranging from 24.5 to 72.9 years. Their results showed that the older groups took significantly longer to perform the task ($\underline{p} < 0.0001$) and made more errors ($\underline{p} < 0.0007$). Because the subjects exhibited an undiminished ability to respond to color and performed well on two of the three color tests, they concluded that figure-ground segregation was impaired by the interaction of figural complexity with contour defined by hue differences alone.

Search tasks. A number of alternatives exist by which the observer's ability to detect or search out specific targets can be measured. Snyder and Maddox (1978) and Baggen (1987) asked subjects to search the display for randomly scattered alphanumeric characters and found the task performance to be sensitive to changing image quality. An important consideration in the use of this task is that it requires a fairly simple, low level of information processing. Perhaps the most positive characteristic of the random search task for the present research is its similarity to real-world VDT tasks such as word processing and data entry.

Reading task. To provide information on a range of cognitive processing, another performance task has been used along with the search task. Since reading requires a higher level of information processing than a search task, a task which measured speed of reading has been used. A modified Tinker Speed of Reading Test (Tinker, 1963) that previously had been used to assess the legibility of different typographies of printed text was adapted and explored in electronic display image quality evaluations (Baggen, 1987; Hunter, 1988; Snyder and Maddox, 1978). The Tinker Speed of Reading Test is composed of short passages constructed to be very simple, eliminating reading comprehension as a factor in reading speed. The subject is instructed to read the passage as quickly as possible, pointing out the one word in the paragraph that is clearly out of context. An example of a passage is shown below. (The target word is underlined.)

> Mary worked several hours every day to earn the
> money to buy herself a shiny new red bicycle.
> Finally the day came when she had earned the
> money she needed to buy her new puppy.

When the individual's reading time is subtracted from a baseline reading time per passage, a differential reading speed is obtained. It seems logical that degradations or enhancements in the quality of the displayed information due to introduction of anti-glare treatments would be reflected in corresponding reading speed variations.

Perceived image quality. The individual's perception of the displayed information could be considered a high level of processing complexity. Asking an observer's impression or rating of the quality of some displayed image requires that observer to consider many factors before making his or her response (e.g., previous experience with displays and which display aspects are considered by the individual to be most important). Many studies have investigated this issue, but those most appropriate for the present application have been reported by Beaton et al. (1985) and Hunter et al. (1987). Both studies employed a number of different methods by which the perceived image quality of anti-glare treatments was measured, finding fairly high agreement among them. Typical psychophysical measures such as paired comparisons, rating scales, magnitude estimation, and rank ordering all yielded fairly similar results, indicating that observers are very capable of differentiating among anti-glare treatments, regardless of the dependent measure employed. This high correlation among the different data collection methods allows the researcher to use the method that seems most appropriate for a particular application.

The ease of data collection found with rating scales makes them an attractive candidate for complex experimental designs. An 11-point scale that ranges from "worst imaginable" to "best imaginable" has been shown by Beaton et al. (1985) to correlate with changes in measured image quality. The use of this scale was expected to facilitate data collection, requiring a minimum number of repeated presentations of the displayed image within each CRT treatment condition.

## CURRENT RESEARCH AND OBJECTIVES

The Panel on Impact of Video Viewing on Vision of Workers of the Committee on Vision (National Research Council, 1983) recommended that research be conducted to determine the effects of workplace illumination, glare, and VDT design. The Working Group on Aging Workers and Visual Impairment of the Committee on Vision (National Research Council, 1987) recommended that research be performed which can isolate the effects of age on the human visual system as they relate to particular visual tasks performed in the work environment. Since the number of workers over the age of 40 years is expected to increase in the future, and since a large percentage of these workers will occupy white collar positions, it is important that the effects of the changing visual system in interaction with the VDT are understood. The National Research Council (1983) report stated,

> "Since VDT workers often include older workers and workers having some visually limited capability, it is particularly critical that research be conducted with stratified subject populations that include those representative of typical VDT workers." (p. 74).

The information obtained from this type of research will aid in the design of work stations for all users. A combination of the research needs specified in each of the National Research Council reports will provide performance information on the interaction of the elderly user with VDT systems.

In a related research project preceding the current research, Hunter (1988) examined the relationships among VDT optical measures (image quality, noise, and signal-to-noise ratios), human performance measures, and perceived image quality under various lighting, resolution, and filter conditions. His research goal was to use regression equations to develop mathematical models to be used for predicting performance under specified viewing conditions.

Eight subjects (4 males and 4 females) between the ages of 18 and 25 participated in Hunter's study. The design, shown in Figure 1, was a 3 x 2 x 16 factorial with lighting at 3 levels, resolution at 2 levels, and filters at 16 levels. The three levels of lighting were dark (used as a baseline level), diffuse, and specular. The two levels of resolution were high (character stroke width was 1 pixel wide and subtended a visual angle of 16.1 arcmin) and low (character stroke width was 2 pixels wide and subtended a visual angle of 32.2 arcmin). The filter levels are specified below. Each of the filter types is described by three factors: (1) surface type, either polished or etched (the degree of etch specified with the numerical designation 25, 45, or 65); (2) transmissivity

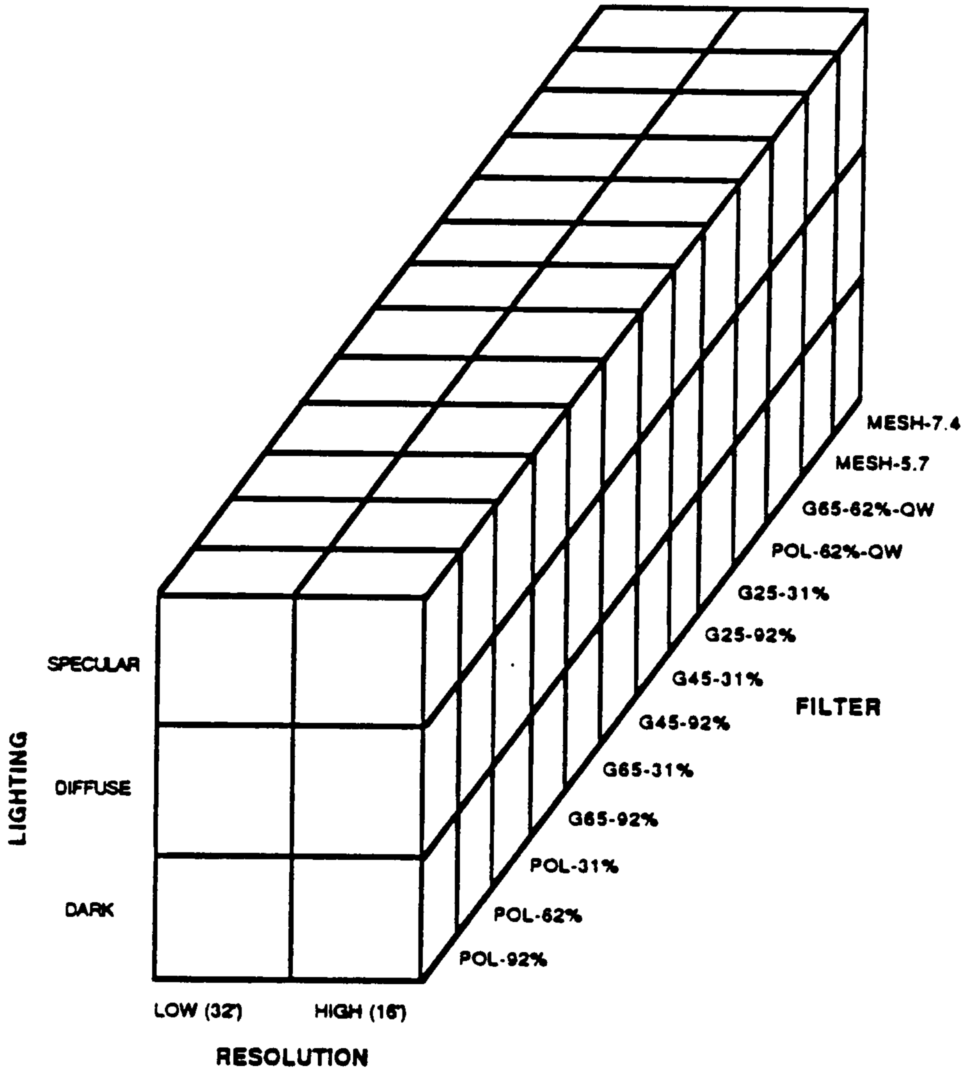


Figure 1. Experimental design used by Hunter (1988).

(either 31%, 62%, or 92%); and (3) whether or not the filter has an HEA (quarterwave) coating.

| | Surface Type | Transmissivity | Coating |
|---|---|---|---|
| 1. | Polished | 92% | |
| 2. | Polished | 62% | |
| 3. | Polished | 31% | |
| 4. | Gloss 65 | 92% | |
| 5. | Gloss 65 | 62% | |
| 6. | Gloss 65 | 31% | |
| 7. | Gloss 45 | 92% | |
| 8. | Gloss 45 | 62% | |
| 9. | Gloss 45 | 31% | |
| 10. | Gloss 25 | 92% | |
| 11. | Gloss 25 | 62% | |
| 12. | Gloss 25 | 31% | |
| 13. | Polished | 62% | HEA |
| 14. | Gloss 65 | 62% | HEA |
| 15 | Mesh 5.7 | 92% | |
| 16 | Mesh 7.4 | 92% | |

The present research, although directly related to Hunter's study in terms of experimental design and equipment, has some important differences. These differences are in three areas; purpose, subject population, and CRT treatment levels. The intent of Hunter's study was to develop prediction models using performance data, subjective ratings, and physical measurements of the CRT. Hunter's data were collected on subjects between the ages of 18 and 29 years of age (mean age 19). This limited population was appropriate for Hunter because he was interested in modeling the young, healthy population of VDT users. The present dissertation is concerned with determining the effects of age on VDT performance. Five age levels are included: 18-29, 30-39, 40-49, 50-59, and 60-69. The data for Group I (18 to 29 years of age) in the present study were taken directly from Hunter's study.

The second difference between these two studies involves the number of filter levels included. The results of Hunter's study indicated that some filters showed no performance effects. For the present study it was determined that if the young healthy subjects could detect no differences between these filters, then the older subjects, who were less likely to detect differences due to visual degradation, would show no differences. Therefore, seven filters were included in the present study on the basis of these results and in an attempt to include filters which would afford a good range for comparison. These are listed below:

| | Surface Type | Transmissivity | Coating |
|---|---|---|---|
| 1. | Polished | 92% | |
| 2. | Polished | 62% | |
| 3. | Polished | 31% | |
| 8. | Gloss45 | 62% | |
| 11. | Gloss25 | 62% | |
| 13. | Polished | 62% | HEA |
| 16 | Mesh 7.4 | 92% | |

## Hypotheses

The objective of this study is to determine the effects of age on performance of typical VDT tasks. Due to the degradation in the general visual system, especially resistance to glare, it was expected that group task completion times would increase with age, particularly over the age of 40 years, for each of the independent variables. The expected interactions of age with these variables are detailed below.

Lighting. It was expected that there would be a significant effect for the age by lighting interaction with completion times being longer for the older age groups. This effect would change with lighting, thereby resulting in the shortest performance times for dark lighting, since no glare would be present, and with specular glare associated with the longest times. It was expected that glare due to specular sources would be a larger problem than contrast reduction resulting from diffuse glare sources.

Resolution. It was expected that the older subjects would require a longer time to read or detect the high resolution characters. These characters require the observer to resolve fine, high spatial frequency information. The size of the characters alone would require resolution of spatial detail of 16 arcmin (high resolution) rather than 32 arcmin (low resolution).

Filter. It was expected that the older subjects would have the shortest completion times with the quarterwave and mesh filters, due to their glare reduction and contrast enhancement properties, and the longest times with the Gloss25 filter, due to reduced character sharpness. It was expected that all subjects would have longer completion times for the Gloss25 filter in the high resolution condition; however, the older age groups would have progressively longer completion times. This was expected as a result of the combination of reduced glare resistance and reduced contrast sensitivity experienced with age.

# METHOD

## Subjects

The subjects were 30 volunteers (15 males and 15 females) obtained through advertisements in the Virginia Tech and local town newspapers. All subjects were tested for 20/20 near and far acuity, normal lateral and vertical phoria, and color vision using a Bausch & Lomb Orthorater. They were also tested for normal near and far contrast sensitivity using a Vistech Consultants Inc. test system. No subjects were included with any known visual disease (particularly cataract and glaucoma), determined through verbal questioning. Subjects were allowed to wear corrective lenses if these were not photosensitive or tinted.

Hunter (1988) tested eight subjects, using the same criteria, within the age range of 18 to 29 years. Since the current study used only six subjects within each age group, the data from six of Hunter's subjects (three male, three female) were randomly chosen for the 18-29 year age group of the present study.

## Design

The experimental design is shown in Figure 2. The study used a 2 x 5 x 7 x 3 x 2 (Gender x Age x Filter x Lighting x Resolution) factorial design. The two blocking variables were age (18-29, 30-39, 40-49, 50-59, and 60-69), and gender. The three within-subject variables were Filter (Polished/92%, Polished/62%, Polished/31%, Gloss45/62%, Gloss25/62%, Quarter Wave/62%, Mesh/92%), Lighting (dark, diffuse, and specular), and Resolution at high (16.1 arcmin) and low (32.2 arcmin).

## Apparatus

Imaging system. A single 50-cm diagonal monochrome P-4 phosphor Video Monitors Inc. CRT (E-M2400-155) was used for testing, thereby eliminating inter-CRT variability. The monitor was used at 1024 x 1024 pixel addressability , non-interlaced, and 60 Hz. The use of a single CRT required that each of the anti-glare treatments be removable from the CRT itself. Each of the various etched panels and the polished baseline glass was clamped to the CRT via an apparatus which allowed easy installation and removal. Because the radius and uniformity of the etched panels could not be matched perfectly to those of the CRT faceplate, small air gaps and their accompanying internal reflections were a potential problem. Using a method developed and described in detail by Hunter (1988), a seal was attached to the front surface of the CRT to hold fluid which was injected in the space

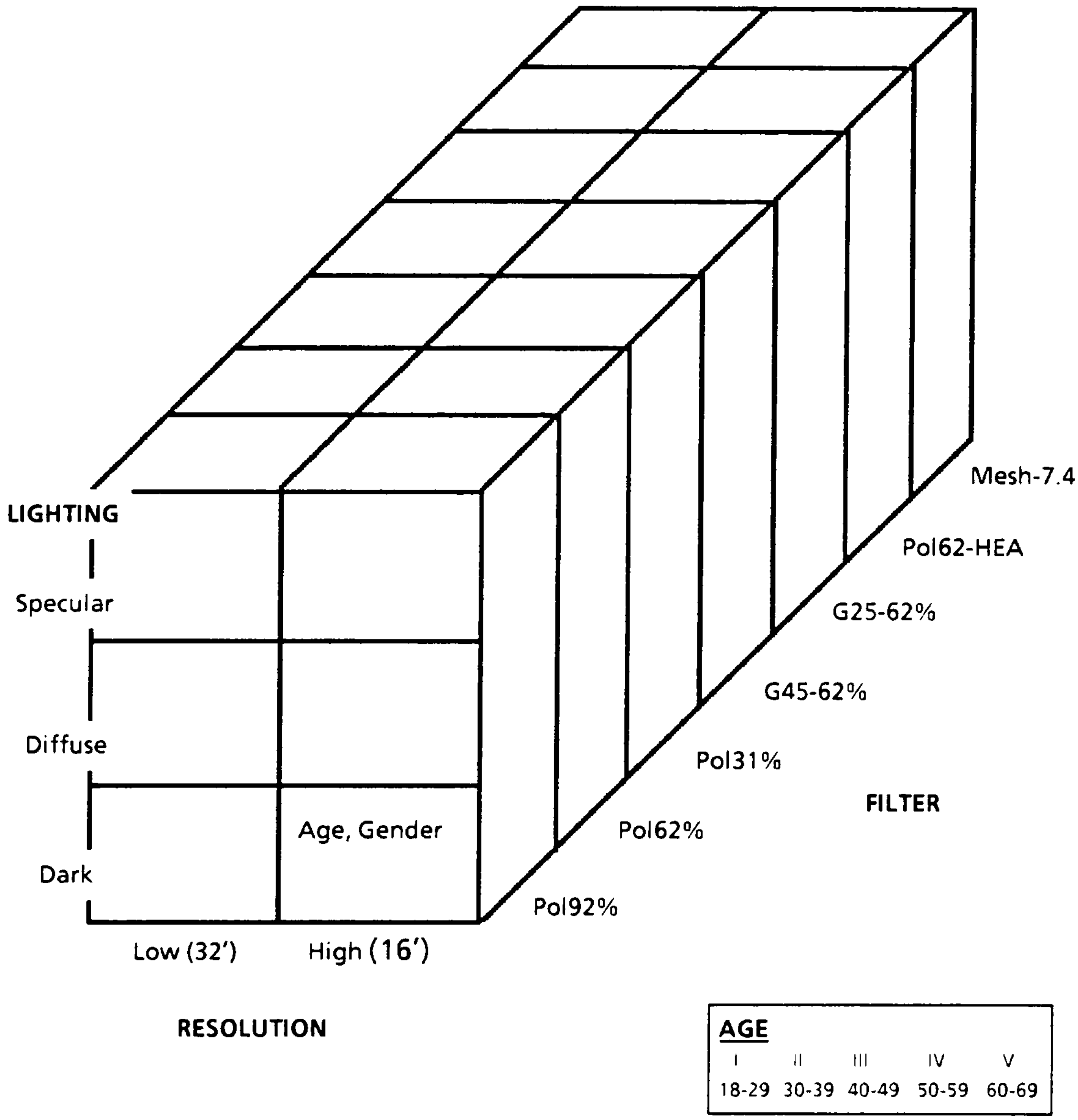


Figure 2. Experimental design.

between the filter and the CRT. Glycerin was the fluid used because its refractive index is almost identical to that of glass (1.427) and, for the purposes of this study, could be considered optically transparent, thus effectively fusing the back surface of the filter treatment to the front surface of the CRT.

All images were produced by a high quality video signal generator, tne OPIX Imager from Quantum Data. The signals produced were low in noise and spatially stable. The OPIX was capable of up to 200-MHz pixel rates with rise/fall times of about 1.8 ns. Primarily a research and testing tool, the OPIX was mated with files from an IBM PC/XT to produce the video signals for the search, reading speed, and perceived image quality characters. The PC was used not only as a storage device for the images to be loaded to the OPIX, but was also used to control the order of presentation of the various experiment conditions through the use of its random number generation facility as well as to record each subject's responses to the tasks.

The CRT was placed on a platform on the table in front of the subject so that the portion of the screen to be viewed was at a height of 132 cm above the floor. The face of the CRT was perpendicular to the table top. Subjects were seated in an office chair adjusted so that the subject's eye height was 117 cm. The subject's viewing angle was approximately +10 deg so the subject could not see his or her own reflection on the face of the CRT. The subject's head was placed against a head rest to maintain the viewing distance of approximately 53 cm and to minimize any head movement.

The face of the CRT was masked by black posterboard to reduce the area of the surface to a rectangular opening (12 cm x 20 cm) in the center of the CRT. The characters produced on the CRT were 7 x 9 Huddleston font characters. At the viewing distance of 53 cm, the characters subtenaed an angle at the eye of 16.1 arcmin vertically for the high resolution case and 32.2 arcmin vertically for the low resolution characters. Figure 3 shows the character structure for both resolution levels. The DC grid voltage of the CRT was varied between resolution conditions to produce different spot sizes. The minimum displayable spot size (best focus) in the high resolution case had a half-amplitude width of approximately 0.40 mm. The low resolution spot was defocused, resulting in a half-amplitude width approximately twice that of the high resolution spot, or 0.80 mm. The center-to-center spacing of the dots was 0.27 mm for the high resolution case and 0.54 mm for low. Thus, the dots in both resolutions overlapped sufficiently so that no dot structure was visible; i.e., the characters appeared as stroke characters.

All surfaces within the viewing area of the CRT were covered with non-reflective materials to eliminate any extraneous reflections. Non-reflective curtains were draped on either side of the lights to minimize extraneous sources of light. All other reflective surfaces in the subject's field of view were covered with black tape.

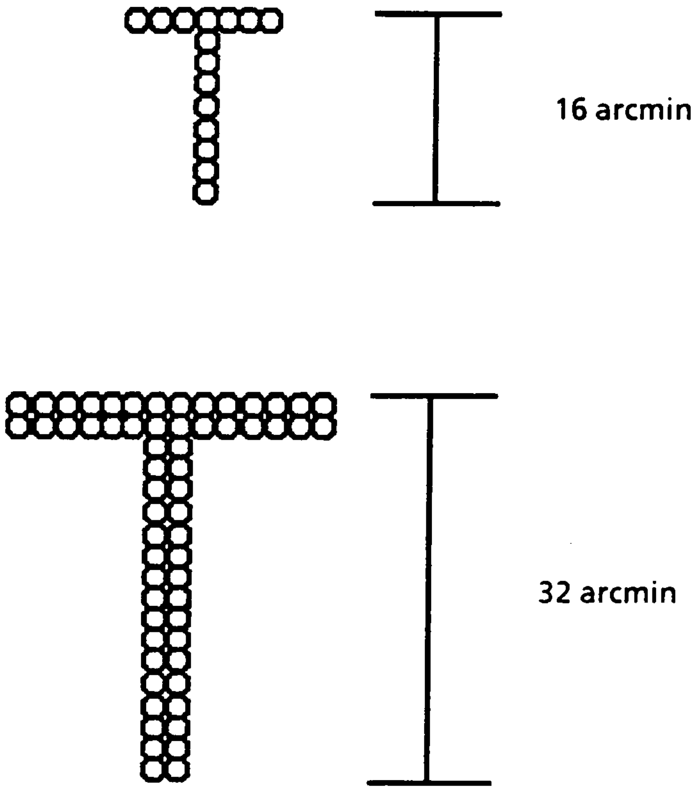


Figure 3. Character pixel makeup and angle subtended at the eye for a viewing distance of 53 cm (adapted from Hunter, 1988).

Since the subjects between the ages of 30 and 69 were expected to be involved in career activities, an attempt was made to minimize data collection time by eliminating any filters that produced no effect in Hunter's (1988) study. While Hunter included three levels of Gloss--25 (heavy), 45 (moderate), and 65 (light)--no performance differences were observed between the Polished and Gloss65 filters; therefore, only the Gloss45 and Gloss25 were included. The same process was used to eliminate eight other filters used by Hunter and not included in this study. If no effect was observed among filters for the young, healthy subjects, it was expected that no effect would be observed for the older subjects with reduced visual abilities.

Anti-glare filters. Seven anti-glare filters were used in this study. These included the following, in which the number after the slash indicates the transmissivity of the filter:

Polished / 92%
Polished / 62%
Polished / 31%
Gloss45 / 62%
Gloss25 / 62%
Quarterwave / 62%
Micromesh-7.4 / 92%

Although some of the filters were produced specifically for Hunter's study (POL92, POL62, POL31, G45, G25), all filters are fairly typical of those found in common usage. The MESH filter, produced by Sunflex (CD-44), had a spatial frequency of 7.4 lines/mm. The quarterwave filter was produced by Optical Coating Laboratories, Inc. The seven filters covered a wide range of commercially available anti-glare surface treatments for CRTs. Surface etch was represented by what could be considered a continuum ranging from no etch (the polished filters) to heavy etch (Gloss 25). Another interesting aspect of the filters included in the study was production cost, ranging from expensive ($100 to $200) for the HEA or similar coating to fairly inexpensive (less than $25) for the MESH.

All panels used were single panel combining both the coating or etch and the transmissivity characteristics, except the MESH filter, which was used in combination with a POL92 filter to allow comparison with the POL92 control condition. Using the HEA-62% allowed comparison with the POL62 control condition as well as the two gloss filters, both at 62% transmissivity.

Lighting. Two 122-cm fluorescent light fixtures were used for the diffuse and specular lighting conditions. The four lamps for each fixture were General Electric WattMiser II, 34-watts each with a color temperature of 4200 deg K and maximum single-lamp output of approximately 2750 lumens. Illuminance measured at the face of the CRT was held constant for both lighting conditions at approximately 600 lx.

The diffuse light source consisted of four 34-watt tubes with a Plexiglas diffusion cover. The diffuse condition did not produce any specular reflections on the CRT because of its placement above and slightly to the rear of the subject's head, thus providing indirect lighting.

The specular condition consisted of the four 34-watt tubes, in front of which was placed a 63-mm thick white Plexiglas sheet to control non-uniformities in the light fixture system. The specular light source was placed at approximately head level, to the rear of the subject, producing a reflection on the face of the CRT which was directed back into the subject's eyes. A black curtain was lowered over this light source when not in use to eliminate light from the CRT reflecting off the plexiglass covering back to the CRT.

Subjects were seated in an adjustable office chair on which a head rest had been attached. An eye position of 118 cm from the floor and 53 cm from the CRT was maintained for all subjects by using the hydraulic height adjustment capability of the chair and the mechanical adjustment on the headrest.

Tasks. The subjects had three tasks to perform, the modified Tinker reading task, the random search task, and the image quality rating task. The presentation orders for the Tinker passages were based on a random order created prior to data collection using the random number generator on the

PC. There were a total of 480 Tinker passages from which each subject was randomly assigned 390. There were an additional 20 passages used for practice trials which were not included in actual testing. Each passage was composed of four lines (a total of two sentences) with a word in the second sentence that was obviously out of context with the rest of the passage. Each line had a maximum width of 44 characters. The presentation orders for lighting conditions, resolution levels, and filter types were counterbalanced for all subjects to minimize any possible carry-over effects.

The Search task required the subject to search a random array of 54 alphabetic characters (both upper and lower case) presented in the center of the display.

The rating task for each filter required the subject to view eight lines of text displayed on the screen in each of the lighting x resolution conditions. The subject verbally rated the image quality using one of the following adjectives:

BEST IMAGINABLE
EXCELLENT
GOOD
OK
PASSABLE
MARGINAL
POOR
AWFUL
WORST IMAGINABLE

## Procedure

Upon completion of the vision screening, the subject was given a general overview of the experiment to read and an informed consent form to sign (required by the Internal Review Board of the University). The subject was seated in the experimental chair in front of the CRT and allowed to adapt to the environment for approximately five minutes. The experimental workstation is illustrated in Figure 4. Chair adjustments were made during this adaptation period to fix the subject's viewing angle and distance as specified above.

After completing the subjective rating for all lighting and resolution conditions, the subject was given a set of instructions for the first task (either reading or search, depending on the subject's presentation order). For the reading task the subject was instructed to place his or her hand on the mouse and to press and hold down the center button when ready for the task to begin. When the button was pressed the passage appeared on the screen. The subject read the four lines of text and determined the word that was out of context with the rest of the passage. When the the word was chosen, the mouse button was released. Releasing the button simultaneously stopped the timer and caused a pattern (one pixel on, one pixel off) to be displayed on the screen. This pattern was intended to mask any after-images resulting from the characters previously presented.

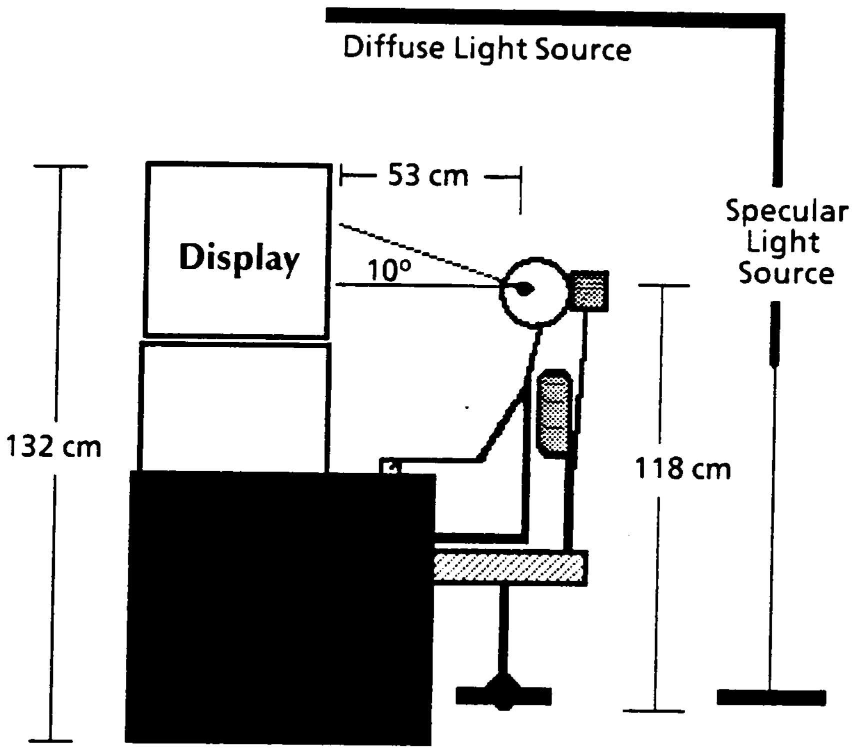


Figure 4. Experimental workstation.

For the random search task the subject was instructed to press the center button on the mouse when ready to begin. A random array of 52 characters was presented with an underlined target character located at the top center position of the screen. The subject was instructed to hold down the mouse button until the target character was located. Releasing the button stopped the timer and replaced the character array with the masking grid pattern described above.

The training procedure was the same for both tasks. After reading the instructions and asking any questions, the subject was given five practice trials. If, at the completion of the five trials, the subject felt the need for more practice, more trials could have been given; however, due to the relatively simple nature of the tasks, no extra practice was requested. After the training session on the first day, no further training was necessary. The same tasks were repeated for each of the seven filters tested, requiring approximately one hour per filter. Upon completion of data collection for the seven filters the subjects were verbally debriefed and paid for their participation.

## Performance Measures

Reading task. The performance measure for the reading task was completion time measured from the time the subject depressed the mouse button to the time the subject released the button. This time was recorded directly to disk in the IBM PC/XT. Error data were typed into the computer and saved with the time data.

Search time. Search completion time and errors were measured in the same manner as for reading time.

Image quality rating. Subjects verbally reported the image quality rating for filter within each experimental condition. The experimenter manually recorded the number corresponding to the adjective list previously shown (1 = "worst imaginable"; 9 = "best).

# RESULTS AND DISCUSSION

The data for each of the dependent measures (Reading time, Search time, and Image Quality rating) were analyzed separately. The analyses consisted of analyses of variance (ANOVA), followed by simple effect F-tests on any significant interaction effects obtained from the ANOVA, and Newman-Keuls multiple comparisons. The results are presented separately for each dependent measure.

## Reading Task

Reading time data (RT) were analyzed with a 5 x 2 x 7 x 3 x 2 (Age x Gender x Filter x Lighting x Resolution) mixed within- and between-subjects repeated measures ANOVA. Each subject provided five responses for each Filter x Lighting x Resolution condition. Prior to analysis the five scores were combined to produce a mean score for each Filter x Lighting x Resolution condition resulting in 42 scores per subject. These 42 mean scores were analyzed using ANOVA with the Statistical Analysis System (SAS). The results are shown in Table 2.

Table 2 shows that all main effects except gender were statistically significant ($p < .05$). These will be presented and discussed followed by the significant 3-way interaction effects, A x F x L and F x L x R. Although a significant four-way interaction (A x F x L x R ) was obtained, it will not be considered due to the difficulty in interpreting an interaction of this order of magnitude.

Age. The analysis of age showed differences in reading time between groups (Figure 6.). A Newman-Keuls analysis was conducted on these data (Table 3) and showed that reading times for the age 18-29 group were faster than those for the age 40-49 and age 60-69 groups, but not faster than those for the 50-59 group.

The Age factor for the RT data showed a fairly linear increase for each Age group except the 50-59 year group. In looking into the background of the members of this particular group, they appeared to be a group of highly educated, professional working people. A transformation was performed on these data which normalized them to a baseline factor (Polished-92%, dark lighting, high resolution). The baseline score for each subject was subtracted from each of his or her 42 scores. This new data set was analyzed using an analysis of variance which resulted in the factor of Age no longer being significant, thus indicating that the faster RTs for the 50-59 year age group were due to the initially faster reading times for this group.

TABLE 2

Analysis of Variance Summary for Reading Time

| SOURCE | df | MS | F | p |
|---|---|---|---|---|
| BETWEEN SUBJECT | | | | |
| Age (A) | 4 | 4575155.16 | 4.56 | 0.0089 |
| Gender (G) | 1 | 1940123.70 | 1.93 | 0.1797 |
| A x G | 4 | 877053.86 | 0.89 | 0.4860 |
| S\|G,A | 20 | 1003778.92 | | |
| WITHIN SUBJECT | | | | |
| Filter (F) | 6 | 119731.82 | 4.68 | 0.0003 |
| Lighting (L) | 2 | 739609.42 | 33.79 | 0.0001 |
| Resolution (R) | 1 | 3577490.96 | 48.28 | 0.0001 |
| F x L | 12 | 86464.44 | 7.70 | 0.0001 |
| F x R | 6 | 77515.05 | 5.04 | 0.0001 |
| L x R | 2 | 322618.63 | 16.20 | 0.0001 |
| F x L x R | 12 | 48720.37 | 4.13 | 0.0001 |
| A x F | 24 | 36595.94 | 1.43 | 0.1066 |
| A x L | 8 | 63416.95 | 2.90 | 0.0121 |
| A x R | 4 | 126934.29 | 1.71 | 0.1867 |
| A x F x L | 48 | 17328.67 | 1.54 | 0.0188 |
| A x F x R | 24 | 18716.09 | 1.22 | 0.2405 |
| A x L x R | 8 | 24604.56 | 1.24 | 0.3042 |
| A x F x L x R | 48 | 17821.36 | 1.53 | 0.0243 |
| G x F | 6 | 30632.05 | 1.20 | 0.3118 |
| G x L | 2 | 6910.57 | 0.32 | 0.7311 |
| G x R | 1 | 3970.68 | 0.05 | 0.8193 |
| G x F x L | 12 | 14702.90 | 1.31 | 0.2134 |
| G x F x R | 6 | 25805.76 | 1.68 | 0.1318 |
| G x L x R | 2 | 1801.88 | 0.09 | 0.9137 |
| G x F x L x R | 12 | 8298.46 | 0.70 | 0.7480 |
| A x G x F | 24 | 35881.72 | 1.40 | 0.1194 |
| A x G x L | 8 | 42871.71 | 1.96 | 0.0775 |
| A x G x R | 4 | 97239.68 | 1.31 | 0.2994 |
| A x G x F x L | 48 | 11620.40 | 1.04 | 0.4191 |
| A x G x F x R | 24 | 22566.60 | 1.47 | 0.0916 |
| A x G x L x R | 8 | 24491.42 | 1.23 | 0.3072 |
| A x G x F x L x R | 48 | 16490.65 | 1.40 | 0.0552 |
| F x S\|G,A | 120 | 25559.92 | | |
| L x S\|G,A | 40 | 21888.35 | | |
| R x S\|G,A | 20 | 74105.11 | | |
| F x L x S\|G,A | 240 | 11226.65 | | |
| F x R x S\|G,A | 120 | 15367.23 | | |
| L x R x S\|G,A | 40 | 19913.87 | | |
| F x L x R x S\|G,A | 240 | 11804.64 | | |
| Total | 1259 | | | |

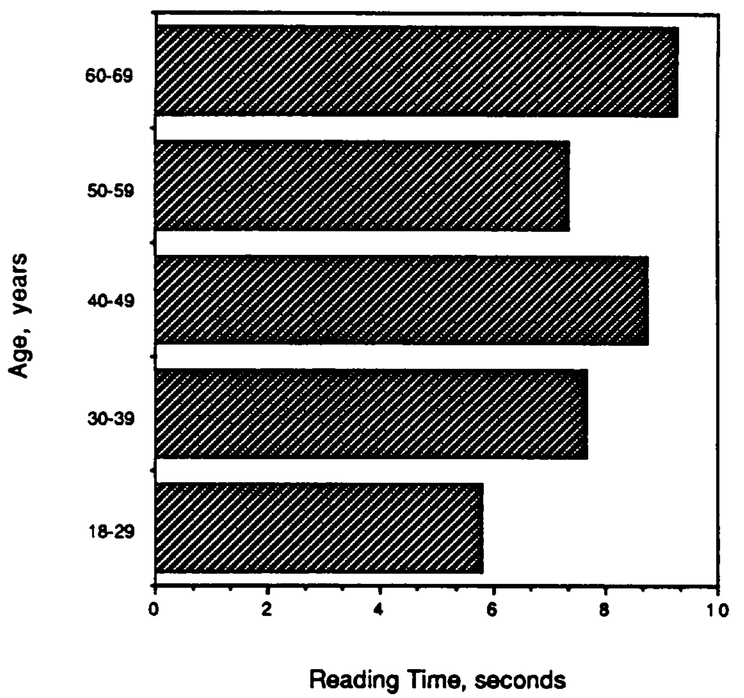


Figure 5. Effect of age on reading time.

Table 3

Newman-Keuls Comparisons of Reading Times for Age

| Age | Mean RT (s) | | | |
|---|---|---|---|---|
| 18-29 | 5.82 | A | | |
| 50-59 | 7.33 | A | B | |
| 30-39 | 7.67 | A | B | |
| 40-49 | 8.75 | | B | C |
| 60-69 | 9.28 | | B | C |

Note: Means with the same letter are not significantly different, $p > .01$.

Filter. The means for each filter are shown in Figure 8. A Newman-Keuls analysis was performed on these data and is shown in Table 4. As can be seen in this table, the reading times for Pol31 and Gloss45 filters were significantly slower than for both Pol92 and Pol62-HEA.

Lighting. Reading times were found to be significantly different among lighting conditions (see Figure 9). A Newman-Keuls analysis is shown in Table 5. Comparisons of means showed reading times for diffuse lighting (7.3 s) to be significantly shorter than either of the other conditions (7.7 s for dark and 8.1 s for specular), but the latter two were not different from each other.

Resolution. The reading times were shorter for the low resolution characters subtending a visual angle of 32 arcmin (7.2 s) than for the high resolution characters, subtending a visual angle of 16 arcmin (8.3 s). This effect is shown in Figure 10.

The discussion of the interactions will begin with the three-way interactions. These will be further reduced to the two-way interactions of interest.

Age by Filter by Lighting. This significant three-way interaction was further analyzed using a simple effects test to localize the significant effects. The results of this test for Filter at each of the A x L combinations are shown

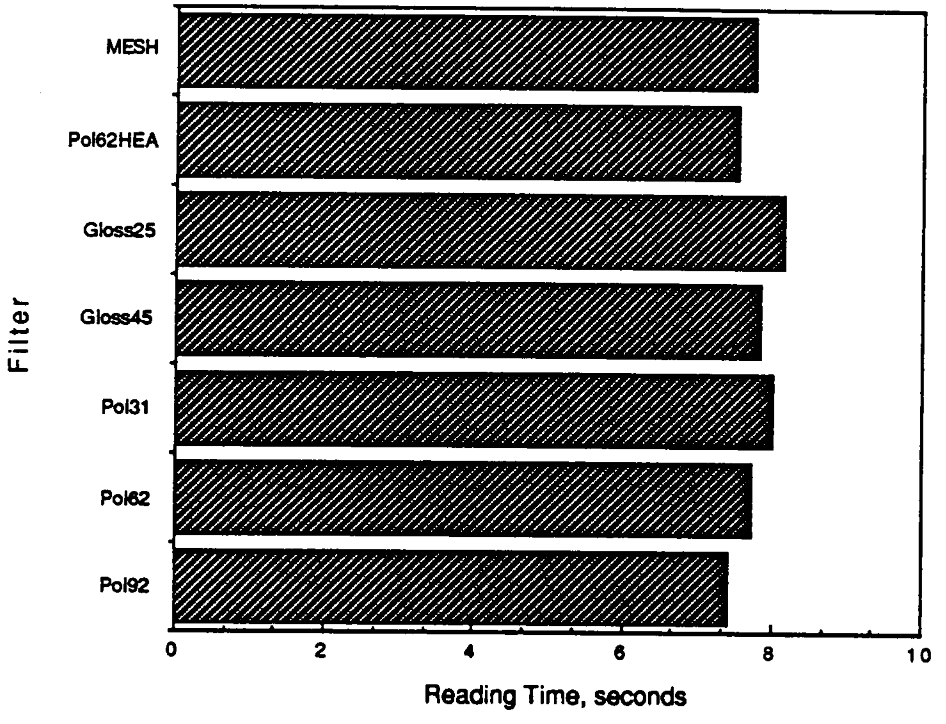


Figure 6. Effect of filter on reading time.

Table 4

Newman-Keuls Comparisons of Reading Times for Filter

| Filter | Mean RT (s) | | | |
|---|---|---|---|---|
| Pol92 | 7.41 | A | | |
| Pol62-HEA | 7.52 | A | | |
| Pol62 | 7.72 | A | B | |
| Mesh | 7.74 | A | B | |
| Gloss45 | 7.84 | A | B | |
| Pol31 | 8.01 | | B | C |
| Gloss25 | 8.15 | | B | C |

Note: Means with the same letter are not significantly different, $p > .05$.

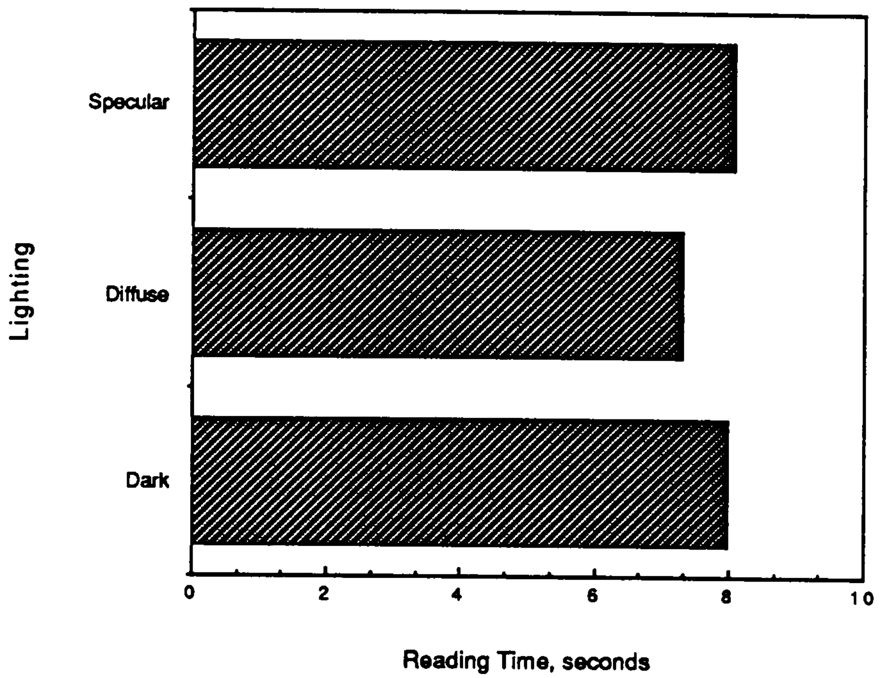


Figure 7. Effect of lighting on reading time.

Table 5

Newman-Keuls Comparisons of Reading Times for Lighting

| Filter | Mean RT (s) | | |
|---|---|---|---|
| Diffuse | 7.29 | A | |
| Dark | 7.97 | | B |
| Specular | 8.05 | | B |

Note: Means with the same letter are not significantly different, $p > .05$.

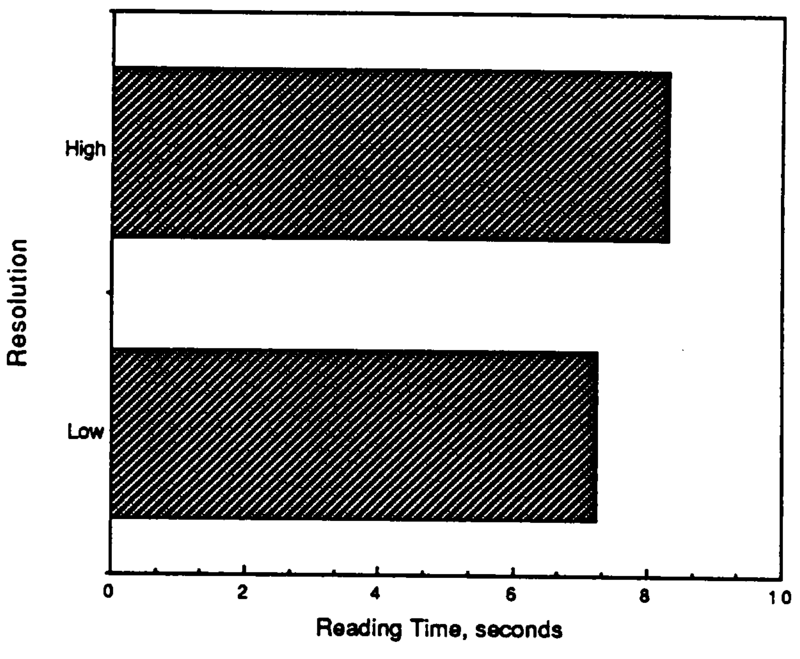


Figure 8. Effect of resolution on reading time.

in Table 6. For each of the three oldest age groups significant effects were observed for Filter within the specular lighting condition. These effects can be seen in Figures 11 through 13. In addition, an effect for diffuse lighting was observed for the 60-69 year group. Newman-Keuls analyses performed on these results are shown in Tables 7 through 9.

For the 40-49 year group, RTs for the Pol62-HEA filter were faster than for Pol31 and the two Gloss filters. In fact, performance with the Gloss25 filter was significantly slower than with all other filters, and performance with Gloss45 was significantly slower than with Pol62-HEA and Pol92. These results are similar to the main effect for Filter. One interesting difference with this interaction was that the two etched filters were associated with the slowest RTs, but the quarterwave filter and the Pol92 with fastest RTs. This result is consistent with previous findings (Hunter, 1988) showing that specular light incident on etched surfaces reduces contrast by creating a veil of light across the surface of the CRT as well as reducing the sharpness of the displayed images. The quarterwave filter appears to be effective in reducing specular glare at the surface of the filter.

Under specular lighting, the 50-59 year group showed performance differences among filters with performance for the Pol31 filter being slower than all other filters. Performance for the Gloss25 filter was slower than for Pol62-HEA, Mesh, and Pol62. For the 50-59 age group the three filters associated with quicker RTs were the quarterwave filter again, followed by

TABLE 6

Simple-Effect F-Tests of Reading Times for Filter under Age by Lighting Combinations

| Conditions | df | MS | F |
|---|---|---|---|
| Age (18-28), Dark | 6 | 32948.89 | 2.96 |
| Age (18-28), Diffuse | 6 | 19853.49 | 1.78 |
| Age (18-28), Specular | 6 | 17775.66 | 1.60 |
| Age (30-39), Dark | 6 | 5260.40 | 0.47 |
| Age (30-39), Diffuse | 6 | 1479.59 | 0.13 |
| Age (30-39), Specular | 6 | 22107.73 | 1.99 |
| Age (40-49), Dark | 6 | 22080.91 | 1.98 |
| Age (40-49), Diffuse | 6 | 17500.94 | 1.57 |
| Age (40-49), Specular | 6 | 127715.84 | 11.47** |
| Age (50-59), Dark | 6 | 23038.48 | 2.07 |
| Age (50-59), Diffuse | 6 | 5107.06 | 0.46 |
| Age (50-59), Specular | 6 | 123168.67 | 11.07** |
| Age (60-69), Dark | 6 | 22615.12 | 2.03 |
| Age (60-69), Diffuse | 6 | 37701.27 | 3.39* |
| Age (60-69), Specular | 6 | 98292.04 | 8.83** |
| F x L x S \| G,A | 240 | 11130.22 | |

* $p<.05$
** $p<.01$

Table 7

Newman-Keuls Comparisons of Reading Times for Filters: Age 40-49 and Specular Lighting

| Filter | Mean RT (s) | | | | |
|---|---|---|---|---|---|
| Pol62-HEA | 7.99 | A | | | |
| Pol92 | 8.49 | A | B | | |
| Mesh | 8.82 | A | B | C | |
| Pol62 | 8.83 | A | B | C | |
| Pol31 | 9.55 | | B | C | |
| Gloss45 | 9.91 | | | C | |
| Gloss25 | 11.07 | | | | D |

Note: Means with the same letter are not significantly different, $p > .01$.

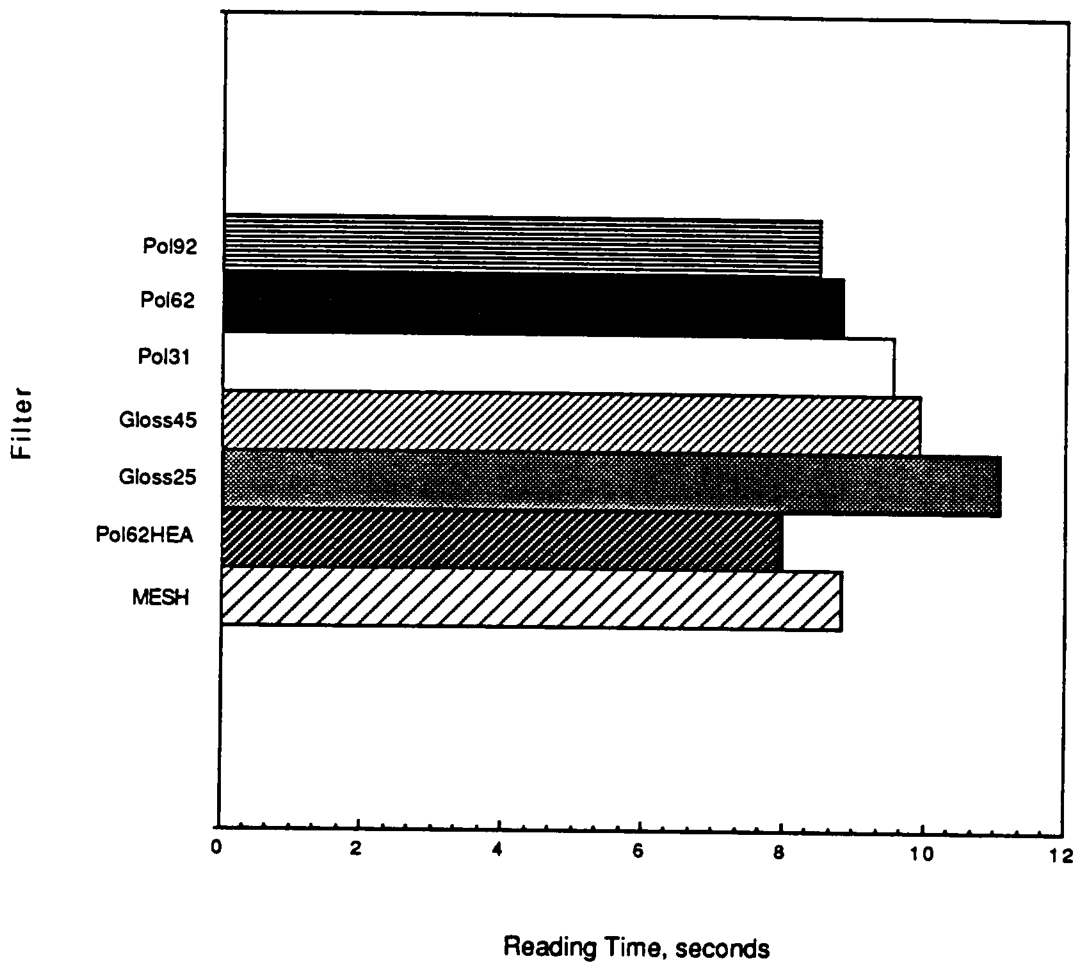


Figure 9. Effect of filter on reading time under specular lighting for the 40-49 age group.

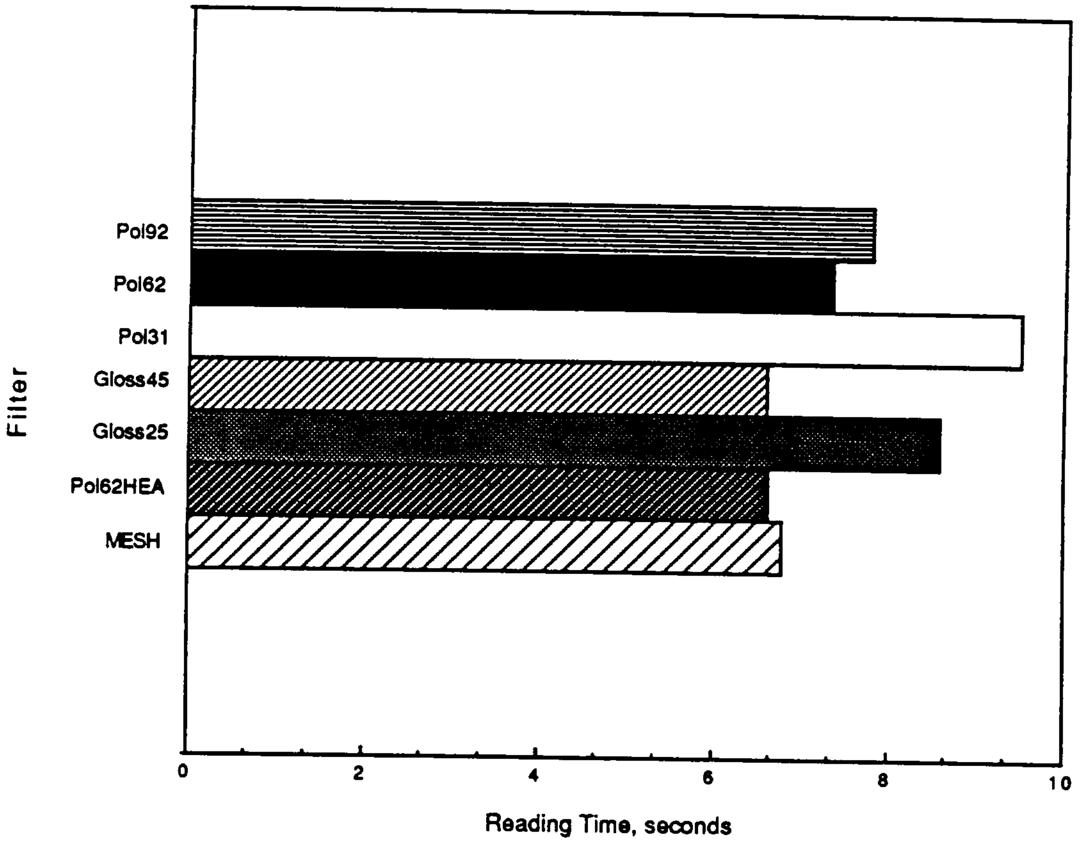


Figure 10. Effect of filter on reading time under specular lighting for the 50-59 age group.

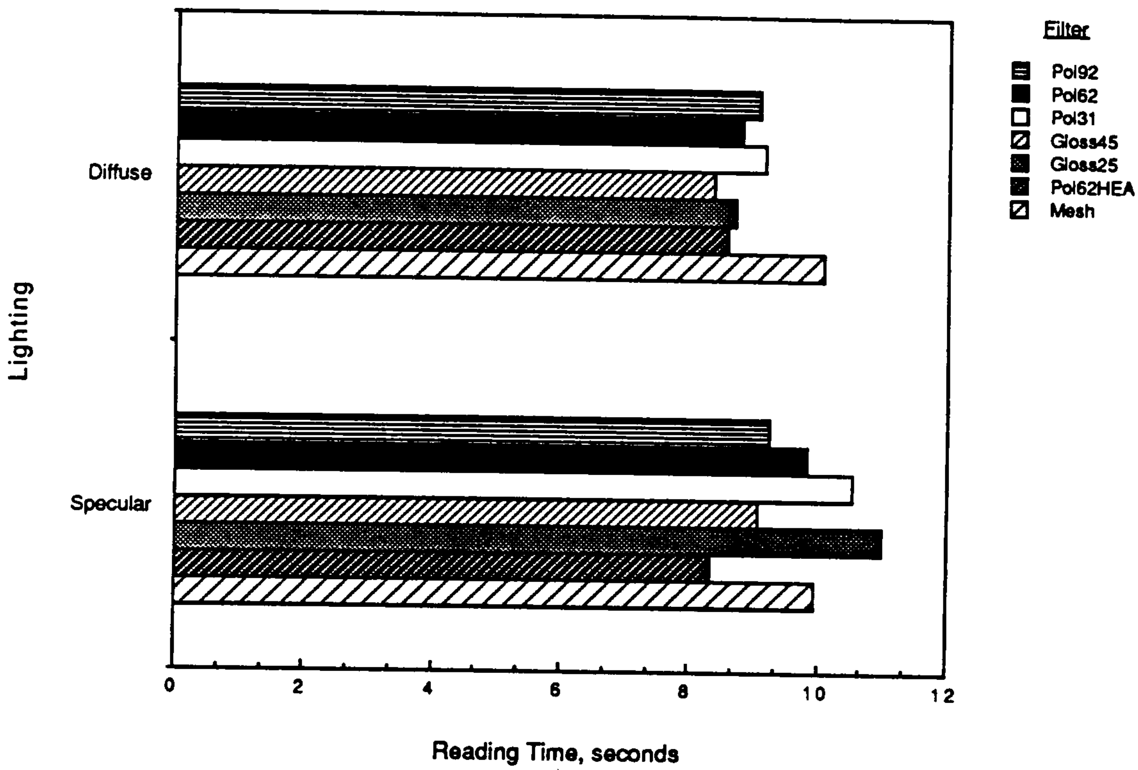


Figure 11. Effect of filter on reading time under specular and diffuse lighting for the 60-69 age group.

Table 8

Newman-Keuls Comparisons of Reading Times for Filters: Age 50-59 and Specular Lighting

| Filter | Mean RT (s) | | | |
|---|---|---|---|---|
| Pol62-HEA | 6.64 | A | | |
| Mesh | 6.80 | A | | |
| Pol62 | 7.36 | A | | |
| Gloss45 | 6.62 | A | B | |
| Pol92 | 7.80 | A | B | |
| Gloss25 | 8.60 | | B | |
| Pol31 | 9.52 | | | C |

Note: Means with the same letter are not significantly different, $p > .01$.

Mesh, and Pol62. The slowest RTs were for the Gloss25 and Pol31. As with the previous age group, the harshest etch produced slow RTs, but the slowest RTs in this case were associated with the Pol31. The low transmission for this filter reduces incident light once as it passes through the filter coming in and again as the light is reflected off of the phosphor surface and back out into the user's eye. The displayed information is only filtered once. This alone might effectively enhance contrast were it not for the specular glare reflected by the front surface of the filter, which can produce a bright spot at the display that reduces the contrast of displayed characters or masks them altogether.

Under the same lighting condition the 60-69 year group showed performance for the Gloss25 filter to be slower than for all but Pol31 (Table 9). Pol31 performance was slower than Pol62-HEA, Gloss45, and Pol92. Although performance with the Pol62-HEA filter was fastest, it was only significantly faster than Pol62, Mesh, Pol31, and Gloss25. The fastest performance was with the quarterwave, as was the case with the other age groups; however, the 60-69 group's next fastest performance was with the Gloss45 filter, then Pol92. People in this age group, according to research discussed earlier, are more susceptible to glare than are younger groups, which may account for the faster RTs associated with the Gloss45 filter. Since this is a moderately etched filter, it spreads the specular glare across the surface of the filter, reducing the glare directed back into the observer's eye. The displayed image will also be affected by the etch, although, since this is a

Table 9

Newman-Keuls Comparisons of Reading Times for Filters: Age 60-69 and Specular Lighting

| Filter | Mean RT (s) | | | | |
|---|---|---|---|---|---|
| Pol62-HEA | 8.34 | A | | | |
| Gloss45 | 9.06 | A | B | | |
| Pol92 | 9.25 | A | B | | |
| Pol62 | 9.82 | | B | C | |
| Mesh | 9.95 | | B | C | |
| Pol31 | 10.54 | | | C | D |
| Gloss25 | 10.99 | | | | D |

Note: Means with the same letter are not significantly different, $p > .01$.

moderate etch, this softening of focus may be offset by the reduction in glare experienced by the observer.

Under diffuse lighting the 60-69 year group also showed a significant effect for Filter. The Newman-Keuls analysis results are shown in Table 10. Performance was slower with Mesh than with all other filters. Interestingly, the 60-69 year group had difficulty with the Mesh filter under diffuse lighting. Although not significant, all age groups under this lighting condition showed RTs for Mesh that were as long or longer than RTs for all other filters. All filter groupings for this age group, under diffuse lighting, were different from those for specular lighting. The three filters associated with the fastest RTs were the two etched filters and the quarterwave filter while all three neutral density filters along with the Mesh filter had slower RTs. This seems to indicate that front surface reflections may have been a problem with this lighting condition for this age group. The diffuse light source spreads light across the front of the filter, effectively reducing the contrast of the displayed letters to the background luminance. Another possible explanation is that, since the front surface of the polished filters reflect approximately 4% of the incident light back into the observer's eye, and this age group is reported to be most susceptible to glare, this reflection may mask the displayed characters.

Filter by Lighting by Resolution . Table 11 shows simple effect F-tests for this interaction. As can be seen in the table, the only significant filter effect is

Table 10

Newman-Keuls Comparisons of Reading Times for Filters: Age 60-69 and Diffuse Lighting

| Filter | Mean RT (s) | | |
|---|---|---|---|
| Gloss45 | 8.35 | A | |
| Pol62-HEA | 8.57 | A | |
| Gloss25 | 8.68 | A | |
| Pol62 | 8.79 | A | |
| Pol92 | 9.05 | A | |
| Pol31 | 9.16 | A | |
| Mesh | 10.06 | | B |

Note: Means with the same letter are not significantly different, $p > .01$.

TABLE 11

Simple Effect F-Tests of Reading Times for Filters at Resolution, Lighting Combinations

| Conditions | df | MS | F |
|---|---|---|---|
| Low Res, Dark | 6 | 11257.89 | 0.95 |
| Low Res, Diffuse | 6 | 3537.74 | 0.30 |
| Low Res, Specular | 6 | 17019.24 | 1.44 |
| High Res, Dark | 6 | 26213.89 | 2.22 |
| High Res, Diffuse | 6 | 40630.61 | 3.44 |
| High Res, Specular | 6 | 365252.84 | 30.94* |
| F x L x R x S \| G,A | 240 | 11804.64 | |

* $p < .01$

found with the high resolution characters under specular lighting. This effect is shown in Figure 14. The Newman-Keuls analysis, Table 12, shows that performance with the Pol62-HEA filter was faster than with all other filters. Performance with the two gloss filters and the Pol31 filter were slower than for Pol62-HEA, Mesh, Pol92, and Pol62. In addition, for each Filter,Lighting combination low resolution performance was faster than high resolution.

Once again the quarterwave filter was associated with the fastest RTs. Both etched filters and the lowest transmission neutral density filter showed longest RTs. The filters fell into three general groupings: first, the quarterwave; next the mesh, Pol92, and the Pol62; and finally, the Gloss45, Pol31, and the Gloss25. The quarterwave and the mesh filters have characteristics which allows them to serve both as contrast enhancers and anti-glare filters. The polished filters can cause problems with the specular reflections from the front surface back into the observer's eye. The etched filters can be particularly problematic with high resolution characters because they reduce high spatial frequency information, which is being displayed with the high resolution characters. The low transmission filter, Pol31, may have long RTs due to the specular reflections from the front surface as well as the reduced transmission of the displayed information.

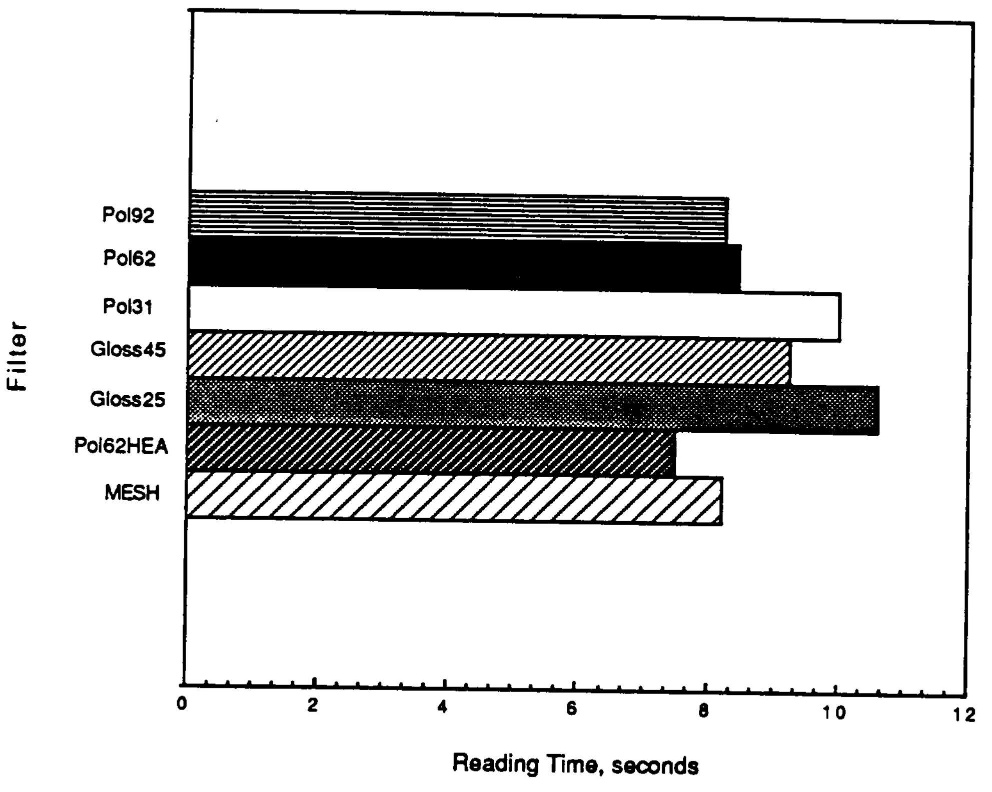


Figure 12. Effect of filter on reading time for specular lighting at high resolution.

Table 12

Newman-Keuls Comparisons of Reading Times for Filters: Specular Lighting and High Resolution

| Filter | Mean RT (s) | | | | | |
|---|---|---|---|---|---|---|
| Pol62-HEA | 7.50 | A | | | | |
| Mesh | 8.22 | | B | | | |
| Pol92 | 8.25 | | B | | | |
| Pol62 | 8.45 | | B | | | |
| Gloss45 | 9.25 | | | C | | |
| Pol31 | 10.00 | | | | D | |
| Gloss25 | 10.61 | | | | | E |

Note: Means with the same letter are not significantly different, $p > .01$.

Search Task

Search time (ST) data were analyzed with a 5 x 2 x 7 x 3 x 2 (Age x Gender x Filter x Lighting x Resolution) mixed within- and between-subjects repeated measures ANOVA. Table 13 shows the source table for this analysis.

Age. This effect can be seen in Figure 15. A Newman-Keuls analysis, Table 14, shows the ST for the 18-29 group to be faster than that for all other age groups. The 60-69 group's performance was slower than for the 18-29, 30-39, and 40-49 groups. For this performance measure each age group had progressively longer STs.

Resolution. As was the case with reading time, the effect of resolution showed performance for low resolution (4.85 s) to be faster than that for high resolution (7.86 s). This result is shown in Figure 16.

Age by Resolution. Since the effect of this two-way interaction was significant, it is necessary to view each of the main effects (Age and Resolution) in terms of its interaction with the other.

A simple effects test, shown in Table 15, was performed on these data to isolate the significant effects. In this case the age effects were significant within both levels of resolution. Newman-Keuls analyses were then

TABLE 13

Analysis of Variance Summary for Search Time

| SOURCE | df | MS | F | p |
|---|---|---|---|---|
| BETWEEN SUBJECT | | | | |
| Age (A) | 4 | 5371390.00 | 12.84 | 0.0001 |
| Gender (G) | 1 | 165839.00 | 0.40 | 0.5361 |
| A x G | 4 | 356146.46 | 0.85 | 0.5096 |
| S\|G, A | 20 | 418388.48 | | |
| WITHIN SUBJECT | | | | |
| Filter (F) | 6 | 126542.63 | 1.30 | 0.2632 |
| Lighting (L) | 2 | 2667217.38 | 41.58 | 0.0001 |
| Resolution (R) | 1 | 28513951.35 | 260.47 | 0.0001 |
| F x L | 12 | 375498.40 | 5.16 | 0.0001 |
| F x R | 6 | 232944.03 | 3.37 | 0.0041 |
| L x R | 2 | 1545472.91 | 17.93 | 0.0001 |
| F x L x R | 12 | 195757.37 | 3.60 | 0.0001 |
| A x F | 24 | 80921.07 | 0.83 | 0.6926 |
| A x L | 8 | 81822.23 | 1.28 | 0.2834 |
| A x R | 4 | 361568.01 | 3.30 | 0.0312 |
| A x F x L | 48 | 78704.63 | 1.08 | 0.3427 |
| A x F x R | 24 | 65126.17 | 0.94 | 0.5447 |
| A x L x R | 8 | 139474.59 | 1.62 | 0.1504 |
| A x F x L x R | 48 | 72984.81 | 1.34 | 0.0792 |
| G x F | 6 | 90509.77 | 0.93 | 0.4771 |
| G x L | 2 | 67685.94 | 1.06 | 0.3576 |
| G x R | 1 | 8751.19 | 0.08 | 0.7803 |
| G x F x L | 12 | 60171.27 | 0.83 | 0.6222 |
| G x F x R | 6 | 65007.59 | 0.94 | 0.4681 |
| G x L x R | 2 | 17174.35 | 0.20 | 0.8202 |
| G x F x L x R | 12 | 55672.15 | 1.02 | 0.4265 |
| A x G x F | 24 | 42376.17 | 0.43 | 0.9897 |
| A x G x L | 8 | 44909.57 | 0.70 | 0.6894 |
| A x G x R | 4 | 245244.48 | 2.24 | 0.1010 |
| A x G x F x L | 48 | 58987.05 | 0.81 | 0.8060 |
| A x G x F x R | 24 | 47990.77 | 0.70 | 0.8482 |
| A x G x L x R | 8 | 43236.20 | 0.50 | 0.8478 |
| A x G x F x L x R | 48 | 74967.80 | 1.38 | 0.0620 |
| F x S\|G,A | 120 | 97474.79 | | |
| L x S\|G,A | 40 | 64147.42 | | |
| R x S\|G,A | 20 | 109469.25 | | |
| F x L x S\|G,A | 240 | 72731.64 | | |
| F x R x S\|G,A | 120 | 69045.22 | | |
| L x R x S\|G,A | 40 | 86212.45 | | |
| F x L x R x S\|G,A | 240 | 54319.64 | | |
| Total | 1259 | | | |

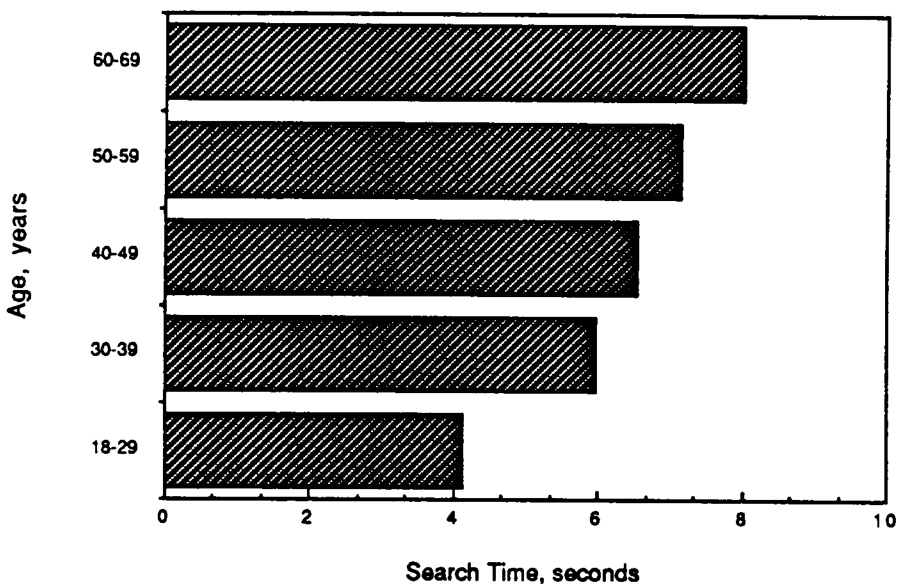


Figure 13. The effect of age on search time.

Table 14

Newman-Keuls Comparisons of Search Times for Age

| Age | Mean ST (s) | | | | |
|---|---|---|---|---|---|
| 18-29 | 4.13 | A | | | |
| 30-39 | 5.96 | | B | | |
| 40-49 | 6.53 | | B | C | |
| 50-59 | 7.14 | | B | C | D |
| 60-69 | 8.02 | | | | D |

Note: Means with the same letter are not significantly different, $p > .05$.

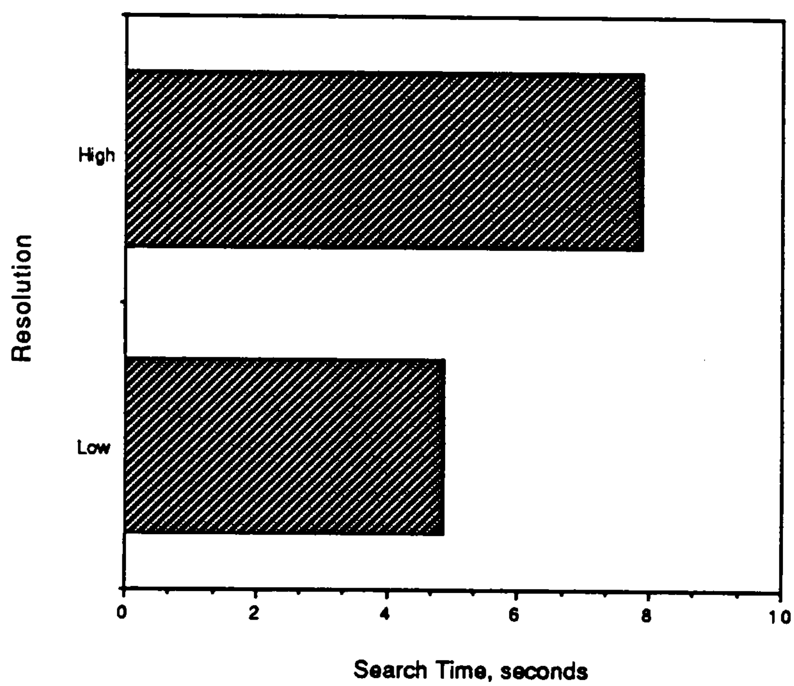


Figure 14. The effect of resolution on search time.

Table 15

Simple Effect F-Tests of Search Times for Age at High and Low Resolution

| Conditions | df | MS | F |
| --- | --- | --- | --- |
| Low Resolution | 4 | 1521552.61 | 13.41* |
| High Resolution | 4 | 4201776.81 | 37.05* |
| A x R x S\|G,A | 20 | 113422.79 | |

*p<.01

Table 16

Newman-Keuls Comparisons of Search Times for Age: Low Resolution

| Age | Mean ST (s) | | | | |
|---|---|---|---|---|---|
| 18-29 | 3.27 | A | | | |
| 30-39 | 4.41 | | B | | |
| 40-49 | 4.98 | | B | C | |
| 50-59 | 5.41 | | B | C | D |
| 60-69 | 6.19 | | | | D |

Note: Means with the same letter are not significantly different, $p > .05$.

Table 17

Newman-Keuls Comparisons of Search Times for Age: High Resolution

| Age | Mean ST (s) | | | | |
|---|---|---|---|---|---|
| 18-29 | 4.98 | A | | | |
| 30-39 | 7.52 | | B | | |
| 40-49 | 8.09 | | B | C | |
| 50-59 | 8.87 | | | C | |
| 60-69 | 9.84 | | | | D |

Note: Means with the same letter are not significantly different, $p > .05$.

performed for Age at low resolution (Table 16) and high resolution (Table 17).

For all age groups the STs were shorter for low resolution characters than for high resolution characters. This effect can be seen in Figure 17. This result was fairly consistent with the results found for reading time, although the 50-59 group performed faster than younger age groups. For the search task this effect, coupled with the effect for Age discussed above, indicates that age appears to be a good predictor of performance .

Within the low resolution condition, the age effects were found to be the same as those for the main effect of Age. Within the high resolution condition the 18-29 year group's STs were still faster than all other groups and the 60-69 group's STs were slower than all other groups, including the 50-59 year group. In addition, the 30-39 year group performance was also significantly faster than the 50-59 year group, but not different from the 40-49 year group. The 40-49 year group was not significantly different from the 50-59 year group. This may indicate a transitional stage at the decade between 40 and 50. For many of the visual functions listed in Table 1, 40-50 was the age at which degradation begins. These data lend some support to the literature cited.

Lighting. The effect of Lighting is shown in Figure 18. Table 18 shows the Newman-Keuls analysis for this effect. All Lighting conditions were

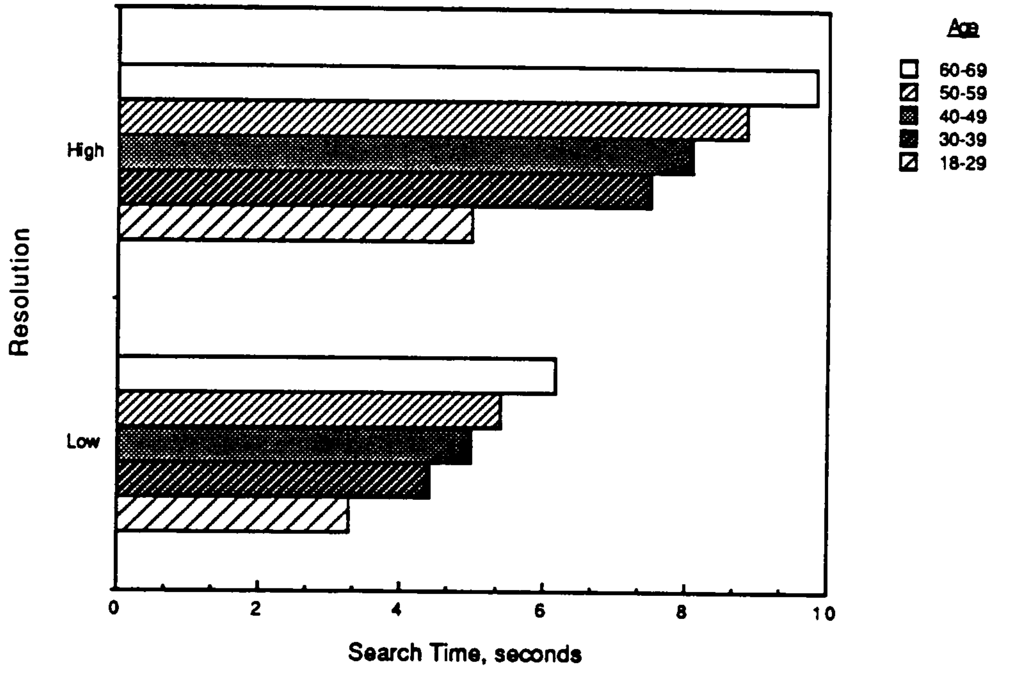


Figure 15. The effect of the age by resolution interaction on search time.

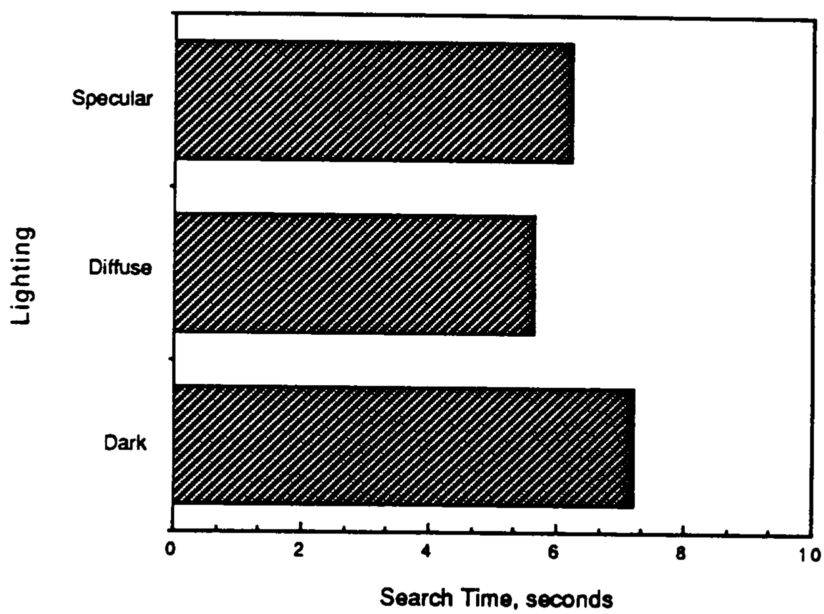


Figure 16. The effect of lighting on search time.

Table 18

Newman-Keuls Comparisons of Search Times for Lighting

| Lighting | Mean ST (s) | | | |
|---|---|---|---|---|
| Diffuse | 5.63 | A | | |
| Specular | 6.22 | | B | |
| Dark | 7.21 | | | C |

Note: All are significantly different, $p < .01$.

significantly different from each other, with the fastest STs for diffuse lighting and slowest for the dark condition. These results are consistent with those of reading time, except that RTs for specular and dark lighting were not significantly different from each other as they were for ST.

Filter x Lighting x Resolution. There was no significant main effect for Filter; however, there were significant effects for Filter x Lighting x Resolution and Lighting x Filter. This discussion will concentrate on the three-way interaction (Filter x Lighting x Resolution). The simple effect F-test results for Filter at each Resolution x Lighting combination are shown in Table 19. It can be seen that the significant Filter effects are located within the high resolution conditions. A Newman-Keuls test was performed on the high resolution data for both dark and specular lighting (Tables 20 and 21). Figure 19 shows this effect.

The results for Filter under dark lighting showed performance for Gloss25 to be slower than for all other filters. Also, Mesh performance was faster than for all but the Pol31 and Pol62 filters. The analysis under specular lighting showed Pol31 performance to be slower than all other filters and performance with Pol62-HEA to be faster than for all but the Mesh filter. Performance with the Mesh filter was significantly faster than for Pol31 and Gloss25. These findings are consistent with RT results and have been previously discussed.

Table 19

Summary for Simple Effect F-Tests of Search Times for Filter at each Lighting, Resolution Combination

| Condition | df | MS | F |
|---|---|---|---|
| Low Resolution: | | | |
| Dark | 6 | 17883.10 | 0.33 |
| Diffuse | 6 | 42936.93 | 0.79 |
| Specular | 6 | 52716.04 | 0.97 |
| High Resolution: | | | |
| Dark | 6 | 546375.96 | 10.06* |
| Diffuse | 6 | 83950.10 | 1.55 |
| Specular | 6 | 757804.49 | 13.95* |
| F x L x R x S\|G,A | 240 | 54319.64 | |

*p< .01

Table 20

Newman-Keuls Comparisons of Search Times for Filters: Dark Lighting and High Resolution

| Filter | Mean ST (s) | | | | |
|---|---|---|---|---|---|
| Mesh | 7.51 | A | | | |
| Pol31 | 8.05 | A | B | | |
| Pol62 | 8.75 | A | B | C | |
| Pol92 | 9.36 | | B | C | |
| Pol62-HEA | 9.62 | | | C | |
| Gloss45 | 9.68 | | | C | |
| Gloss25 | 11.68 | | | | D |

Note: Means with the same letter are not significantly different, $p > .05$.

Table 21

Newman-Keuls Comparisons of Search Times for Filters: Specular Lighting and High Resolution

| Filter | Mean ST (s) | | | | |
|---|---|---|---|---|---|
| Pol62-HEA | 5.86 | A | | | |
| Mesh | 6.83 | A | B | | |
| Pol62 | 7.35 | | B | C | |
| Pol92 | 7.65 | | B | C | |
| Gloss45 | 7.75 | | B | C | |
| Gloss25 | 8.78 | | | C | |
| Pol31 | 10.87 | | | | D |

Note: Means with the same letter are not significantly different, $p > .05$.

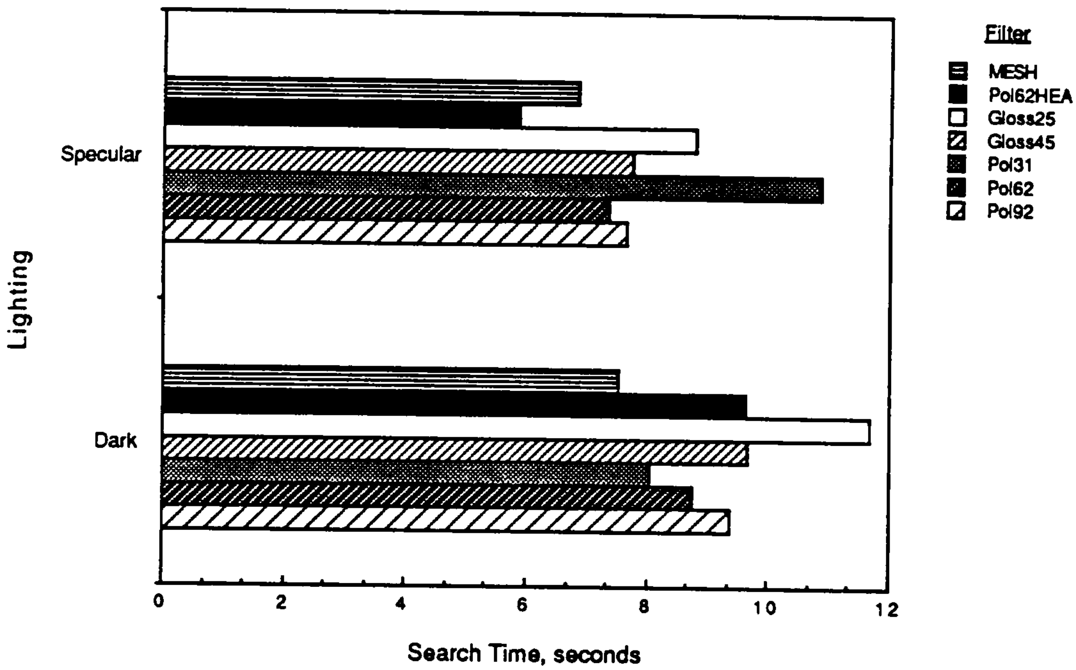


Figure 17 . The effect of filter on search time under specular and dark lighting, high resolution.

Table 22 shows a simple effect F-test for Lighting at all Filter, Resolution combinations. This analysis shows no significant effects for the low resolution characters. Within the high resolution case, all filters except Mesh show significant effects for Lighting. Search times were longer for the dark condition than for either diffuse or specular for all but the Pol31 filter. The ST for Pol31 was longest for specular lighting, which was significantly longer than for both diffuse and dark lighting. Interestingly, performance for STs and some RT conditions was found to be slowest in the dark lighting condition. This effect will be discussed in more detail later.

Image Quality Rating

The rating scores were analyzed using a 5 x 2 x 7 x 3 x 2 (Age x Gender x Filter x Lighting x Resolution) mixed within- and between-subjects repeated measures analysis of variance model. The results are shown in Table 23.

Filter. The significant effect for Filter is shown in Figure 20. A Newman-Keuls analysis was performed on these data (Table 24) and showed Pol62-HEA to be rated higher than all other filters. All but Pol31 were rated higher than Gloss25, with Mesh and Pol92 being rated higher than Pol31. These results are consistent with the results for both performance measures. The quarterwave filter was associated with the fastest RTs and STs. The two etched filters and the Pol31 filter were rated lowest, which also is consistent with results previously discussed.

Table 22

Summary for Simple Effect F-Tests on Search Times for Lighting within Filter, Resolution Combinations

| Condition | df | MS | F |
|---|---|---|---|
| Low Resolution: | | | |
| Pol92 | 2 | 33678.62 | 0.62 |
| Pol62 | 2 | 28109.63 | 0.52 |
| Pol31 | 2 | 53718.09 | 0.99 |
| Gloss45 | 2 | 108654.64 | 2.00 |
| Gloss25 | 2 | 149838.97 | 2.76 |
| Pol62-HEA | 2 | 13426.69 | 0.25 |
| Mesh | 2 | 72012.52 | 1.33 |
| High Resolution: | | | |
| Pol92 | 2 | 468238.26 | 8.62* |
| Pol62 | 2 | 464681.48 | 8.56* |
| Pol31 | 2 | 1851924.48 | 34.03* |
| Gloss45 | 2 | 607079.00 | 11.18* |
| Gloss25 | 2 | 2453139.09 | 45.16* |
| Pol62-HEA | 2 | 1300845.33 | 23.95* |
| Mesh | 2 | 34878.20 | 0.64 |
| F x L x R x S\|G,A | 240 | 54319.64 | |

*$p < .01$

TABLE 23

Analysis of Variance Summary for Image Quality Rating

| SOURCE | df | MS | F | p |
|---|---|---|---|---|
| BETWEEN SUBJECT | | | | |
| Age (A) | 4 | 26.04 | 0.65 | 0.6339 |
| Gender (G) | 1 | 0.50 | 0.01 | 0.9125 |
| A x G | 4 | 5.20 | 0.13 | 0.9698 |
| S\|G, A | 20 | 40.09 | | |
| WITHIN SUBJECT | | | | |
| Filter (F) | 6 | 27.54 | 13.76 | 0.0001 |
| Lighting (L) | 2 | 360.65 | 57.86 | 0.0001 |
| Resolution (R) | 1 | 81.78 | 9.90 | 0.0051 |
| F x L | 12 | 19.32 | 19.51 | 0.0001 |
| F x R | 6 | 8.33 | 6.43 | 0.0001 |
| L x R | 2 | 6.43 | 6.45 | 0.0037 |
| F x L x R | 12 | 0.64 | 1.15 | 0.3201 |
| A x F | 24 | 3.61 | 1.81 | 0.0202 |
| A x L | 8 | 3.93 | 0.63 | 0.7472 |
| A x R | 4 | 4.09 | 0.50 | 0.7394 |
| A x F x L | 48 | 0.95 | 0.96 | 0.5604 |
| A x F x R | 24 | 1.62 | 1.25 | 0.2157 |
| A x L x R | 8 | 0.87 | 0.87 | 0.5489 |
| A x F x L x R | 48 | 0.45 | 0.82 | 0.8000 |
| G x F | 6 | 5.07 | 2.53 | 0.0240 |
| G x L | 2 | 7.26 | 1.16 | 0.3227 |
| G x R | 1 | 17.62 | 2.13 | 0.1597 |
| G x F x L | 12 | 0.52 | 0.52 | 0.8988 |
| G x F x R | 6 | 0.66 | 0.51 | 0.8010 |
| G x L x R | 2 | 1.27 | 1.28 | 0.2901 |
| G x F x L x R | 12 | 0.78 | 1.40 | 0.1654 |
| A x G x F | 24 | 2.16 | 1.08 | 0.3789 |
| A x G x L | 8 | 1.22 | 0.19 | 0.9901 |
| A x G x R | 4 | 15.47 | 1.87 | 0.1546 |
| A x G x F x L | 48 | 0.98 | 0.99 | 0.4939 |
| A x G x F x R | 24 | 0.87 | 0.67 | 0.8729 |
| A x G x L x R | 8 | 0.58 | 0.58 | 0.7898 |
| A x G x F x L x R | 48 | 0.50 | 0.90 | 0.6575 |
| F x S\|G,A | 120 | 2.00 | | |
| L x S\|G,A | 40 | 6.23 | | |
| R x S\|G,A | 20 | 8.26 | | |
| F x L x S\|G,A | 240 | 0.99 | | |
| F x R x S\|G,A | 120 | 1.30 | | |
| L x R x S\|G,A | 40 | 1.00 | | |
| F x L x R x S\|G,A | 240 | 0.56 | | |
| Total | 1259 | | | |

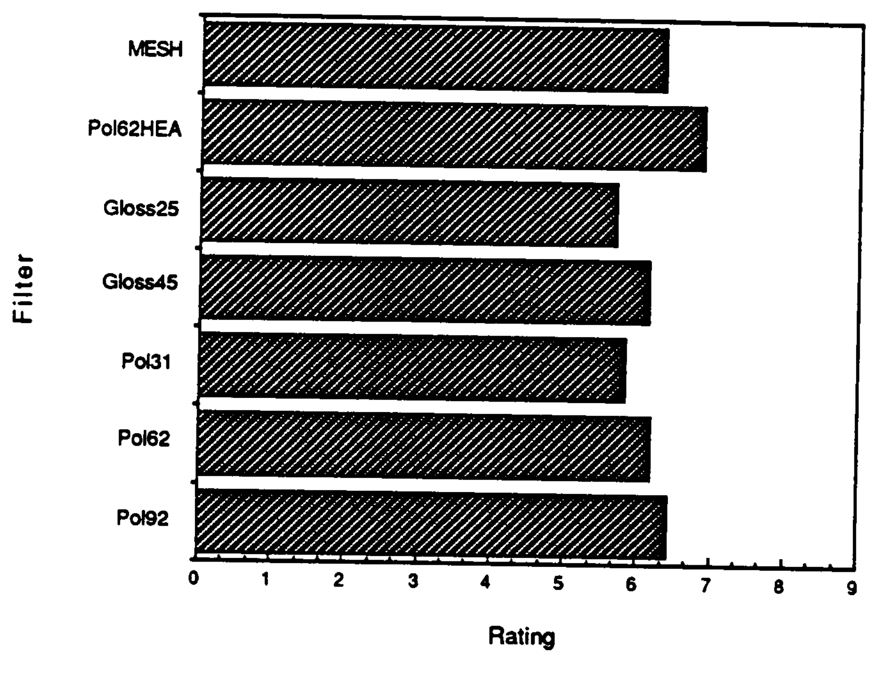


Figure 18. The effect of filter on rating.

Table 24

Newman-Keuls Rating Comparisons for Filter

| Filter | Mean Rating | | | | |
|---|---|---|---|---|---|
| Gloss25 | 5.70 | A | | | |
| Pol31 | 5.84 | A | B | | |
| Gloss45 | 6.14 | | B | C | |
| Pol62 | 6.17 | | B | C | |
| Mesh | 6.34 | | | C | |
| Pol92 | 6.43 | | | C | |
| Pol62-HEA | 6.88 | | | | D |

Note: Means with the same letter are not significantly different, $p > .05$.

Age by Filter. As can be seen from Table 24 there were no differences among ratings attributed to Age alone. There was, however, a significant Age x Filter interaction. A simple effect F-test was performed on these data and showed significant differences among filters only for the 50-59 and the 60-69 year groups (Table 25). These effects are shown in Figure 21. The Newman-Keuls tests, Tables 26 and 27, indicate that both groups rated the Pol62-HEA filter highest, although the 50-59 group only rated it higher than Gloss45, Pol31, Pol62, and Gloss25. This age group also rated Mesh and Pol92 higher than Gloss45 and Pol31. The highest rating for the quarterwave filter was consistent with performance results; however, the Gloss25 filter was rated higher than might be expected, especially taking into account the performance data for this filter.

The 60-69 group rated the Pol62-HEA filter higher than Gloss25 and Mesh. They also rated Pol62 and Gloss45 higher than Gloss25. Recall from the reading and search data that the oldest subjects showed poorest performance with the Mesh and best performance with the Pol62-HEA filters. Again, the quarterwave filter was rated highest with Gloss25, the harshest etched filter being rated lowest. This group also rated the Mesh filter quite low, which is consistent with their performance data. The Mesh filter acts both as a contrast enhancer and an anti-glare filter. It does have several disadvantages, among these is the tendency to produce Moiré patterns (previously explained) and, in some lighting conditions, diffuse and dark in

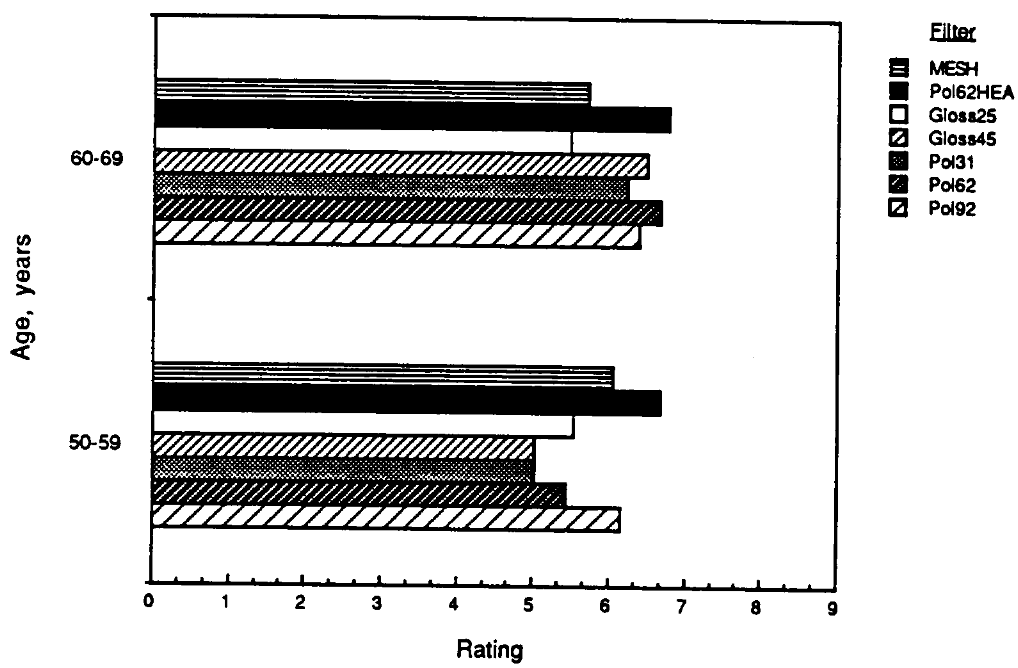


Figure 19. The effect of age by filter on rating.

TABLE 25

Simple Effect F-Tests on Ratings for Filter at all Ages

| Age Group | df | MS | F |
|---|---|---|---|
| Age (18-25) | 6 | 7.24 | 3.62 |
| Age (30-39) | 6 | 6.45 | 3.23 |
| Age (40-49) | 6 | 6.13 | 3.07 |
| Age (50-59) | 6 | 13.66 | 6.83* |
| Age (60-69) | 6 | 8.51 | 4.26* |
| F x S \| G,A | 120 | 1.999 | |

* $p < .01$

Table 26

Newman-Keuls Rating Comparisons for Filters: Age 50-59

| Filter | Mean Rating | | | |
|---|---|---|---|---|
| Gloss45 | 5.03 | A | | |
| Pol31 | 5.03 | A | | |
| Pol62 | 5.44 | A | B | |
| Gloss25 | 5.53 | A | B | |
| Mesh | 6.06 | | B | C |
| Pol92 | 6.16 | | B | C |
| Pol62-HEA | 6.67 | | | C |

Note: Means with the same letter are not significantly different, $p > .05$.

Table 27

Newman-Keuls Rating Comparisons for Filters: Age 60-69

| Filter | Mean Rating | | | |
|---|---|---|---|---|
| Gloss25 | 5.47 | A | | |
| Mesh | 5.72 | A | B | |
| Pol31 | 6.22 | A | B | C |
| Pol92 | 6.39 | | B | C |
| Gloss45 | 6.50 | | | C |
| Pol62 | 6.66 | | | C |
| Pol62-HEA | 6.78 | | | C |

Note: Means with the same letter are not significantly different, $p > .05$.

this study, the filter reduces contrast by reducing the transmission of displayed information. This reduction, coupled with the diffusion of light across the surface of the filter can effectively reduce contrast. In the dark condition, the filter reduces the luminance of the displayed characters, although this should not have significantly reduced the contrast since no background luminance was present.

Lighting. The significant effect for Lighting is shown in Figure 22. A Newman-Keuls analysis (Table 28) showed that the ratings for dark and diffuse lighting were higher than for specular lighting, but dark and diffuse lighting were not different from each other.

Resolution. The effect for resolution was also statistically significant. This effect can be seen in Figure 23. Low resolution (6.23) was rated higher than high resolution (5.96). This result is also consistent with the performance measures. In all cases performance for the low resolution characters was faster than for the high resolution characters. This result was true for all interactions with Resolution and other factors, Age, Filter, and Lighting.

Filter by Resolution. Simple effect F-tests were performed on these data, with the results presented in Table 29. In nearly every case low resolution characters were rated higher than high resolution. Differences among filter image quality were found to be significant for each level of resolution (Figure 24). A Newman-Keuls test among filters within low resolution, Table 30,

Table 28

Newman-Keuls Rating Comparisons for Lighting

| Lighting | Mean Rating | | |
|---|---|---|---|
| Specular | 5.15 | A | |
| Dark | 6.73 | | B |
| Diffuse | 6.77 | | B |

Note: Means with the same letter are not significantly different, $p > .05$.

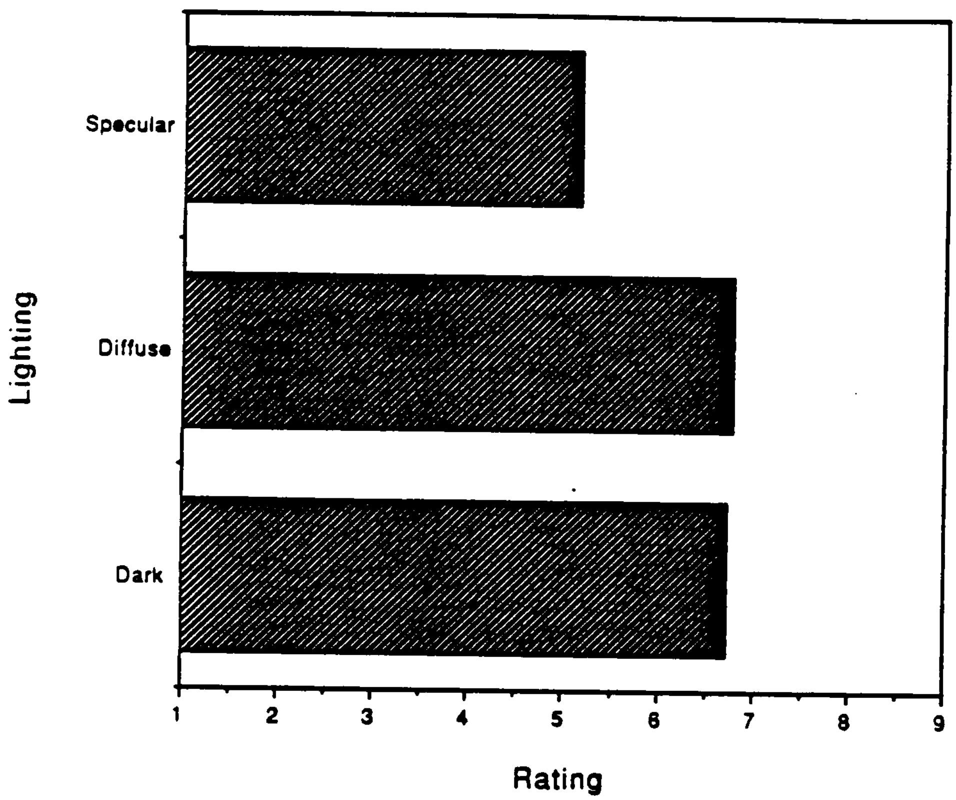


Figure 20. The effect of lighting on rating.

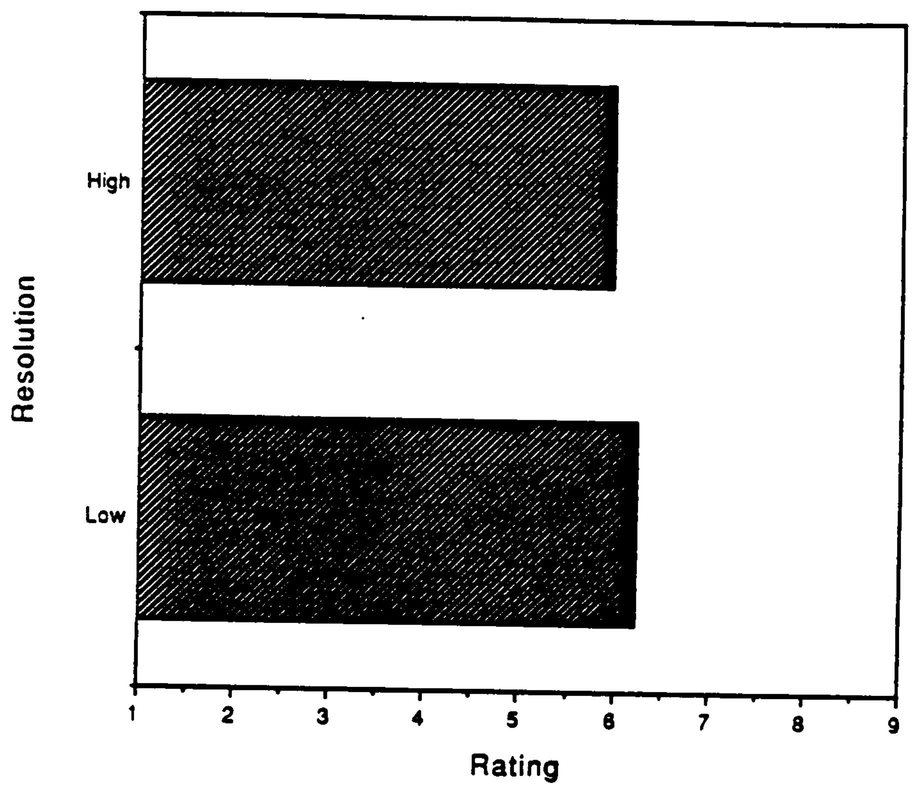


Figure 21. The effect of resolution on rating.

TABLE 29

Simple Effect F-Tests on Ratings for Filters: Resolution Conditions

| Resolution | df | MS | F |
|---|---|---|---|
| Low Resolution | 6 | 7.60 | 5.85* |
| High Resolution | 6 | 28.26 | 21.74* |
| F x R x S \| A,G | 120 | 1.30 | |

* $p < .01$

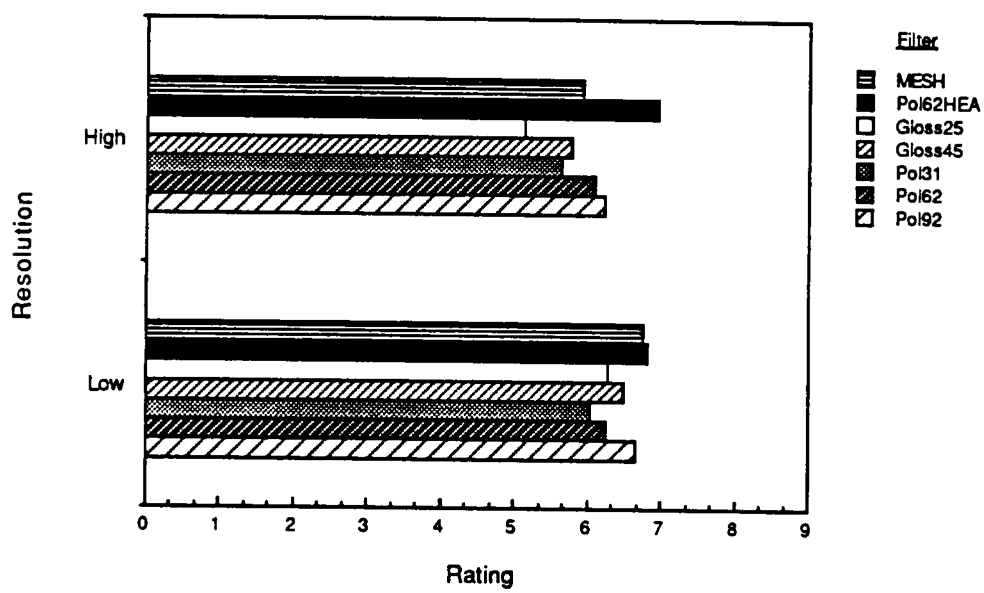


Figure 22. The effect of filter by resolution on rating.

Table 30

Newman-Keuls Rating Comparisons for Filters: Low Resolution

| Filter | Mean Rating | | | |
|---|---|---|---|---|
| Pol31 | 6.03 | A | | |
| Pol62 | 6.26 | A | B | |
| Gloss25 | 6.28 | A | B | |
| Gloss45 | 6.50 | | B | C |
| Pol92 | 6.66 | | B | C |
| Mesh | 6.76 | | | C |
| Pol62-HEA | 6.81 | | | C |

Note: Means with the same letter are not significantly different, $p > .05$.

showed that Pol62-HEA and Mesh were rated higher than Pol31, Pol62, and Gloss25. Also, Gloss45 and Pol92 were rated higher than Pol31.

For the high resolution characters Table 31 shows that Pol62-HEA was rated higher than all other filters and that Gloss25 was rater lower than all other filters. Pol92 and Pol62 were also rated higher than Pol31.

Filter by Lighting. A significant effect for the Filter x Lighting interaction was further analyzed using simple effect F-tests. It can be seen from Table 32 that significant effects were observed only for the dark and specular conditions. These effects are shown in Figure 25. Newman-Keuls analyses among filters for each of these two lighting condition are shown in Tables 33 and 34. Within the dark condition, ratings for Gloss25 were significantly lower than for all other filters. In fact, both etched filters were rated lower than Pol92. With specular lighting Pol62-HEA was rated higher than all other filters and Pol31 filter was rated lower than all other filters. Mesh and Pol92 filters were rated higher than Pol31, Gloss25, Pol62, and Gloss45.

The most inconsistent finding for Filter between dark and specular lighting was that Pol31 had the lowest rating for specular lighting and was only rated lower than Pol62-HEA for the dark condition. Again, this may be due to the reflective front surface on this filter. With specular lighting the reflected glare would be directed back into the observer's eye, either

Table 31

Newman-Keuls Rating Comparisons for Filters: High Resolution

| Filter | Mean Rating | | | | |
|---|---|---|---|---|---|
| Gloss25 | 5.12 | A | | | |
| Pol31 | 5.64 | | B | | |
| Gloss45 | 5.78 | | B | C | |
| Mesh | 5.93 | | B | C | |
| Pol62 | 6.09 | | | C | |
| Pol92 | 6.21 | | | C | |
| Pol62-HEA | 6.94 | | | | D |

Note: Means with the same letter are not significantly different, $p > .05$.

TABLE 32

Simple Effects F-Tests Summary of Ratings for Filters at each Lighting Condition

| Lighting | df | MS | F |
|---|---|---|---|
| Dark | 6 | 5.40 | 5.45* |
| Diffuse | 6 | 2.73 | 2.76 |
| Specular | 6 | 58.07 | 58.66* |
| F x L x S \| A,G | 240 | 0.99 | |

* $p < .01$

Table 33

Newman-Keuls Rating Comparisons for Filters: Dark Lighting

| Filter | Mean Rating | | | |
|---|---|---|---|---|
| Gloss25 | 6.20 | A | | |
| Gloss45 | 6.63 | | B | |
| Mesh | 6.68 | | B | C |
| Pol62-HEA | 6.73 | | B | C |
| Pol62 | 6.75 | | B | C |
| Pol31 | 6.97 | | B | C |
| Pol92 | 7.17 | | | C |

Note: Means with the same letter are not significantly different, $p > .05$.

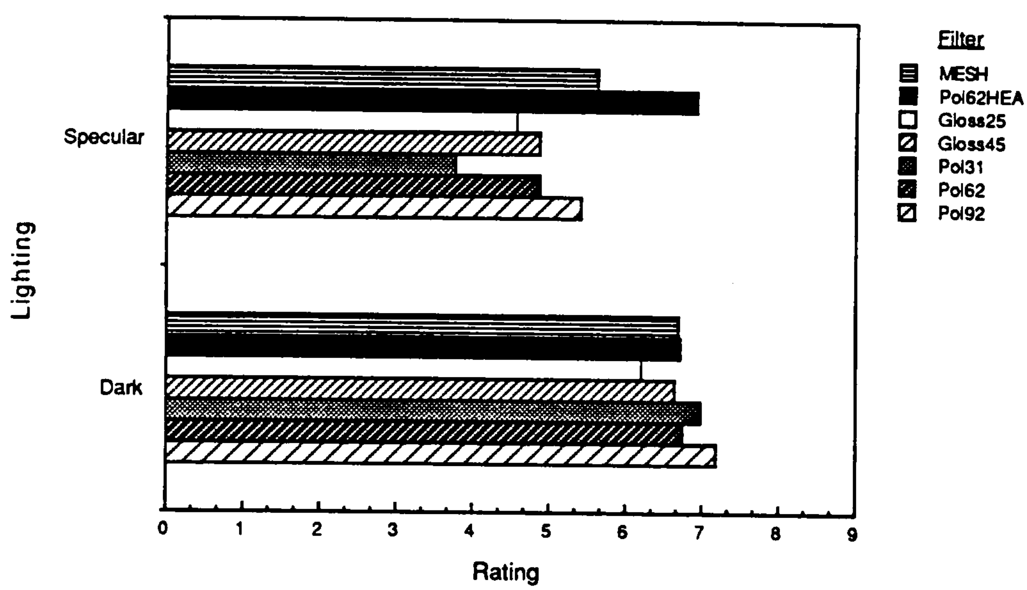


Figure 23. The effect of filters on ratings, dark and specular lighting.

Table 34

Newman-Keuls Rating Comparisons for Filters: Specular Lighting

| Filter | Mean Rating | | | | |
|---|---|---|---|---|---|
| Pol31 | 3.77 | A | | | |
| Gloss25 | 4.57 | | B | | |
| Pol62 | 4.87 | | B | | |
| Gloss45 | 4.88 | | B | | |
| Pol92 | 5.40 | | | C | |
| Mesh | 5.62 | | | C | |
| Pol62-HEA | 6.92 | | | | D |

Note: Means with the same letter are not significantly different, $p > .05$.

reducing contrast or creating a bright spot on the display which could mask or reduce the displayed information.

As can be seen in Figure 25 specular lighting received the lowest rating with all filters. For all filters, dark and diffuse lighting conditions were rated significantly higher than specular, but were not found to be different from each other, except with Pol92. Characters in diffuse lighting were rated highest for Pol62, Gloss45, Gloss25, and Mesh, while those in the dark were rated highest for Pol92 and Pol31. All three lighting conditions were found to be significantly different from each other only with the Pol92 filter.

The ST analyses produced similar results for filters under diffuse lighting for the 60-69 age group, which performed faster with etched filters.

Lighting by Resolution. As was the case with the other two dependent variables, in all instances where resolution was involved, low resolution came out ahead. Figure 26 shows this effect. In terms of image quality, low resolution characters (32 arcmin) were rated higher than high resolution characters (16 arcmin). The result was that subjects performed faster with low resolution characters and rated them higher.

The results for the simple effect F-tests for lighting within the two levels of resolution (Table 35) showed significant effects for both low and high resolution. The results from the Newman-Keuls analysis (Tables 36 and 37)

TABLE 35

Simple Effect F-Tests on Ratings for Lighting within each Resolution Condition

| Resolution | df | MS | F |
|---|---|---|---|
| Low Resolution | 2 | 135.39 | 135.53* |
| High Resolution | 2 | 231.70 | 231.93* |
| F x R x S \| A,G | 40 | 0.999 | |

* $p < .01$

Table 36

Newman-Keuls Rating Comparisons for Lighting at Low Resolution

| Lighting | Mean Rating | | |
|---|---|---|---|
| Specular | 5.54 | A | |
| Dark | 6.92 | | B |
| Diffuse | 6.95 | | B |

Note: Means with the same letter are not significantly different, $p > .05$.

Table 37

Newman-Keuls Rating Comparisons for Lighting at High Resolution

| Lighting | Mean Rating | | |
|---|---|---|---|
| Specular | 4.75 | A | |
| Dark | 6.55 | | B |
| Diffuse | 6.59 | | B |

Note: Means with the same letter are not significantly different, $p > .05$.

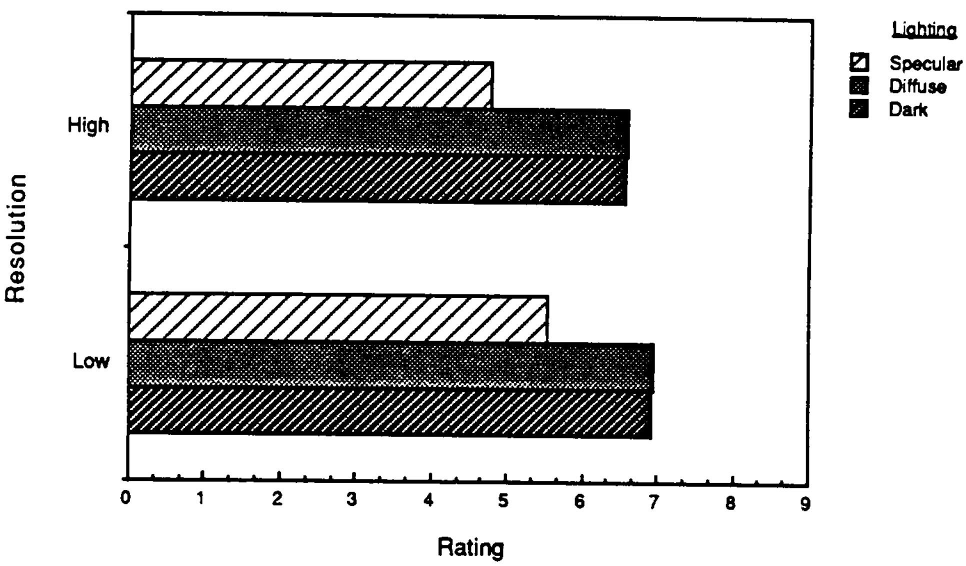


Figure 24. The effect of lighting by resolution on rating.

are consistent with the main effect results for lighting. Within both high and low resolution conditions subjects rated the image quality for specular conditions to be lower than dark and diffuse lighting, but no difference between diffuse and dark lighting was found.

The ratings for lighting showed one inconsistency with performance measures. Under dark lighting the characters for both resolution levels were rated higher than for specular lighting. The ST performance measures indicated that subjects performed slower under dark than either specular or diffuse lighting, but rated dark higher. The high contrast characters are apparently perceived as having high image quality but, in fact, reduce performance.

Filter by Gender. The final significant interaction for rating was between filter and gender and is interesting in that it was the only effect among all three dependent variables in which gender was found to be significant. This effect is shown in Figure 27. A simple effect test, Table 38, shows that the only significant effect of gender within filter was for the Gloss25 filter, for which males (6.0) rated the image quality higher than females (5.4). This effect was not considered to be of practical significance and will not be discussed further.

TABLE 38

Simple Effect F-Tests on Ratings for Gender at each Filter

| Filter | df | MS | F |
|---|---|---|---|
| Pol92 | 1 | 2.22 | 1.11 |
| Pol62 | 1 | 0.14 | 0.07 |
| Pol31 | 1 | 1.25 | 0.63 |
| Gloss45 | 1 | 0.45 | 0.23 |
| Gloss25 | 1 | 17.42 | 8.71* |
| Pol62-HEA | 1 | 1.42 | 0.71 |
| Mesh | 1 | 8.02 | 4.01 |
| F x S \| A,G | 120 | 1.999 | |

* p<.05

# CONCLUSIONS

This research was conducted to determine whether the contrast enhancement and anti-glare characteristics of filters under representative lighting and with two character resolutions would differentially affect performance and image quality ratings for subjects ranging in age from 18 to 69 years.

## Age

In general the results indicate that performance for the oldest age group (60-69) was slower than for the other groups for both performance measures, while the performance for the youngest group (18-29) was generally faster than all other groups. There was a strong linear trend for the Age results for the search task. The results of an analysis using mean STs for each age group showed these means to fit a straight line ($r = 0.98$). It should be recalled that all subjects were screened for 20/20 near and 20/22 distant visual acuity and their contrast sensitivity was measured using a Vistech Consultants test system. Therefore, the differences should not be attributed to visual acuity, but rather to other age-related effects.

Contrast

As was discussed in the introduction to this dissertation, contrast sensitivity is reported to decrease with age. This reduction is further affected by the presence of glare. This study directly manipulated the apparent contrast of displayed characters by using two levels of resolution, high resolution, for which single pixel wide characters were used whereby each pixel was highly focused, and low resolution, for which two pixel wide characters were used, with each pixel defocused. These defocused pixels resulted in a softening of the edges, thus increasing the amount of displayed high spatial frequency information.

Hunter's (1988) study included physical measurements taken of the display. The basis of several of these measurements was the modulation transfer function (MTF), which describes the system's ability to transmit spatial frequency information. A system which can display high frequency information with a powerful signal will appear to have a crisper and sharper image, and will obtain a high MTF value. The MTFA is another measure used by Hunter which calculates the area under the MTF curve and, based on the known contrast threshold function (CTF) for humans, determines the part of the area under the MTF curve which can be perceived by humans. These measurements are taken in the dark so that extraneous light sources do not affect the calculations. A variation of the MTF measurements is a measurement developed by Hunter which takes MTF measurements in lighted conditions. These measurements, called the Glare MTF (GMTF), takes the measurement of the displayed image as well as the reflection from the front surface of the display. Determining the GMTFA gives information on the spatial frequency content of the first surface reflection and indicates the loss in contrast experienced under varying lighting conditions. These measurements may be useful in explaining some of the results of the present study. Table 39 shows the GMTFA values for each filter under all Lighting by Resolution conditions. It can be seen from the table that the MTFA values for the low resolution display in the dark are very tightly grouped. This grouping becomes looser under diffuse lighting and the values are reduced. For the specular condition, the values become very small and the variance increases. It should be noted that the largest reduction is seen with the etched filters. Also, the quarterwave filter has the highest GMTFA value under specular lighting.

For the high resolution characters the same trend is observed, except that the MTFA values are much higher than those for the low resolution case. Interestingly, the MTFA values (dark) for the etched filters are lower to begin with for the high resolution characters, indicating that the etched filter reduces the high spatial frequency information in the baseline condition (dark). As with low resolution the quarterwave filter has the highest GMTFA value under specular lighting.

TABLE 39

MTFA and GMTFA Values for Filter, Lighting, Resolution Combinations (Adapted from Hunter, 1988)

| | High Res-Dark | High Res - Diffuse | High Res-Specular |
|---|---|---|---|
| Filter | MTFA | GMTFA | GMTFA |
| Pol92% | 9.039 | 3.178 | 2.144 |
| Pol62% | 9.104 | 4.087 | 2.465 |
| Pol31% | 9.073 | 5.489 | 2.085 |
| Gloss45-62% | 7.810 | 3.221 | 1.193 |
| Gloss25-62% | 6.526 | 2.426 | 0.899 |
| Pol62-QW | 9.293 | 4.267 | 3.330 |
| MESH-7.4 | 8.523 | 3.827 | 2.570 |

| | Low Res-Dark | Low Res - Diffuse | Low Res-Specular |
|---|---|---|---|
| Filter | MTFA | GMTFA | GMTFA |
| Pol92% | 4.823 | 1.686 | 0.984 |
| Pol62% | 4.784 | 2.193 | 1.214 |
| Pol31% | 4.764 | 2.968 | 1.080 |
| Gloss45-62% | 4.267 | 1.925 | 0.767 |
| Gloss25-62% | 4.157 | 1.825 | 0.680 |
| Pol62-QW | 4.811 | 2.150 | 1.629 |
| MESH-7.4 | 4.428 | 2.147 | 1.237 |

Note: MTFA measurements were only made under dark lighting conditions and that, under dark conditions GMTFA were equivalent to MTFA.

These results are consistent with the performance and rating results obtained in the current research. Under specular lighting conditions subjects performed faster and gave higher ratings to the quarterwave filters and, conversely, performed slowest with the Gloss25 filter and gave it the lowest ratings.

Resolution

In terms of preference for low resolution and faster performance with the larger characters, Hunter's (1988) results can also help to explain these. For the GMTFA results at high resolution, there was a large change between the dark (MTFA) measurements and the specular measurements. This indicates a large loss in high frequency power. There was a much smaller change from the values for the low resolution characters in the dark condition to those in specular lighting indicating a smaller loss in high frequency information. This is understandable since the low resolution characters were transmitting less high spatial frequency information to begin with. This, coupled with the larger size of the low frequency characters, may have assisted subjects in viewing these characters. It is typical that larger (low resolution) characters are found faster in a search task (Snyder and Maddox, 1978).

The high resolution characters used in this study were 16 arcmin, which is at the minimum of the recommendations in the American National Standard for Human Factors Engineering of Visual Display Terminal Workstations

(1988). Under glare conditions, with reduced contrast, it should be expected that performance would be adversely affected. Larger size did seem to compensate for the lower contrast when the etched filters were in place.

Lighting

Performance in the dark lighting condition was generally slowest across resolution and filter conditions. This finding is consistent with that of Hunter (1988). Hunter discusses three possible explanations for this phenomenon. These will be summarized, but the reader is referred to Hunter (1988) for a more in-depth discussion. This summary will include any information relevant to the aging visual system when possible.

Hunter's first possible explanation is the autokinetic effect which occurs when a bright point of light is imposed on a dark background. The resulting illusion is that the point appears to drift across the surface of the display. He suggests that the increased performance time may be due to the observer continually adjusting to this drifting. This explanation is supported by comments from several of the subjects in the current study which indicated that they were having difficulty "following" the images across the screen in the search task, particularly in the high resolution conditions.

The second explanation is that the dark background does not give the visual cues necessary for the observer to accommodate to the displayed information. He explains that the CRT spot has a Gaussian luminance distribution which is a poor stimulus for accommodation. In normal lighting conditions the phosphor plane is excited by the illumination or reflects incident light and thus gives the observer a cue for accommodating to that distance. In the dark there is no such cue. This may be especially problematic to the older observers because their accommodative near point moves out with increasing age and their dark focus (the accommodative state to which the eye tends to automatically move in darkness when there is no object on which to focus) is also reported to move out. This could explain some of the extended time required by the older subjects to complete the performance tasks in the dark lighting condition.

Finally, Hunter explains that the pupillary response to the lack of light is to increase in size from 2.0 mm up to a maximum of about 7.0 mm. A large increase in the size of the pupil might reduce the observer's depth of focus. He further suggests that the increased performance times may be due to reduction in total illuminance at the eye rather than the lack of luminance in the background. This may actually be less of a problem for the older subjects due to the developmental reduction in the size of the pupil (miosis), which results in a maximum pupillary opening of only 4.5 mm for older subjects in the dark.

A final explanation of this phenomenon may have to do with stimulus-persistence. As discussed earlier, Kline and Schieber (1982) and Kline et al.

(1982) reported that older subjects experience a sort of "smearing" of stimulus information due to the slowing of stimulus processing. A slowing of processing the high contrast characters in the dark lighting condition of this study may have produced the appearance of characters moving across the screen as the subject moved his or her head. Since this phenomenon was not reported in any other lighting conditions, it may be that the extremely high luminance contrast increases the likelihood of this occurring.

Recommendations

It is recommended that attention be given to increasing the size of characters on the VDT display. This recommendation is supported both by preference and performance data. The ANSI Standard (1988) recommends a minimum of 16 arcmin with a preferred height of 20 to 22 arcmin. Snyder (1984) recommends 16 to 25 arcmin with some consideration to other aspects of the display. He recommends that the raster line structure not be visible, and that the matrix structure of the individual characters not be visible (caused by the dot spacing being greater than the dot diameter).

Within specular lighting conditions all subjects (regardless of age) preferred the quarterwave filter to all other filters and performed faster with this filter for both performance measures, but only significantly better than Pol92 under specular lighting for the high resolution characters. It would be difficult to recommend the expense of the quarterwave filter over the Pol92 filter based on these findings. The simplest recommendation would be to remove specular glare sources from the office environment whenever possible. Subjects across the board preferred diffuse lighting to specular lighting. Although this is not a surprising result, it highlights the need to reduce specular light sources in the VDT environment.

## Future Research

The finding that subjects in all age groups prefer and perform faster with low resolution characters (subtending a visual angle of 32.2 arcmin) suggests the need to determine the character size that would be optimal for VDT viewing on displays to be used by older users. The two character sizes used in the current research (16.1 arcmin and 32.2 arcmin) covered only two fairly extreme ends of the size continuum. It is likely that the optimum character size lies somewhere within these two points. It is also likely that the relationship between performance and character size is not linear and the optimum character size may differ for different age groups. Finding the optimum character size would probably enhance performance across age groups and might also reduce some of the postural problems experienced by users who wear bifocals or trifocals.

As also recommended by Hunter (1988) the same research paradigm should be used to test the long term effects of Filter by Lighting by Resolution on a wide age range of subjects. It may be that, as subjects become accustomed to the various conditions, their performance will become less variable.

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