Display Technology and Ambient Illumination Influences on Visual Fatigue at VDT Workstations

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(ABSTRACT)

The concept of “visual fatigue” has been studied for 70 years or more. In that time, no single metric of measuring visual fatigue nor one agreed-upon set of tasks to induce visual fatigue has been settled upon. Not even a robust definition of visual fatigue has been established. This research worked to solve some of those problems.

This research first set out to develop an index of visual fatigue that could be used effectively in quantifying the subjective experience of visual fatigue. Then it sought to create a set of measurable tasks, representative of office work, that would induce visual fatigue. Taking these two developments, an experiment using human participants was conducted to validate these developments and work toward solving two issues in the visual fatigue field: how visual display technology and ambient illumination affect the onset of visual fatigue. A 4x4 within-subjects design was developed and executed to study how these two independent variables affected ratings of visual fatigue, performance on the task battery, subjective image quality judgments, and contrast sensitivity shifts.

Two cathode ray tube (CRT) and two active-matrix LCD (AMLCD) monitors were used in this study. While many instances of the monitors as a whole caused significant differences in reports of visual fatigue, performance, subjective image quality, and contrast sensitivity loss, only a slight effect of display technology was found. Four of eleven visual fatigue and two of eight subjective image quality dimensions showed that the LCD monitors induced more visual fatigue and were rated poorer than the CRT monitors.

Ambient illumination levels of 0, 300, 600, and 1200 lux affected all four groups of dependent variables. On the whole, lighting caused visual fatigue, with “watery eyes” and “glare from lights” being adversely affected by brighter lighting. The 0 and 1200 lux were associated with the worst performance, while 300 lux was associated with the best performance. Subjective image quality was affected by lighting, with increasing lighting causing bothersome screen reflections and more temporal (e.g., flicker and jitter) distortions; 600 lux induced more reports of image sizing anomalies. Finally, it caused significantly worse shifts at the 6.0 c/deg spatial frequency on the contrast sensitivity test. The data show that lighting of 300 lux is the best of these four illumination levels.

The results of this study not only contribute to the body of research in the areas of display technology and ambient illumination, but several developments of this research are offered to the research community: a complete survey metric of visual fatigue, a standardized battery of tasks for studying visual fatigue and image quality, and a comprehensive subjective image quality survey.

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While this may not be as long as *The Winning of the West*, but hopefully it has been done just as well.

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1.0 INTRODUCTION

The use of computers in modern society is omnipresent. They are used for innumerable applications in various sizes and forms. Over the past 20 years, the personal computer has become widely used, both in the office and at home. People use computers to write documents, maintain databases, manage finances, draw diagrams and graphics, make presentations, compile mailing lists, search computer databases, write application programs, use the Internet, and myriad other tasks. In the United States, there were 19 million personal computers (PCs) in use in 1985; in the year 2000, it is expected that 154 million personal computers will be operating in the United States alone, with 535.6 million PCs projected to be in use worldwide (Brunner, 1998).

The principal information output device and means to interact with the computer for the user is the visual display, or “monitor.” For PCs, the standard display technology used for monitors has been the cathode ray tube (CRT) – the same technology used for television sets. The CRT is a very robust and mature technology, meaning that it can meet the computer user’s requirements for a visual display at a reasonable price. There are some drawbacks to this technology, however. CRT monitors are bulky and very heavy, with sizable electrical power requirements. Obviously these characteristics make it unsuitable for use with a portable PC and thus a “flat” display technology needed to be adopted. The liquid crystal display (LCD) technology was mated with notebook computers (Menozzi, Napflin, and Krueger, 1999) Initially, portable PC users were willing to make the sacrifices that came with the use of the passive-matrix LCD technology that needed to be used, such as smaller viewing angles, lower resolution, poorer color rendering, and an overall lower image quality. More recently, however, the active-matrix LCD (AMLCD) technology has been closing the flat-panel gap between LCD and CRT technologies. It offers equitable image quality to the CRT technology with the gains of size, weight, and power consumption. The major barrier at this point is price, which, like most electronics, is dropping. With these advantages, it is expected that AMLCD technology will compete effectively with CRTs for use with personal computers.

Another innovation in display technology is the “flat” CRT which is much like the old CRTs, with the exception that they use planar (flat) faceplates instead of curved faceplates. (These curved faceplates are either curved in the horizontal plane, as part of a cylindrical shape, or in both the horizontal and vertical planes, as part of a spherical shape.) These flat CRTs reportedly provide better image quality because their planar faceplates are less prone to imaging distortions and annoying reflections from ambient illumination (Beaton, 1999).

This migration from one display technology to another poses a range of human factors research questions. The issues of how humans are affected by and use CRT monitors have been studied at length. From health issues related to its emissive nature, to comparison of it with hard copy, to how to optimize display parameters to achieve peak performance, a body of knowledge has been developed for human factors researchers and practitioners to consult. How the flat CRT and LCD technologies may differ from the older CRTs has yet to be fully studied by human factors engineers.

One important area of study for CRT monitors used at video display terminal (VDT) workstations has been visual fatigue. With the increasing use of computers, at both work and home, what effect such prolonged viewing may have on the user has been a concern in the recent past and will continue to grow as a topic of importance to human factors researchers (Dillon and Emurian, 1996). No longer are computers used by only specialized personnel for short periods of time during the work day. Computers are being used more widely and for longer periods of time at work (Aarås, Horgen, Bjørset, Ro, and Thoresen, 1998; Sotoyama, Jonai, Saito, and Villanueva, 1996). Additionally, computers are used more and more in the home (Davenport, Wu, Barnes, Mihran, Wachtel, Kim, Yang, Becker, and Matsis, 1997). Not only does this mean that the duration of use of the eyes is increasing, but rest time for the eyes is becoming scarcer. The issue of visual fatigue is continuing to grow in importance.

The objective of this research project was to determine how the new flat CRT and AMLCD display technologies affect personal computer users with respect to visual fatigue. In order to do that, two developments needed to be made. First, an index of visual fatigue was constructed in an effort to quantify the visual fatigue experience of a VDT user. Second, a task battery representative of common workplace and home uses of the computer was developed, along with metrics to evaluate the performance of the users in these tasks. Once these have been developed, human factors experiments using visual fatigue index and the task battery were carried out.

Before these developments and experiments are presented, it is proper to present a discussion of the state of knowledge in the area of visual fatigue at VDT workstations and a brief review of how the CRT and LCD display technologies function.

2.0 BACKGROUND

The concept of visual fatigue is not new. Research has been conducted concerning it during the entire century. In fact, as far back as 1933 Snell published a summary work on visual fatigue and how it might relate to motion pictures and television (Snell, 1991). Even then it was realized that the concept of “visual fatigue” was not a unified process that could be measured directly, but rather the approach needed to be directed toward the individual processes involved in vision (Snell, 1991). It has only been in the past 15 to 20 years, with the advent of the personal computer and its accompanying visual display, that research has begun to concentrate again on this area.

Chi and Lin (1998) and Goussard, Martin, and Stark (1987) have reported that visual fatigue (or computer vision syndrome [CVS]) is the most common complaint of video display terminal (VDT) (sometimes also referred to as a visual display unit [VDU]) users and it is estimated that 50% of operators of VDTs are affected by visual fatigue (Lunn and Banks, 1986). Jebaraj, Tyrrell, and Gramopadhye (1999) reported that, for people involved in certain kinds of precision work, as many as 96% suffer from visual fatigue. Finally, Gallimore and Brown (1993) relate the results of a survey of optometrists where 14.25% of all patients primarily attributed adverse visual symptoms to use of VDTs.

With as many as 10 million people reporting symptoms of visual fatigue in the United States per year (Gallimore and Brown, 1993), the research community must work to provide a reasonably good definition of the problem. What constitutes “visual fatigue,” however, remains vaguely defined and may even refer to different subjective complaints and, hence, different underlying phenomena (Goussard, Martin, and Stark, 1987). In fact, visual fatigue has not been limited to the eyes. Oftentimes headaches, general malaise, musculoskeletal pain, dizziness, and nausea have been included in its definition; in addition to the more expected subjective measures, such as eyestrain, pain in or around the eyeball, burning, itching, and red eyes, blurred and double vision, and “flickering” vision. These symptoms have sometimes been grouped under the aegis of “asthenopia.”

More formally, Megaw’s (1995) review of visual fatigue does not offer an actual definition of the affliction, instead listing some key points that should be included in any formal definition. Briefly, those points are:

- visual fatigue does not occur instantaneously
- visual fatigue should be distinguishable from mental workload demands
- visual fatigue can be overcome by rest
- visual fatigue should be discernible from any adaptive response of the visual system
- symptoms of asthenopia are the main reason for assuming the existence of visual fatigue
- symptoms of asthenopia can be caused by nonvisual factors

Tyrrell and Leibowitz (1990) took a less structured approach to defining visual fatigue when they borrowed their definition from the National Research Council: “any subjective visual symptom or distress resulting from the use of one’s eyes” (NRC, 1983, p. 153). This is a rather all-encompassing approach, but one that treats the human operator as the final arbiter for what constitutes visual fatigue – a solid rationale from the human factors perspective.

2.1 Classification of Visual Fatigue

No single research method or objective measure has yet emerged that consistently and accurately correlates with visual fatigue. No doubt this effort is hampered by the lack of a coherent definition. However, many techniques have been devised that do measure certain contributing factors to visual fatigue. These methods span a wide range of fields. From a human factors engineering perspective, these methods can generally be grouped into two categories: those that deal with medical and optometric measurements (e.g., EMG and contrast sensitivity) and those that are of greater practical interest to the human factors/ergonomics researcher and practitioner (e.g., performance and surveys).

2.1.1 Medical and Optometric Issues

One of the most obvious places to begin investigations of visual fatigue is with the eye itself. Numerous aspects of the visual system have been studied to determine what might be either causally related to or correlated with visual fatigue. Those major features have been grouped here either because they are of a medical or optometric nature and, as a consequence, measurement is complex, or because the features are associated with factors of the human that can not be controlled from an engineering perspective since they are innate to the individual.

Contrast Sensitivity

One of the most studied aspects of the visual system with respect to visual fatigue has been contrast sensitivity. One of the earlier studies of this was Lunn and Banks (1986) who hypothesized that lines of single-spaced text on a computer screen creates a periodic stimulus to the eye similar to sine-wave grating patterns (or square-wave grating patterns [Conlon, Lovegrove, Hine, Chekaluk, Piatek, and Hayes-Williams, 1998]) used in spatial frequency analysis. This periodicity of text is in the range of two to six cycles per degree (c/deg) (depending on the properties of the VDT and viewing distance) and causes contrast adaptation in the visual system, thus impairing the eyes' ability to accommodate. This adaptation, in turn, is cited as causing many of the same reports of asthenopia as VDTs induce (Conlon et al., 1998; Lunn and Banks, 1986), as well as inappropriate reflexive accommodation responses in the eyes because it has lost sensitivity in these critical spatial frequencies. This adaptation phenomena is a result of the global pattern structure of the text and not internal pattern components (Conlon et al., 1998). Lunn and Banks's experiment showed that, after as little as ten minutes of reading text aloud from a CRT screen, significant contrast sensitivity reductions for 2, 3, and 5 c/deg were found, but not for the other tested frequencies of 7, 9, 11, 13, and 15 c/deg (Lunn and Banks, 1986).

Magnussen, Dyrnes, Greenlee, Nordby, and Watten (1992) extended this work and found that reading times of up to an hour did not greatly increase contrast adaptation, but did markedly increase recovery time. Contrast adaptation is a relatively slow process building up over 30 minutes to an hour, and then decaying as a power function of time, with ultimate correction equal in time to the original exposure (Magnussen et al., 1992; Megaw, 1995). Watten, Lie, and Magnussen (1992) also found that contrast adaptation occurred after using a VDT for two or four hours (with no significant difference between the two time spans). However, they found adaptation occurred at spatial frequencies of 1.5, 3.0, 6.0, 12.0, and 18.0 c/deg – across Lunn and Banks's range, but also at the higher spatial frequency of 18.0 c/deg – above that used by Lunn and Banks (1986). When correlated with subjective measures of discomfort, a multi-factor account of visual fatigue seems to emerge (Watten, Lie, and Magnussen, 1992). For the two hour trial, both the low frequencies are impaired as well as the highest frequency –implying that contrast adaptation has occurred, but that transient myopia also may be present. For the four hour trial, less correlation between subjective measures of visual discomfort and contrast sensitivity adaptation is present, but a greater degree of discomfort overall was reported. These results are not unexpected since adaptation seems to saturate after an hour whereas visual fatigue steadily increases over time (Watten, Lie, and Magnussen, 1992).

In a study related to visual fatigue, Conlon, Lovegrove, Chekaluk, and Pattison (1999) exposed participants to square-wave patterns of 1.0, 2.0, 4.0, 8.0, 12.0, and 16.0 cycles/degree for 3.0 seconds and collected data regarding somatic (i.e., asthenopic) and perceptual difficulties. They found an increasing amount of difficulty over the range from 1.0 to 12.0 cycles/degree (with 16.0 being no different from 12.0). Conlon et al. (1998) cite previous research that suggests people are most sensitive in the 2.5 to 4.0 c/deg range (Conlon, 1993, as cited in Conlon et al., 1998) – similar to the 2-6 c/deg range Lunn and Banks (1986) report. Thus, it would seem that periodic stimuli can induce symptoms of visual fatigue.

Taken as a whole, it would seem that contrast adaptation is a very important issue in visual fatigue and one that begins to alter vision almost from the beginning of the work period. However, after perhaps an hour, this effect may become overridden by other considerations such as general fatigue.

Accommodation and Convergence

Another field that has received considerable research attention has been accommodation and convergence of the eyes caused by visual work. These are physical responses of the eye to help the visual system clearly see the target. Accommodation occurs when the eye’s muscles bending the lens in order to focus the image at the retina; convergence occurs when the eyes are horizontally rotated to aim at the target so that the images of both eyes are directed onto the fovea. Both of these require muscles in the eyes to work and, it is assumed, that this function can cause muscle fatigue to occur just as other muscles in the body tire (Megaw, 1995). Early measures of these accommodations concentrated on change in visual acuity and the near point of focus, but yielded inconsistent results (Tyrrell and Leibowitz, 1990). However, using Landolt Cs in their experiment, Muraoka, Nakashima, Mizushina, Shimodaira, and Ikeda (1998) found that visual acuity worsened from 10-30% over a 90 minute work period. In more recent studies, dark focus and dark vengeance points have been studied. (Dark focus and dark vengeance are the resting positions of the visual system in total darkness.) Not only has it been found that these resting states are located at an intermediate range (instead of afar, as previously thought), but that there is a great degree of individual difference between individuals (Jaschinski, Heuer, and Kylian, 1999; Tyrrell and Leibowitz, 1990).

Individual difference also applies to another factor that affects the dark vengeance point: the vertical tilt of the head. Called the Heuer Effect, dark vengeance points are greater for elevated head tilts and nearer for lowered head tilts for some people (Megaw, 1995). Tyrrell and Leibowitz (1990) confirmed previous research that suggested that visual fatigue is positively correlated with vengeance effort. That is, those with more distant dark vengeance points suffered more visual fatigue than those with near vengeance points. This result also was found by Jebaraj, Tyrrell, and Gramopadhye (1999) who found that participants with a larger dark vengeance reported more visual fatigue. Tyrrell and Leibowitz (1990) also found that those who exhibited the Heuer Effect were affected by their gaze elevation; that a downward head tilt (which caused a closer dark vengeance point) decreased the amount of visual fatigue they suffered. This research seems to be pointing toward that conclusion that greater dark focus and, especially, dark vengeance points induce greater visual fatigue.

Eye Tracking

Eye tracking has been used to determine how eye movement relates to visual fatigue. One appeal of eye tracking data is that they are more readily quantifiable than other indicators of visual performance that have been developed. Goussard, Martin, and Stark (1987) developed a “visual fatigue indicator” (VFI) based on eye movement data. While they found that the VFI was worse for reading from a CRT compared to a book, they did not establish any link to visual fatigue. In a study of eye movement velocity, Chi and Lin (1998) found that velocity was a significant predictor of subjective ratings of visual fatigue for dynamic tracking tasks, with greater eye movement velocities inducing significantly more fatigue. Ziefle (1998) also found that the number and duration of eye fixations was correlated with fatigue, though this link was only for a low resolution condition of the experiment. Conversely, Miyao, Hacisalihzade, Allen, and Stark (1989) did not find a link between eye movement and resolution, though their experimental design is questionable (participants were allowed to adjust their viewing distance and the screen’s brightness).

Other Medical/Optometric Factors

Lastly, myriad other factors such as critical fusion frequency (CFF), blink rate, EMG, and pupil size have been studied. Chi and Lin (1998) report several studies that looked at CFF and found that it did correlate with visually loaded tasks; whether or not this is related to visual fatigue was not mentioned. Their own experiment found CFF to be more negatively affected by a 60 minute task when compared to a 20 minute task, though the correlation to subjective visual fatigue was not significant (Chi and Lin, 1998). Shieh and Chen (1997) found that CFF fell significantly from baseline to one hour of work and from one to two hours of work, but not from two to three hours of work. However, their study did not use any other measure of visual fatigue and even cited a study (Oohire, 1986, as cited in Shieh and Chen, 1997) cautioning against using CFF as a measure of visual fatigue.

Blink rate is another indicator known to correlate with the amount of effort a person is putting forth (i.e., workload), but nothing that solidly correlates it with visual fatigue. Miyao et al. (1989) found that a higher resolution monitor caused lower blink rates when compared to a lower resolution monitor and Megaw (1995) relates a study that shows blink rate increases as a function of reading time, but they could not tie this to any measure of visual fatigue. Overall, however, blink rates are less for viewing VDTs than for hard copy.

Megaw (1995) also relates a study that used EMG recording of the muscles around the eye that control blinking, as well as other efforts such as squinting. The study reports a positive relationship between time and spectral power distribution, but again, this was not related to any measure of visual fatigue.

Lastly, pupil size has been studied to some degree since this part of the visual system controls the depth of focus and may contribute to visual fatigue. It is known the ambient illumination and display polarity can change pupil size; bright lighting and positive polarity inducing more pupil constriction (Taptagaporn and Saito, 1990). Davenport et al. (1997) report that pupils are more constricted after long trials with VDTs, though this was not directly related to symptoms of visual fatigue. One issue pupil size does raise and which goes back to one of Megaw’s elements of what constitutes visual fatigue is that changes in pupil size could either be the result of the visual system’s adaptation to the situation or it could be an adverse response and thus indicative of fatigue. Pupil size does change, but whether the causes and effects of it are related to visual fatigue is still uncertain (Chi and Lin, 1998: Megaw, 1995).

2.1.2 Human Factors/Ergonomics Issues

From a broad viewpoint, the contributions of research into the medical and optometric studies of visual fatigue are of great importance and continue to slowly unravel the mysteries of visual fatigue. However, from a more pragmatic viewpoint, if solutions are to be devised for use by those suffering visual fatigue, especially VDT operators, then issues directly related to work and hardware design need to be addressed by the research community.

Time on Task

Curiously, although the amount of time spent performing visually demanding tasks would seem to be of the greatest importance to visual fatigue, few if any studies have looked at it in a systematic fashion. Most studies, while manipulating the time of the task, have only done so as one of several independent variables, using what seems to be arbitrarily set time frames. As an sample, Table 2.1 lists test times various experiments uses.

TABLE 2.1 – Time on Task for Several Visual Fatigue Experiments

Experiment	Time on Task
Lunn and Banks (1986)	10 minutes
Magnussen et al. (1992)	10 to 60 minutes
Chi and Lin (1998)	20 and 60 minutes
Jebaraj, Tyrrell, and Gramopadhye (1999)	40 minutes
Miyao et al. (1989)	1 hour
Tyrrell and Leibowitz (1990)	just under 2 hours
Goussard, Martin, and Stark (1987)	2 hours
Gallimore and Brown (1993)	2 hours
Watten, Lie, and Magnussen (1992)	2 and 4 hours
Ziefle (1998)	~2.5 to 3.0 hours.

To be fair, these studies were not all studying the same visual fatigue issues and thus, using exactly the same time frames should not be expected. However, these studies offer little in the way of a consensus about how long a person can expect to work before the onset of symptoms of visual fatigue nor is there much of a guide to researchers attempting to replicate and extend this work. It does appear from the above studies, however, that contrast thresholds begin to change with as little as ten minutes of work and saturates at around one hour; accommodation and convergence responses occur at 40 minutes; reading may take as much as 2-3 hours to fatigue a person; and for overall visual fatigue ratings, the advancement occurs over at least a four hour period, and perhaps more (Matthews, Lovasik, and Mertins, 1989; Watten, Lie, and Magnussen, 1992).

Viewing Distance

Next to time, viewing distance seems to be the most importance factor being studied in visual fatigue research. Few studies have manipulated it as an independent variable, while other studies let participants choose their viewing distance. The latter likely was a practical consideration, as in Watten, Lie, and Magnussen (1992) where participants worked up to four hours. Also, it is possible that this was done to better emulate true working conditions. However, to uncover any viewing distance effects on visual fatigue and to have a reasonable expectation of comparing data between studies, a definitive viewing distance is needed. For the single-distance experiments Tyrrell and Leibowitz (1990) used 20 cm, Ziefle (1998) used 50 cm, Goussard, Martin, and Stark (1987) and Magnussen et al. (1992) used 57 cm, and Lunn and Banks (1986) used 76 cm. Tyrrell and Leibowitz (1990) cite studies that found viewing distances from 50 to 76 cm to be preferred by VDT users. Three of the reviewed experiments manipulated distance. Chi and Lin (1998) used distances of 40 and 80 cm in a monitoring task and Jebaraj, Tyrrell, and Gramopadhye (1999) used distances of 20 and 60 cm in their study of a visual inspection task. Both studies found greater subjective ratings of visual fatigue and lower objective performance for the nearer condition. Jaschinski, Heuer, and Kylian (1999) did not as strictly control viewing distance, but used distances of “about” 66 and 98 cm in their study and found less eyestrain and general fatigue at the distant condition; after individual adjustments by the participants, a preferred viewing distance of 90 cm was found. While this does not mean that farther is better, these studies' better range of 60 to 90 would seem to corroborate the preferred range of 50 to 76 cm cited by Lunn and Banks (1986) and the 95% preferred viewing distance range of 50 to 70 cm reported by Stammerjohn, Smith, and Cohen (1981, as reported in MacKenzie and Riddersma, 1994). However, it should be noted that Tyrrell and Leibowitz (1990) stated that near work greatly affects only some people and not others. This would seem to coincide with the large individual differences for dark focus and dark vengeance points mentioned above.

A last, interesting note. Many ergonomic standards promulgate that source documents and visual displays should be at the same viewing distance. The theory here being that different viewing distances would cause frequent vergeance and accommodation efforts, increasing the likelihood of visual fatigue. However, a study by Jaschinski-Kruza (1990) found that subjective ratings of visual discomfort were not different for when both display and hard copy were at 50 cm and when the display was at 70 cm and the hard copy remained at 50 cm.

Gaze Angle

Although related to viewing distance, gaze angle seems to have an effect on visual fatigue. As discussed in the previous section regarding the Heuer Effect, lower gaze angle may be less fatiguing. Sotoyama et al. (1996) referenced research that found VDT users felt worse with a gaze angle of 0 degrees (measured to Reid's line) than gaze angles of –15 or –30 degrees (Abe et al., as cited in Sotoyama et al., 1996). Jaschinski, Heuer, and Kylian (1999) manipulated gaze angle in their study and found participants preferred a gaze angle of –10 degrees, though they referenced research that found gaze angles of –30 to –45 degrees may be advantageous. However, they caution that there are great individual differences to be found, both for gaze angle and viewing distance (Jaschinski, Heuer, and Kylian, 1999).

Display Technology

The original introduction of VDTs into office working environments fundamentally changed the nature of work and how it was to be done. As a consequence, prior experiments could not adequately assess if the introduction of computers and their visual displays helped or hurt people and their productivity because a hard copy control group did not adequately represent the type of work VDTs allow people to perform (Dillon and Emurian, 1996). Numerous studies of have tried to assess this, with mixed results (Dillon, 1994; Ziefle, 1998). But as a practical matter for most people, computers are now a fact of life in daily work and in the home.

The new research question ought to be: what types of displays should be used? The predominance of research into visual fatigue has used CRT displays, but a few, scattered studies have investigated LCDs, usually as they relate to CRT displays.

In a study using a passive matrix LCD screen compared with a CRT, MacKenzie and Riddersma (1994) found that the LCD screen performed poorer on a target selection task. Of particular note, were the “comet tails” and “submarining” effects on the LCD display as the cursor was moved. The poorer performance of passive matrix LCD displays for dynamic visual presentations is supported by another study of dynamic visual performance for head-mounted displays. Rabin and Wiley (1995) found that higher rates of presentation (i.e., target velocity of greater than 4 deg/s and duration of less than 250 ms) caused an AMLCD display to perform worse than a CRT of like color, spatial resolution, and luminance. There was, however, no significant difference between display technologies at slower rates of presentation. This similarity for slower moving stimuli also was found in a study of cockpit displays for transport aircraft by Toms and Cone (1995). Although these studies do not speculate on how this shortcoming of the LCD technology may impact visual fatigue, the reduced visibility of the cursor for pointing tasks and fast-moving targets (such as may be useful for full-motion video) may lead to additional eyestrain and thus visual fatigue.

A study by Muraoka et al. (1998) did compare visual acuity responses between a CRT and Thin Film Transistor LCD (TFT-LCD a type of AMLCD) displays. They found that acuity worsened by 10% for the TFT-LCD display over a 90 minute work session, but that the CRT display worsened acuity by 30% over the same time period. However, the authors did not speculate on possible display technology differences.

With regard to glare on the faceplate of visual displays, there is some belief that the organic materials used for LCD screens may provide better glare control when compared to the glass used for CRT displays (Menozzi, Napflin, and Krueger, 1999).

Finally, Beaton (1999) found that subjective ratings of image quality were better for some flat-screen CRTs, but there was no speculation about whether this was related to the flat-screen technology or simply the display itself.

Display Resolution

A very systematic investigation of monitor resolution effects on visual fatigue was carried out by Ziefle (1998). Resolutions of 62, 69, and 89 dpi were studied and it was found that higher resolution lessened visual fatigue. This was determined by both objective performance measures (search speed and eye fixation duration) and subjective measures (pre-/post-test differences on a questionnaire) of visual fatigue, where the lower resolution of 62 dpi was significantly worse than the resolution of 89 dpi, with the intermediate value not differing from either extreme (Ziefle, 1998).

Luminance Contrast

Display luminance contrast is another important issue for visual fatigue that has been studied, along with the accompanying issue of glare. Glare affects the eye in three ways. It reduces the contrast sensitivity of the eye, it constricts the pupil's diameter to compensate for the increased amount of light entering the eye, and it reduces the apparent contrast of what is being viewed. Although pupil size has not been related to visual fatigue, contrast sensitivity changes in the eye have been shown to be related directly to visual fatigue (Lunn and Banks, 1986; Magnussen et al., 1992; Watten, Lie, and Magnussen, 1992). While it is known that extremely low illumination levels for hard copy reading can produce visual fatigue (Megaw, 1995), the issue of luminance contrast for visual displays has had few studies where it was manipulated. Chi and Lin (1998) used two different luminance contrasts for a reading task, but they did not report the results in meaningful detail to make any assertion as to what level of luminance contrast might induce visual fatigue.

Little research has investigated glare due to ambient illumination while using visual displays. Davenport et al. (1997) used glare in their experiments to help induce visual fatigue, but they did not report the type of glare (e.g., diffuse or specular) or the ambient illumination conditions to make an assessment of how glare may have played a role. Aarås et al. (1998) performed an ergonomic intervention by changing the luminaries present in a work area and found that reducing glare and improving overall lighting from ~300 to ~600 lux significantly reduced reports of visual discomfort and, to a lesser degree, headaches. It is known, however, that ambient illumination does affect performance at a VDT workstation (Beaton, 1999; Kempic, Olacsi, and Beaton, 1998), its effect on visual fatigue has not been determined.

Other Human Factors/Ergonomics Factors

Other human factors/ergonomics issues for visual fatigue that have received some attention have been polarity, color, flicker, CRT phosphor type, demographics, and environmental conditions. Magnussen et al. (1992) found that contrast adaptation for negative polarity (bright characters on a dark background) was faster than positive polarity (dark characters on a bright background), though this was only for low spatial frequencies (~1.4 c/deg) and recovery times were the same for both polarities. Taptagaporn and Saito (1990) reported that participants “appreciated” a positive polarity display in 500 lux ambient illumination, in comparison to five other combinations with negative polarity and 20 and 1200 lux lighting. Using CFF as a measure of visual fatigue, Shieh and Chen (1997) found no difference in black on white vs. white on black presentations under 350 lux ambient illumination. Almost all other studies reviewed used positive polarity for tasks.

With the numerous studies of color and its human factors/ergonomics implications, little work has been done to see what positive or negative effect it might have on visual fatigue (Dillon and Emurian, 1996). Matthews, Lovasik, and Mertins (1989) carried out an experiment that studied several different color combinations and found no significant impact on visual fatigue between them. Shieh and Chen (1997) also found no difference due to foreground/background color combinations. While it may be assumed that the introduction of color leads to better contrast on the screen, it is not known whether the addition of color contrast to luminance contrast – and its beneficial effect on visual fatigue – is superfluous or not.

For VDTs, it is well known that flicker is a source of annoyance (ANSI/HFS-100, 1988) and while it is known that flicker causes greater eye saccades (Megaw, 1995), its impact on visual fatigue is uncertain from a research perspective. Few studies have looked at refresh rate and phosphor persistence to determine what minimum standards for there should be in order to minimize asthenopic effects. It is probably that these issues have been overlooked since it is expected that any VDT should be “flicker free” regardless of whether it causes fatigue or not.

In a review of several studies that investigated visual fatigue’s possible relationship with demographic data, Dillon and Emurian (1996) reported that factors such as gender, age, level of education, years of work experience, marital status, and ethnic background were not significantly related to subject reports (i.e., by questionnaire) of visual fatigue.

Finally, the environmental conditions in a work place can affect visual fatigue. Air that is dry, has a high flow rate, or has an inordinate amount of particles in it will dry out and irritate the eyes, directly causing some of the symptoms of asthenopia (Megaw, 1995; Sotoyama et al., 1996). Some of the asthenopic reports are directly related to the VDT – users of VDTs tend to blink less often and thus the refreshing effect of blinking does not occur as frequently (Megaw, 1995). Also, by looking straight ahead we expose more of the eye’s surface directly to the air compared to when we look downward at a VDT or hard copy (Sotoyama et al., 1996).

2.2 Human Factors/Ergonomic Methods for Evaluating Visual Fatigue

Since visual fatigue may be different for each person and no exact definition for it has been agreed upon, much less a single measure adopted for evaluating it, methods to describe visual fatigue necessarily are indirect and varied. Many physiological measures can be used to evaluate responses for the medical and optometric issues addressed above.

For engineering applications, quantitative measures of visual fatigue can be classified by which indirect approach is taken. An experiment may try to induce fatigue and, if most or all other factors are controlled (e.g., lighting conditions, general fatigue factors, etc.), performance reduction over time is attributed to visual fatigue. The other method is to interview or give a questionnaire to a person engaged in what is thought to be visually fatiguing activities and then try to ascertain how they feel before and after such work. Usually visual fatigue questionnaires are administered before and after the task since change in the level of visual fatigue is more important than an absolute measure (Ziefle, 1998). Some studies use the survey once to query VDT operators' opinions regarding visual fatigue in their work (Rechichi, De Moja, and Scullica, 1996). Since neither the interview or questionnaire are particularly robust when used by themselves, they are oftentimes used together. Some of the methods used in previous research are described here.

2.2.1 Visual Fatigue Experiments

The most common task to investigate visual fatigue has been a reading study. To ensure that participants read for the entire time, some experiments used a short quiz (Chi and Lin, 1998; Conlon et al. 1999; Gallimore and Brown, 1993; Tyrrell and Leibowitz, 1990) or had participants read aloud (Goussard, Martin, and Stark, 1987; Lunn and Banks, 1986; Miyao et al., 1989). For performance measures, Chi and Lin (1998) used a variety of physiological measures as well as subjective visual fatigue ratings; Conlon et al. (1999) used reading rate and comprehension score as their measures of performance; Gallimore and Brown (1993) used the modified Tinker Reading Test which measures reading speed and accuracy and a reading comprehension task adapted from the National Teachers Examination, in addition to measurement of visual acuity, posture, and subjective ratings of comfort; Tyrrell and Leibowitz (1990) used vengeance adaptation and subjective responses on a six-question survey to measure visual fatigue. Goussard, Martin, and Stark (1987) used eye movement as a dependent measure of visual fatigue; Lunn and Banks used contrast adaptation as measured using the psychophysical Method of Adjustment; Miyao et al. (1989) measured blink rate during reading and differences in smooth pursuit visual tracking from before and after the reading task.

A variation of the reading task is proofreading. Ziefle (1998) used a proofreading task to induce visual fatigue with speed (words read per minute) and accuracy (number of misspelled words correctly identified) as objective measures of performance and used a survey and interview for subject evaluations. After this initial study, however, Ziefle (1998) concluded that there exists a major drawback to the proofreading task. Different cognitive strategies for participants seemed to have introduced a degree of variance that obscured any possible effect from the differing resolutions. To simulate reading, but to remove any such confounding effects, a continuous visual search task was devised that had participants search for target letters in rows of letters. Participants were instructed to search across entire rows and then to return to the beginning of the next row – emulating reading; eye movements were monitored to ensure that participants actually did this. The data were used also as measures of visual fatigue, in addition to time and accuracy of identifying target letters and subjective visual fatigue responses.

Another variation of reading was to use the computer to perform computer programming exercises for students in a computer class (Watten, Lie, and Magnussen, 1992). The dependent measures of visual fatigue for this experiment were changes in visual acuity and contrast sensitivity over the work period and participants’ ratings of fatigue.

Jebaraj, Tyrrell, and Gramopadhye (1999) used a simulated industrial inspection task to measure visual fatigue in their study. Enlarged images of cosmetic contact lenses with six possible types of defects were presented on the screen. Each lens image contained one defect and the task was to identify the defect and then click on the portion of the image that contained the defect. Performance measures were the number of lenses inspected and the accuracy with which defects were identified.

Gallimore and Brown (1993) employed a search task as a third method of visual work. Participants were to locate as quickly and as accurately as possible a target alphanumeric character appearing on the screen. These measures were in addition to the visual acuity, posture, and subject comfort ratings collected for the overall experiment.

In addition to the reading task, Chi and Lin (1998) used a monitoring and a tracking task in their experiment. The monitoring task consisted of four cells on the screen with a number above and below each cell. The task was to keep the cell number within the upper and lower bounds and was measured by hit and correct rejection rates for the task, as well as subjective visual fatigue ratings and various physiological measures. The tracking task consisted of a radar scope presentation where participants were asked to follow the clockwise movement of a line and identify target shapes. Hit, correct rejection, subjective visual fatigue ratings, and physiological measures also were used for the tracking task.

Finally, Conlon et al. (1999) carried out an experiment using the Wechsler Intelligence Scale for Children – Revised (WISC-R) to measure attention and concentration. This experiment, however, did not try to induce visual fatigue, but rather to measure differences in visual fatigue symptoms amongst three groups of participants thought to be at varying susceptibility to visual fatigue.

2.2.2 Visual Fatigue Questionnaires

Since complaints of visual fatigue are related to many physiological and performance measures for visual fatigue, a well designed survey can provide meaningful insight into the fatiguing experiences of a VDT user (Dillon and Emurian, 1995).

Tyrrell and Leibowitz (1990) developed a short six question survey that they administered before and after the fatiguing task in their study. The survey can be found in the article, but it briefly addresses the issues of:

- back and neck pain
- headache

- blurry vision
- mental fatigue
- eyestrain
- overall fatigue

Jebaraj, Tyrrell, and Gramopadhye (1999) used this survey as well as another one developed by Yoshitake (1978, as cited in Jebaraj, Tyrrell, and Gramopadhye, 1990).

Other visual fatigue symptoms used by Aarås et al. (1998), Chi and Lin (1998), Conlon et al. (1999), Dillon and Emurian (1995), Jaschinski, Heuer, and Kylian (1999), Matthews and Desmond (1998), and Watten, Lie, and Magnussen (1992) are:

- dry eyes
- eyestrain
- difficulty in focusing
- eyes are irritated or burning
- pain, tension, or aching behind or around the eyes
- pain in the eyeball
- tearing eyes
- need to rub eyes
- problems with line-tracking
- heaviness of the eyes
- “foggy” letters; glare from lights
- “doubling” of words or letters
- “jumping” lines or letters
- “shivering” text
- unintentional rereading of text

Fatigue related to other parts of the body also is inquired about in visual fatigue surveys, such as:

- neck pain
- shoulder pain
- arm/wrist pain
- stiff legs and/or arms

- dizziness
- nausea
- bored/apathetic

These characteristics of fatigue usually were measured using a Likert-type scale or a continuous scale of perceived magnitude. While no single survey has emerged as a standard for evaluating subjective ratings of visual fatigue, many of the same symptoms have been used in the various surveys in the literature (Dillon and Emurian, 1995).

2.3 The CRT and LCD Display Technologies

As a further explanation of how visual fatigue may be affected by visual display technology, a brief review of the cathode ray tube (CRT) and liquid crystal display (LCD) technologies are presented here.

2.3.1 CRT Display Technology

The CRT display is the most widely used technology for visual displays. Its technology is over 100 years old and this has allowed it to become very mature – both with respect to its technical developments and manufacturability.

The CRT display, essentially, is an oddly-shaped glass vacuum tube, with one end very narrow and the other coming to a nearly flat (or sometimes completely flat) rectangular face. This face is the viewing screen of the display whose inside surface is covered with a matrix of thousands to millions of tiny phosphor dots. Phosphor is a material that emits visible light energy if it is excited by electrons, and different types of phosphor emit different wavelengths of light, causing different colors to be seen. Each dot consists of one of three types of phosphor: red, green, or blue. These groups of three phosphors make up a single pixel. The most common configuration of the three phosphor dots is in a “triad” as shown in Figure 2.1.

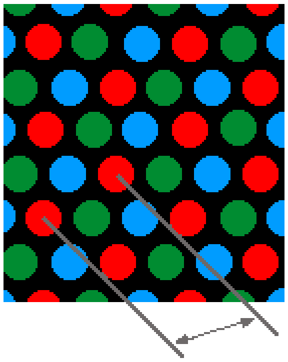

Figure 2.1. A close-up view of phosphor dots in a triad that make a pixel.

The measured distance shown in Figure 2.1 is what is known as the “dot pitch” or the distance between any two given points of adjacent pixels. There are other configurations for phosphors as well, the most radically different being Sony’s Trinitron which uses vertical stripes of phosphor instead of dots.

To create an image, the phosphor needs to be excited by electrons. This starts on the opposite side of the tube from the screen, in the narrow neck of the bottle. Here, an electron gun (three guns for a color display) sends out a stream of electrons generated from a cathode; the intensity of this stream can be controlled for each gun and consequently the brightness of each colored phosphor dot.

Before the electron stream reaches the phosphor, it has to be controlled. This is done by a magnetic shield that acts as a yoke to deflect the electron stream at the right location, “painting” the back of the screen. It starts in the top left corner (as viewed from the front) and flashes on and off as it moves

across the row, or “raster.” Once a pass has been completed, the electron beam moves down one raster and begins again. This process is repeated until an entire screen is drawn, at which point the beam returns to the top to start anew. The number of pixels in a raster and the number of rasters is the addressibility of the display; how many pixels and raster lines are in a given distance is the display’s resolution. The number of times in one second the entire screen is drawn is considered the “refresh rate.”

One last feature helps to control the electrons, making sure they fall precisely on the intended phosphor dots and not spilling over to their neighbors. At the front of the tube, and before the screen, is one of two types of grating structures: a shadow mask or an aperture grill. The shadow mask is used for the phosphor dots depicted in Figure 2.1 and the aperture grill is used for the Trinitron technology. These structures are analogous to the screen door on a house and provide holes through which the electron beam may pass to the proper pixels, and masking errant electrons. Figure 2.2 shows how these features are combined to form a CRT display.

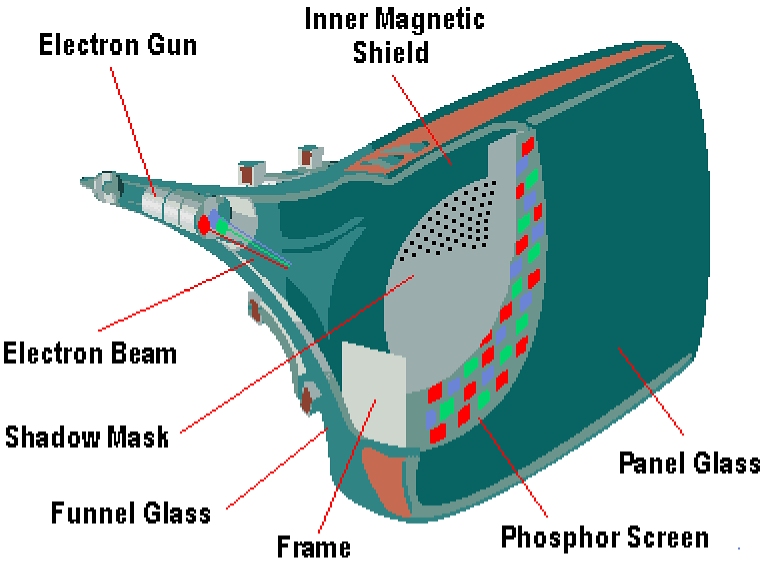

Figure 2.2. A depiction of how a cathode ray tube (CRT) display works.

Starting inside the cathode, an electron is excited and bursts forth from the electron gun. It is then aimed by the magnetic field of the yoke, aiming it at a particular spot on the screen. It then passes through the shadow mask to make sure it is on the proper course. Finally, it strikes the dot of phosphor that gives off a specific color of light which, when the eye combines it with the intensity and wavelength of the other two phosphors in its triad, a single pixel of light is shown on the front of the screen.

2.3.2 LCD Display Technology

LCDs currently are the most widely used of the flat-panel (“thin”) visual displays. In their passive matrix form, they were first widely used with the advent of the portable PC. Recently, active matrix liquid crystal displays (AMLCDs) have become more popular as they build upon the older, passive matrix heritage due to their improved image quality.

In both cases, the display is built around a matrix of thousands of crisscrossing wires and a layer of liquid crystal, sandwiched between two pieces of glass. The liquid crystals are transparent and exhibit the properties of both a solid and a liquid, whose long molecules tend to orient themselves roughly parallel to each other. To perfectly align these molecules, the liquid crystals can be placed along a finely grooved surface, such as an etched plate of glass. In an LCD, the two sandwiching plates of glass have grooves running in perpendicular directions – one plate's grooves are cut north-south and the other go east-west. This causes one end of the liquid crystal molecules to align north-south and the other end to line up east-west, forcing the molecules to "twist" 90°.

As light passes through liquid crystal, it follows the alignment of the liquid crystal molecules. Thus, the light follows the twisted molecules from one plate of glass to the other. This twisting is depicted in Figure 2.3.

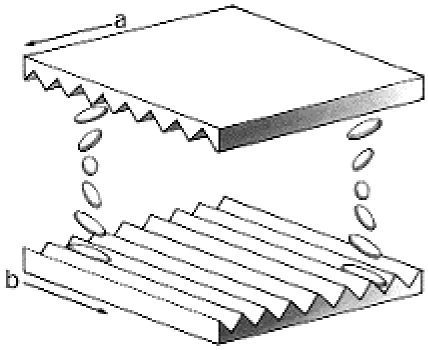

Figure 2.3. The twisting of the liquid crystal between the perpendicularly grooved panes of glass.

However, by putting an electrical voltage across the liquid crystals, the molecular alignment can be straightened, which in turn straightens the light passes through the crystals.

To get the light to follow the molecules, the light first needs to be polarized. Polarized light is comprised entirely of waves in the same plane. As can be seen in the top portion of Figure 2.4, an LCD is constructed with two polarizing filters. Just as the grooves in the glass plates are aligned perpendicularly, so are the filters. Ordinarily, this would totally block all light coming through both filters. In between the filters, however, is the twisted liquid crystal to realign the light. Therefore, light waves from the backlight (usually in the form of fluorescent tubes that snake through the back of the unit) enter the first polarizer, are twisted 90° by the liquid crystals, and then allowed to pass through the second polarizing filter, which then can be seen by the viewer. However, when the electrical voltage mentioned above is applied across the liquid crystal, the molecules straighten and do not twist the light, causing it to be blocked by the second filter. This means that when no voltage is applied, light passes through, and darkness is created when a voltage is applied. This arrangement saves energy for positive polarity displays, but could be reversed if predominantly negative polarity displays are desired.

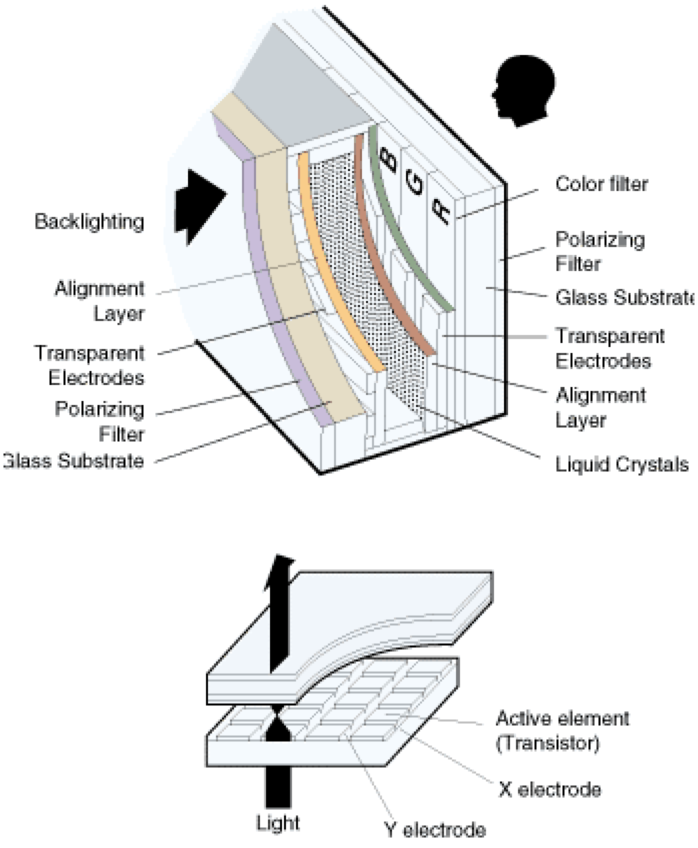

Figure 2.4. (Top) The anatomy of a liquid crystal display. (Bottom) The configuration of transistors in an AMLCD.

These voltages are created at each cell by a series of electrodes at the end of every row and column. The crisscrossing of these electrodes activates an individual cell of liquid crystal (diode) and constitutes the basis for a displayed image. This is how “passive matrix” LCDs work.

To create color, there are three cells for each pixel – one for red, green, and blue. To produce a wide range of colors, however, different intensities of red, green, and blue need to be created. This is done by applying differing voltages to the liquid crystals which induce them to only untwist partially, in proportion to the voltage applied.

Since the individual diodes in these passive matrix LCDs are relied upon for their persistence to create the on/off effect, the physical properties of the liquid crystal are very important for the display’s image quality. There are some shortcomings to those properties, however, including low contrast, “ghosting,” and slow response times. To correct these problems, transistors are added to each RGB element for each pixel of the entire display. These transistors drive the individual diodes, instead of the crisscrossed voltages, and create an “active matrix” display. The layout of the transistors is depicted in the bottom portion of Figure 2.4.

Light from the fluorescent backlighting of an LCD display first passes through a polarizer before entering the first plate of glass used for alignment of the liquid crystals. It then moves through the layer of liquid crystal, which may or may not be twisted, depending on whether a voltage is being applied to it by electrodes (for a passive matrix display) or transistors (for an active matrix display). The light then passes through a color filter to create a desired intensity of red, green, or blue light, and then finally meets the final polarizing filter. If the light has followed a twisted liquid crystal molecule, it will be able to pass through the second polarizer and emerge on the face of the display as light for the viewer to see. If the liquid crystal molecule had been straightened by voltage, the light wave will not be able to pass through the second polarizer and a dark pixel will appear on the screen.

This review of the current state of display technology indicates that a change is taking place in the computer world. Before this change is fully realized the human factors engineers need to assess what impact it may have on humans and offer improvements based on empirical evidence. The issue of visual fatigue is important to this technological change, but the review of the existing body of research points to many gaps in the research community's knowledge of visual fatigue and how best to assess it.

This dissertation research's objectives were to fill in the gaps of visual fatigue research methodology and to resolve the issue of how different display technologies impact visual fatigue.

3.0 METHODS

This dissertation research consisted of two phases of research. First, optical measurements of four computer displays were made. Second, a human factors engineering experiment was conducted with human participants using one curved CRT, one flat (planar) CRT, and two active matrix LCDs.

3.1 Monitors

In order to test for visual fatigue effects attributed to display technology, several displays were used in this experiment. The displays were: (1) a conventional curved-screen CRT: the Mitsubishi Model: RD17G III which has a 17” picture tube (15.87” viewable area) using Trinitron technology with 0.28mm stripe pitch; (2) a flat-screen CRT technology: the LG Electronics Model: Flatron 78 FT using has a 17” picture tube (15.87” viewable area) using slot-mask technology with 0.28mm dot pitch: (3) an active-matrix LCD: the LG Electronics/Philips Model: Studioworks 880 LC with a 18.1” viewable area and an intrinsic resolution of 1280x1024 pixels; and another active-matrix LCD: the Samsung Model: Sync Master 800 TFT with a 18.1” viewable area and an intrinsic resolution of 1280x1024 pixels. All displays are high-end commercial models provided by LG Electronics for use in this research.

During the experiment, the monitor casings were blocked to hide their identification from the participants.

3.2 Optical Image Quality Testing

To gather data of a more objective nature, tests of the optical properties of the four monitors were carried out.

3.2.1 Equipment

The photometric equipment used for this work is located in the Displays and Controls Laboratory at Virginia Polytechnic Institute and State University. The equipment consists of a two-dimensional CCD detector (Photometrics, Model AF 200), mounted on a large-area XYZ translation stage (Areotech, Model: 101SMB2-HM). The translation stage and photometer are coupled to a vibration-isolated optical bench that contains a stand for accurate positioning of the displays under test conditions (see Figure 3.1). Additionally, a hand-held photometer (Minolta, Model: CS-100) with a one-degree circular aperture was used. All photometric equipment was calibrated to NIST-traceable standards for luminance before measurements were taken.

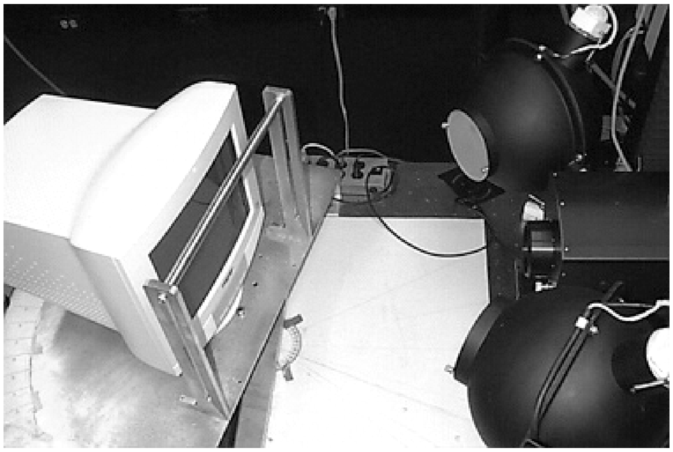

Figure 3.1. Photometric equipment configuration, showing CRT under test, display positioning stand, dual glare sources (integrating spheres), and microphotometer.

3.2.2 Procedures

First, the four monitors were calibrated with respect to active image area, addressibility, and display luminance contrast. Each monitor was measured for its maximum and minimum capability in each of these categories and a common a setting across all four monitors was found. Table 3.1 lists the common monitor settings.

TABLE 3.1 – Calibrated Monitor Settings

Display Characteristic	Value
Active Image Area	15.88" (diagonal)
Addressibility	1152x870
Maximum Luminance (center)	85 cd/m^2
Minimum Luminance (center)	0.5 cd/m^2
Refresh Rate	75 Hz

These settings were used for all human performance measurements.

3.3 Human Performance Test

The following describes the overall architecture of the experiments, the participants who were recruited to carry out the study, what resources were used for the experiment, and finally a description of the tasks that the participants were asked to perform, including the independent and dependent variables.

For the human performance experiment, participants were asked to perform several tasks that typically occur at computer workstations. These tasks included a word processing task, a data entry task, and a Web browsing task. This group of tasks collectively is known as the Office Task Battery (OTB). Although these three tasks have been used in other studies related to computer work (Probst, 2000; Simmons and Manahan, 1999), this task battery is being developed specifically for this research.

3.3.1 Methods

The human performance study for this dissertation research was conducted over a five-week period. The experiment used Lighting (ambient illumination) and Monitors as independent variables. Ambient illumination of the work area was set at 0, 300, 600, or 1200 lux. The four monitors described in Section 3.1 constituted the four levels of the Monitors variable. The 16 treatment conditions (4 Lighting x 4 Monitors) these independent variables create are shown in Table 3.2.

TABLE 3.2 – Treatment conditions for the Human Performance Experiment

	Ambient Illumination			
Monitor	0 lux	300 lux	600 lux	1200 lux
LG Electronics Flat CRT (LGF)	Participants 1-10 (T1)	Participants 1-10 (T5)	Participants 1-10 (T9)	Participants 1-10 (T13)
Mitsubishi Curved CRT (Mitsu.)	Participants 1-10 (T2)	Participants 1-10 (T6)	Participants 1-10 (T10)	Participants 1-10 (T14)
LG Electronics/ Philips AMLCD (LGLCD)	Participants 1-10 (T3)	Participants 1-10 (T7)	Participants 1-10 (T11)	Participants 1-10 (T15)
Samsung AMLCD (SLCD)	Participants 1-10 (T4)	Participants 1-10 (T8)	Participants 1-10 (T12)	Participants 1-10 (T16)

The experiment used a within-subjects design whereby each participant received each treatment condition once.

The experiment sessions were conducted as follows. Participants arrived at 8:00am on Day #1. The first hour was devoted to an initial visual acuity and contrast sensitivity test to determine if their vision was adequate for the experiment. The rest of the hour was devoted to training, in which the participants performed trials of each OTB task until they felt comfortable with the task demands. Participants then were given a short break and asked to return at approximately 9:00am. Starting then, participants alternated 90 minute experiment sessions with 60 minute breaks. Their hour break allowed for sufficient recovery from any visual fatigue experienced during the first trial (Magnussen et al., 1992; Megaw, 1995). A day consisted of four experiment sessions and three breaks, totaling nine hours. Thus, Day #1 lasted ten hours from 8:00am-6:00pm and Days #2-4 lasted nine hours, from 8:00am-5:00pm.

Table 3.3 shows the treatment orders for each participant by day. The order of presentation was designed to counterbalance the lighting and monitor conditions.

TABLE 3.3 – Treatment Order for the Human Performance Experiment

	Day 1				Day 2			
Part. #	1	2	3	4	1	2	3	4
1	T1	T15	T12	T5	T2	T16	T11	T6
2	T2	T16	T11	T6	T1	T15	T12	T5
3	T5	T11	T16	T1	T6	T12	T15	T2
4	T6	T12	T15	T2	T5	T11	T16	T1
5	T9	T8	T3	T13	T10	T7	T4	T14
6	T10	T7	T4	T14	T9	T8	T3	T13
7	T13	T4	T7	T9	T14	T3	T8	T10
8	T14	T3	T8	T10	T13	T4	T7	T9
9	T6	T10	T15	T3	T1	T13	T12	T8
10	T7	T11	T14	T2	T4	T16	T9	T5

	Day 3				Day 4			
Part. #	1	2	3	4	1	2	3	4
1	T3	T14	T9	T7	T4	T13	T10	T8
2	T4	T13	T10	T8	T3	T14	T9	T7
3	T7	T10	T13	T3	T8	T9	T14	T4
4	T8	T9	T14	T4	T7	T10	T13	T3
5	T11	T5	T2	T15	T12	T6	T1	T16
6	T12	T6	T1	T16	T11	T5	T2	T15
7	T15	T1	T6	T11	T16	T2	T5	T12
8	T16	T2	T5	T12	T15	T1	T6	T11
9	T5	T9	T16	T4	T2	T14	T11	T7
10	T8	T12	T13	T1	T3	T15	T10	T6

During each 90 minute session, participants were given an initial contrast sensitivity test and a visual fatigue questionnaire to fill out. Then, they entered the experiment room and were given three minutes to adjust to the lighting level. Once they adapted, they performed the OTB tasks for a period of 75 minutes – 25 minutes for each of the three tasks. (A description of these tasks can be found in Section 3.3.4.) Upon completion of the tasks, the participants immediately completed a second contrast sensitivity test, a second visual fatigue questionnaire and a subjective image quality survey.

3.3.2 Participants

The experiment employed ten participants (five female, five male). They were between the ages of 18 and 40 years (the upper limit was to preclude participants who may have had significant presbyopia), were tested with an Ortho-Rater device to verify each had 20/30 visual acuity or better for corrected, near, binocular vision, and attested in the Informed Consent form to be free of ocular diseases that may have impaired their vision. Those who required glasses or contact lenses to correct their acuity were required to wear their correction during the experiment and all vision tests; no sunglasses, tinted eyeglasses, or tinted contact lenses were allowed. The participants were recruited by a local temporary employment agency to have skill with basic office tasks (e.g., typing), the Microsoft Office software suite, and a Web browser.

3.3.3 Equipment

The human performance test was conducted in the Displays and Controls Laboratory at Virginia Polytechnic Institute and State University. The experiment room was designed to produce calibrated ambient illuminations levels in the vertical plane of the monitor from 0 to over 1300 lux, using overhead fluorescent lights.

To complete the experiment, each participant used a single Apple Macintosh G3 personal computer. Foam core/cardboard masks were placed over the monitors to conceal their identity from the front, top, and sides.

The software participants used to perform the OTB was comprised of Microsoft Word 98, Microsoft Excel 98, and Internet Explorer 4.5. Additionally, the tasks were presented and time-to-completion data and web browsing target counts data were recorded using software developed by the experimenter in SuperCard 3.6.

3.3.4 Procedures

During the 90 minute experiment sessions, each participant worked continuously for 75 minutes in an effort to induce visual fatigue. For the three tasks of the OTB, the monitors were set to positive polarity (i.e., dark characters on a light background). This contrast polarity setting was used primarily because most modern display workstations (especially using the Macintosh operating system) use positive polarity; subjective ratings of image quality also have been found to be higher using positive polarity than negative polarity (i.e., light characters on a dark background) (Beaton, 1999).

Described below are the three OTB tasks and how they were carried out by the participants.

3.3.4.1 Word Processing Task

In the word processing task, participants were asked to transfer text from one application window (presented by the SuperCard program) to a window of a word processor (Microsoft Word 98 for Macintosh). The time to completely enter the text into the word processor window, as well as the number of typographical and formatting errors committed during transfer, was measured.

Each window of the SuperCard program (termed a “card”) had a screen of text to be transferred to the word processor; the text was locked so that copying and pasting could not be used to transfer the text to the word processor. A sample passage of text is presented in Figure 3.3.

when bird lock tramp below *win* beard bob end
sofa how *coast* nest was bomb taffy eve dodge
cat what court **ocean** bike bag left other zag
crumb sky home left table rib dark **homer** bug
beep par party was life law brim catch lodge
three eat ice fried live map under germ case
forum rent *lit* union pat carp beige dent eel
spent ink bunt sniff zoo neon mop **fruit** life
green guard add evil her **brick** camp bud over

Figure 3.2. A sample of source text for word processing task (adapted from Henning, Callaghan, Guttman, and Braun, 1995).

The text was chosen such that each line contained a randomly-ordered series of three three-letter words, three four-letter words, and three five-letter words. This is an adaptation of a similar text-entry task used by Henning, Callaghan, Guttman, and Braun (1995). However, in their task, one of the first four letters was asked to be typed backward to increase cognitive load. In this task, one of the nine words per line was presented in bold, italics, or underlined in an effort to increase visual load.

The timer began as the card was shown to the participant. The participant was instructed to faithfully transfer the text (including proper spelling and formatting) to the word processor window. The number of mistakes in transferring the text was used as the accuracy measure for this task. When they completed transferring the text, they were instructed to click on the “Next Word Set” button in the SuperCard window. This button click stopped the timer for the previous text passage and took the participant to a inter-trial screen. (The SuperCard timer measures to 1/60th of a second.) While on the inter-trial screen, participants were asked to insert a page break below the text passage in the word processing window and then to resume typing as quickly as possible. Participants continued to enter text passages until the first 25 minute time period of the experimental session was complete. Incomplete passages due to the end of the time period were thrown out.

3.3.4.2 Data Entry Task

The second 25 minute session began immediately after each participant closed the word processor window and opened the spreadsheet application (Microsoft Excel 98 for Macintosh). A similar arrangement from that used in the word processing task was used for this task. A SuperCard window was open in addition to the spreadsheet window and a data set was shown in it. The participants were asked to faithfully transfer the entire set of data over to the spreadsheet window, including column headers, decimal points, and hyphens. A sample data set used for this task is presented in Figure 3.4.

SS#	AGE	GENDER	EXP. (YRS.)	VALUE A	VALUE B	VALUE C	VALUE D	VALUE E	VALUE F	
3	7	18	1	0	187.2725	20090450	0.9292123	5.646591	1743	1.042353
1	6	22	1	1	113.9934	49494405	1.888472	6.106489	2334	0.7676536
6	2	21	1	4	83.939	13303120	1.659481	5.388202	1844	0.1989363
7	0	18	2	0	101.8653	49158992	1.945669	6.95987	2056	0.8178297
5	5	33	2	11	54.80767	44202522	2.133082	6.924398	2409	0.9624075
8	0	47	2	25	41.6118	42649158	0.3685111	5.863209	2682	0.1240636
7	1	31	2	8	91.96536	10428026	1.387612	5.179986	2373	0.4943875
8	1	24	1	4	162.929	59062159	1.093035	5.944434	1581	0.7620388
7	9	28	2	6	190.9677	26610620	1.882545	6.236019	2189	0.1596225

Figure 3.3. A sample of source data for the data entry task.

Task completion time and accuracy were used as dependent measures of performance. Time was measured from the opening until the closing of a card in the SuperCard window. Accuracy was measured by how many numerals and any other requisite characters (e.g., hyphens or decimal points) were transferred incorrectly.

Again, an inter-trial card was used to allow the participants time to insert a page break below the transferred data set and encouraged to move onto the next data set as quickly as possible. Participants continued to enter sets of data until the 25 minute session was complete. Incomplete data sets due to the end of the time period were thrown out.

3.3.4.3 Web Browsing Task

The final 25 minute session involved browsing the World Wide Web. This task asked the participants to utilize some of the features of a Web browser and the Web itself. Specific directions were given to search for a particular page and then follow anywhere from two to five links before reaching a page that contained mostly text. This page of text was chosen to be between 10-15Kbytes in size. Once there, they were asked to count the number of instances of a particular word (e.g., “the”) on the page. They were instructed that they were not to read the page and that they were only judged on time and the correct count of the target word. They also were instructed not to use the Web browser’s “Find” feature. A sample Web browsing task is shown in Figure 3.5.

Sample of a web-browsing task:

Go to the Yahoo search engine at: http://www.yahoo.com and enter “winston churchill” (no quotes) into the Search field.
Select link: International Churchill Societies
Select link: Written Word
Select link: Book Reviews
Select link: Churchill and People
Select link: His Father's Son: The Life of Randolph Churchill
Search for the word “he”

Figure 3.4. A sample instruction set for the web browsing task.

Again, task completion time and accuracy were measured. As with the two previous tasks, instructions were displayed in the SuperCard window; response time was measured as the length of time the card remained on the screen, and accuracy was measured as the difference between the participant’s count of the target word and the actual number of times it appeared on the Web page. Participants continued to perform the web browsing task until 25 minutes elapsed. Incomplete scannings of the Web page due to the end of the time period were discarded.

Each of these three computer-based tasks were different in terms of demands on the user. The word processing task requires both hands to be used for typing on the major portion of the keyboard, with minimal use of the mouse, except to navigate the windows and position the cursor. The data entry task relies on use of the numeric keypad of the keyboard. As in the word processing task, minimal use of the mouse is needed. Finally, the Web browsing task relied on use of the mouse to navigate the Web pages, with limited use of the keyboard. It also created a more dynamic screen as the participant scrolled through the Web pages. The written instructions that the participants were given for these three tasks can be found in Appendix D.

3.4 Visual Fatigue Measurement

The principal measurement of visual fatigue in this dissertation research was by a pre- and post-session questionnaire (Appendix B). Numerous symptoms associated with intensive work at a VDT, and in turn with visual fatigue, were inquired by the questionnaire (Chi and Lin, 1998; Conlon et al., 1999; Dillon and Emurian, 1995; Jebaraj, Tyrrell, and Gramopadhye, 1999; Matthews and Desmond, 1998; and Watten, Lie, and Magnussen, 1992). The visual fatigue questionnaire used a continuous response scale (Tyrrell and Leibowitz, 1990) which is less prone to response carry-over effects (i.e., from the pre-test while taking the post-test or from a previous session). Participants were asked how noticeable each of the following symptoms were at the time they filled out the questionnaire:

- dry eyes
- watery eyes
- eyes are irritated, gritty, or burning
- pain in or around the eyeball
- heaviness of the eyes
- problems with line-tracking

- difficulty in focusing
- “shivering/jumping” text
- “foggy” letters
- glare from lights
- blurry vision
- double vision

In addition, some questions about general fatigue were included in the questionnaire:

- headache
- neck pain
- dizziness
- nausea
- mental fatigue

Response scale anchors for the continuum were used, with the left end-point being termed “Not noticeable at all,” the mid-point termed “Somewhat noticeable,” and the right end-point termed “Extremely noticeable.” The distance of the participant’s response (i.e., a vertical mark) from the left endpoint of the scale was measured to the nearest half millimeter, divided by the entire scale’s length (99 mm), multiplied by 100, and rounded to the nearest tenth to index the response. Thus, a greater value indicates more noticeable fatigue symptoms. The questionnaire is shown in Appendix B.

3.5 Performance Measurement

Dependent variables measuring performance collected in this study were time and errors. For each of the three tasks, each variables was averaged per task trial. Greater values for each variable indicated poorer performance.

3.6 Subjective Image Quality Rating

Immediately after each 75 minute experiment session, the post-session contrast sensitivity test, and the post-session visual fatigue questionnaire, the participants completed a short survey about their subjective rating of the image quality of the monitors they had just used. Subjective ratings about the following monitor characteristics were collected:

- Size too small
- Flicker
- Blur/Sharpness
- Reflections
- Inhomogeneous luminance (uniformity)

(Menozzi, Napflin, and Krueger, 1999)

- Symbol distortion (e.g., stair-stepping, lack of clarity/sharpness, smearing)
- Symbol Color Anomalies (e.g., color contrast, color purity, color variations)
- Brightness Anomalies (e.g., brightness contrast, roping, brightness variations across displays or symbols)
- Anomalies associated with flicker, jitter, or noise

(Toms and Cone, 1995)

Participants used a continuous rating scale for all monitor characteristics which were included, with the exception of overall image quality which was indexed a 9-point Likert-type scale (Hunter, 1988). Adjective anchors for overall image quality assisted the participants in making their judgment (i.e., 1-worst imaginable, 5-passable, 9-best imaginable, etc.). The survey is shown in Appendix C.

3.7 Contrast Sensitivity Measurement

A second indicator of visual fatigue was the difference in pre- and post-session visual contrast sensitivity. Contrast sensitivity was measured using the VisTech Contrast Sensitivity Test System. The system uses sine-wave grating patterns of 1.5, 3.0, 6.0, 12.0, and 18.0 cycles/degree of visual angle on a chart that the participant views from ten feet away. Under proper illumination, each spatial frequency has gratings of decreasing contrast that the participant identifies the orientation of grating lines. For this experiment, two charts with different grating alignments were used to make it more difficult for participants to learn the test's answers.

Numerical values for contrast sensitivity were obtained with the VisTech system for 1.5, 3.0, 6.0, 12.0, and 18.0 cycles/degree. The contrast sensitivities were measured before and after each 75 minute session and the difference from pre- to post-test ($\Delta CS=CS_{(post)}-CS_{(pre)}$) was recorded. Negative values indicate a decrease in the contrast sensitivity of the eye.

4.0 RESULTS AND DISCUSSION

After the data were collected they were subjected to mathematical and statistical analyses. The first step of data analysis involved standardizing the data; Z-score transformations of the participants' data for each of the dependent variables were computed. This resulted in 360 subsets of data (10 participants x 36 dependent variables). Arithmetic means and standard deviations for these data subsets were calculated and the 16 data points in each subset had its respective subset mean subtracted from it and then divided by its respective subset standard deviation.

The results of the analyses performed using the standardized data are presented below, followed by a discussions of the results.

4.1 Visual Fatigue

The focus of this dissertation research was to investigate how display technology and ambient illumination influence the subjective experience of visual fatigue while working at VDT workstations. This was investigated by means of a 17-question survey administered before and after a 75 minute experimental session. The data generated by the survey were analyzed by first reducing of the survey by means of a Principal Components Analysis (PCA) and a Factor Analysis (FA), followed by a multivariate analysis of variance (MANOVA), univariate analysis of variance (ANOVA), and a correlational analysis are presented below.

4.1.1 Visual Fatigue Questionnaire Reduction

The development of the original 17-question visual fatigue questionnaire for this research was designed to encompass a wide range of symptoms of visual fatigue that have been used in previous studies. As such, it was designed to be somewhat inflated so that the survey could more fully explore what factors of visual fatigue are the most beneficial for inquiry. Thus, the first step in the analysis of the visual fatigue data was to determine which of the 17 questions were to be included in data analysis and for the proposed comprehensive questionnaire.

The standardized visual fatigue data were initially subjected to a PCA and a FA to determine if any questions in the questionnaire contributed little to no variance to the survey as a whole. Figure 4.1 lists the eigenvalues and eigenvectors of the PCA, Figure 4.2 lists the factor pattern from the FA, and Figure 4.3 shows the scree plot of the eigenvalues from both analyses.

```
            Eigenvalues of the Covariance Matrix

     Eigenvalue    Difference    Proportion    Cumulative

1    4.05196435    2.60844102        0.2668        0.2668
2    1.44352333    0.06951544        0.0950        0.3618
3    1.37400789    0.23706743        0.0905        0.4523
4    1.13694046    0.18923324        0.0749        0.5271
5    0.94770722    0.08164028        0.0624        0.5895
6    0.86606694    0.09593014        0.0570        0.6465
7    0.77013680    0.03584485        0.0507        0.6973
8    0.73429195    0.06849332        0.0483        0.7456
9    0.66579863    0.09968336        0.0438        0.7894
10   0.56611527    0.04238747        0.0373        0.8267
11   0.52372780    0.06893773        0.0345        0.8612
12   0.45479008    0.00573836        0.0299        0.8911
13   0.44905172    0.08254764        0.0296        0.9207
14   0.36650408    0.04777751        0.0241        0.9448
15   0.31872656    0.02870125        0.0210        0.9658
16   0.29002531    0.06073912        0.0191        0.9849
17   0.22928619                      0.0151        1.0000

                         Eigenvectors

          Prin1     Prin2     Prin3     Prin4     Prin5

SVF1   0.079969  -.156316  -.090004  0.630487  0.500978
SVF2   0.252664  0.234748  -.296990  -.373986  0.174372
SVF3   0.294132  0.182464  -.347145  -.057169  0.204313
SVF4   0.250715  0.162965  -.444583  0.190761  -.116160
SVF5   0.305482  0.086277  -.055722  -.273157  -.120287
SVF6   0.324995  0.012060  0.052155  -.040817  0.038634
SVF7   0.351018  -.306614  -.092451  -.125856  0.184861
SVF8   0.223668  -.122787  0.092691  0.009613  -.349265
SVF9   0.328013  -.388716  0.095995  -.059490  0.032696
SVF10  0.210566  -.105102  0.251691  -.099530  -.239670
SVF11  0.297657  -.358910  0.209972  0.078309  0.169131
SVF12  0.187587  -.036351  0.110013  0.352315  -.382945
SVF13  0.202683  0.322287  -.136374  0.427191  -.283480
SVF14  0.160274  0.362959  0.246043  0.036053  0.195781
SVF15  0.141019  0.284192  0.365370  0.031347  0.202106
SVF16  0.036824  0.266940  0.361971  -.032800  0.280696
SVF17  0.210906  0.253011  0.300270  0.034592  -.138441
```

Figure 4.1. The eigenvalues and eigenvectors from the PCA of all visual fatigue data.

```
                                Factor Pattern

               Factor1        Factor2        Factor3        Factor4        Factor5

SVF1           0.16326       -0.18228        0.03036        0.61495        0.59865
SVF2           0.51726        0.00253       -0.43164       -0.42482        0.07803
SVF3           0.60562       -0.08559       -0.44724       -0.09315        0.17257
SVF4           0.55026       -0.22417       -0.58852        0.20874       -0.04189
SVF5           0.62936        0.01046       -0.12279       -0.30218       -0.11451
SVF6           0.71831        0.03419        0.04073       -0.06782        0.02581
SVF7           0.71617       -0.35001        0.16378       -0.17289        0.21623
SVF8           0.49708       -0.08233        0.21872        0.07764       -0.44114
SVF9           0.66909       -0.29897        0.39739       -0.07822        0.07363
SVF10          0.43208        0.05658        0.30228       -0.08582       -0.18468
SVF11          0.60802       -0.17595        0.47706        0.05832        0.20869
SVF12          0.41928        0.02217        0.15057        0.49937       -0.39219
SVF13          0.42475        0.15601       -0.40032        0.46529       -0.17617
SVF14          0.36155        0.56477       -0.08082        0.01843        0.17065
SVF15          0.32196        0.58139        0.11864        0.02834        0.12236
SVF16          0.09577        0.66170        0.15512       -0.05459        0.26268
SVF17          0.47346        0.45695        0.06658        0.04521       -0.17942
```

Figure 4.2. The factor pattern from the FA of all visual fatigue data.

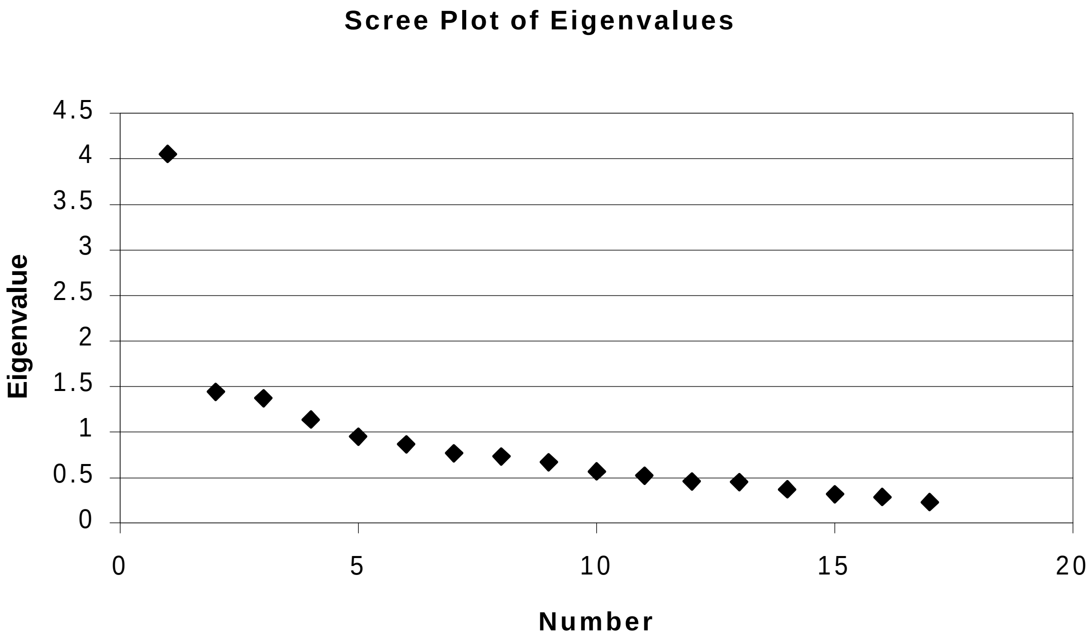

Figure 4.3. The scree plot of eigenvalues for all standardized visual fatigue data.

The first principal component accounts for 27% of the variance in the data set and is, by far, the largest principal component. Figure 4.3 shows the first eigenvalue to be much greater than the other 16, which are grouped together below 2.0. This finding indicates that the first principal component explains much of the variance associated with visual fatigue and that the group of questions strongly associated with the first principal component from the PCA and the first factor from the FA should be considered for a refined analysis of the questionnaire. By inspection of the first principal component, a value of 0.20 is a reasonable cut-off point, which removes the first Standardized Visual Fatigue (SVF1) question (Dry Eyes), SVF12 (Double Vision), SVF14 (Neck Pain), SVF15 (Dizziness), and SVF16 (Nausea) from further analysis. From the first factor of the FA, selecting a cut-off point of 0.42 results in the removal of these same variables. Thus, a second iteration of the PCA and FA was conducted with these variables removed from the data set.

PCA and FA with SVF1, SVF12, SVF14, SVF15, and SVF16 Removed

```
                Eigenvalues of the Covariance Matrix

     Eigenvalue    Difference    Proportion    Cumulative

1    3.77675905    2.38182817        0.3451        0.3451
2    1.39493088    0.37907996        0.1275        0.4726
3    1.01585092    0.15882819        0.0928        0.5654
4    0.85702273    0.11833135        0.0783        0.6437
5    0.73869137    0.07249453        0.0675        0.7112
6    0.66619684    0.03919668        0.0609        0.7721
7    0.62700016    0.05920264        0.0573        0.8294
8    0.56779752    0.16534440        0.0519        0.8813
9    0.40245312    0.04624426        0.0368        0.9181
10   0.35620887    0.05907529        0.0326        0.9506
11   0.29713357    0.05379192        0.0272        0.9778
12   0.24334166                      0.0222        1.0000

                              Eigenvectors

           Prin1         Prin2         Prin3         Prin4         Prin5

SVF2       0.271810      0.347421      -.382970      0.307540      0.108070
SVF3       0.310260      0.371489      -.256460      0.098947      -.074290
SVF4       0.266389      0.426100      0.008213      -.236945      -.219857
SVF5       0.325658      0.075422      0.119314      0.434072      0.081646
SVF6       0.336149      -.024280      0.086543      -.006892      0.279281
SVF7       0.378883      -.194654      -.300489      -.153802      -.114626
SVF8       0.225889      -.136795      -.023592      -.121451      0.520623
SVF9       0.350457      -.367999      -.111050      -.212047      -.135327
SVF10      0.216856      -.237304      0.310813      0.467280      -.593094
SVF11      0.308846      -.413852      -.025273      -.230416      -.027570
SVF13      0.196508      0.365778      0.477303      -.508391      -.195341
SVF17      0.203517      0.006975      0.580970      0.194285      0.395755
```

Figure 4.4. The eigenvalues and eigenvectors from the PCA of the visual fatigue data with SVF1, SVF12, SVF14, SVF15, and SVF16 removed.

```
                          Factor Pattern

                        Factor1        Factor2        Factor3

          SVF2          0.53896        0.40175       -0.36625
          SVF3          0.61973        0.44156       -0.25328
          SVF4          0.56994        0.56585       -0.03801
          SVF5          0.65021        0.08238        0.13333
          SVF6          0.71933       -0.04013        0.10490
          SVF7          0.75149       -0.23405       -0.33132
          SVF8          0.48506       -0.19783       -0.03877
          SVF9          0.69374       -0.44466       -0.13670
          SVF10         0.42912       -0.28792        0.28884
          SVF11         0.61059       -0.50413       -0.04456
          SVF13         0.39738        0.44660        0.43317
          SVF17         0.43890       -0.00718        0.70090
```

Figure 4.5. The factor pattern from the FA of the visual fatigue data with SVF1, SVF12, SVF14, SVF15, and SVF16 removed.

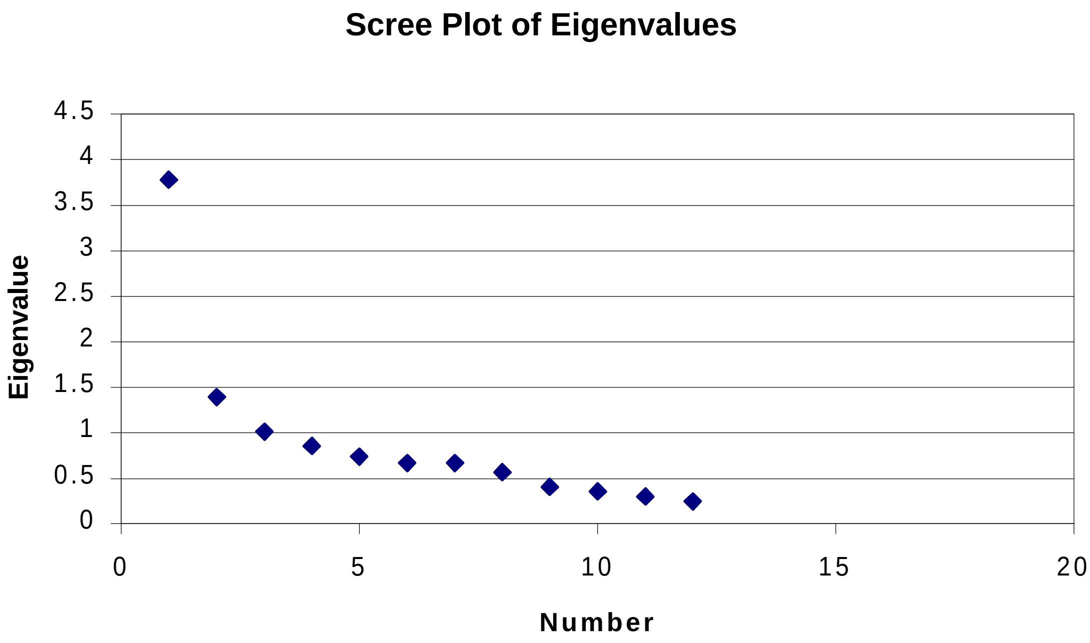

Figure 4.6. The scree plot of eigenvalues of the visual fatigue data with SVF1, SVF12, SVF14, SVF15, and SVF16 removed.

Using the previous cut-off points of 0.20 and 0.42 for the PCA and FA, respectively, both result in the removal of SVF13 (Headache) from further analysis. The disassociation of eigenvalue 1 in Figure 4.6 indicates only one strong combination of variables, thus a third iteration of the PCA and FA was performed, removing SVF13 in addition the previously removed variables.

PCA and FA with SVF1 and SVF12-16 Removed

```
                         Eigenvalues of the Covariance Matrix

                     Eigenvalue    Difference    Proportion    Cumulative

                 1   3.66447360    2.34743061        0.3664        0.3664
                 2   1.31704298    0.36927643        0.1317        0.4982
                 3   0.94776655    0.19351362        0.0948        0.5929
                 4   0.75425293    0.08501392        0.0754        0.6684
                 5   0.66923902    0.01888975        0.0669        0.7353
                 6   0.65034927    0.04078698        0.0650        0.8003
                 7   0.60956229    0.18725632        0.0610        0.8613
                 8   0.42230597    0.03113630        0.0422        0.9035
                 9   0.39116967    0.06415724        0.0391        0.9426
                10   0.32701243    0.08020173        0.0327        0.9753
                11   0.24681070                      0.0247        1.0000

                                      Eigenvectors

           Prin1         Prin2         Prin3         Prin4         Prin5

SVF2       0.275834      0.464261      -.118133      -.129844      0.250402
SVF3       0.311891      0.455496      -.089711      -.096882      0.082703
SVF4       0.253670      0.405793      -.044044      -.006001      -.156073
SVF5       0.332467      0.117986      0.359113      -.070215      -.187507
SVF6       0.342972      -.005838      0.121045      0.323187      -.167373
SVF7       0.393350      -.124895      -.352068      -.085308      -.225349
SVF8       0.232841      -.122342      -.069483      0.472259      0.778655
SVF9       0.364360      -.346738      -.253111      -.064972      -.155470
SVF10      0.224605      -.253228      0.438383      -.687661      0.356559
SVF11      0.319895      -.422140      -.210062      0.009112      -.049975
SVF17      0.199120      -.072409      0.635053      0.396043      -.178995
```

Figure 4.7. The eigenvalues and eigenvectors from the PCA of the visual fatigue data with SVF1 and SVF12-16 removed.

```
                         Factor Pattern

                     Factor1         Factor2         Factor3

         SVF2        0.53902         0.52830        -0.11393
         SVF3        0.61415         0.53094        -0.07637
         SVF4        0.53608         0.53372        -0.05429
         SVF5        0.65421         0.12881         0.32285
         SVF6        0.72377        -0.01437         0.14690
         SVF7        0.76860        -0.13976        -0.36359
         SVF8        0.49312        -0.17299        -0.08628
         SVF9        0.71054        -0.40397        -0.26192
         SVF10       0.43785        -0.29959         0.33674
         SVF11       0.62309        -0.49811        -0.21203
         SVF17       0.42420        -0.11673         0.73705
```

Figure 4.8. The factor pattern from the FA of the visual fatigue data with SVF1 and SVF12-16 removed.

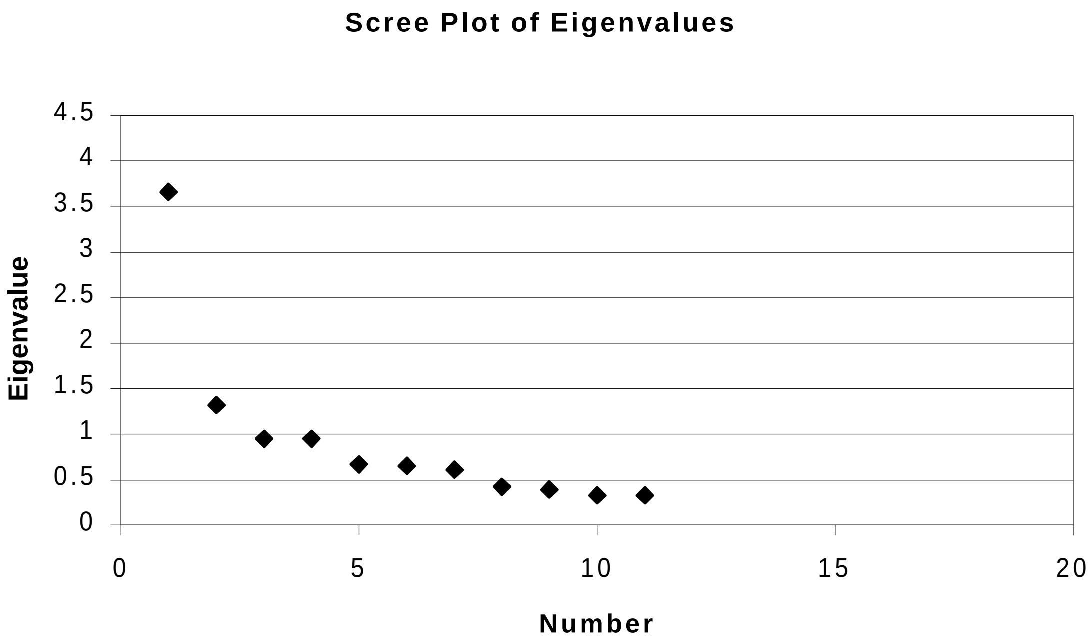

Figure 4.9. The scree plot of eigenvalues of the visual fatigue data with SVF1 and SVF12-16 removed.

While SVF17 (Mental Fatigue) falls below the 0.20 criterion for the PCA, it remains above the 0.42 cut-off point for the FA. Since SVF17's eigenvector for the PCA is very close to the cut-off point (0.19912) and exceeds the cut-off point for the FA, it was retained for the analysis. A single, relatively large eigenvalue is seen again in Figure 4.9, indicating a single variable grouping is suggested by the PCA and FA. As such, a single group of visual fatigue questions, consisting of SVF2-SVF11 and SVF17, was used for further data analysis.

4.1.2 Multivariate Analysis of Variance

Figure 4.10 shows results of the Multivariate Analysis of Variance (MANOVA) tests for the two main effects and one interaction on the whole of the reduced visual fatigue data.

(a) Lighting

```
MANOVA Test Criteria and F Approximations for the Hypothesis of No Overall Lighting Effect
                         H = Type III SSCP Matrix for Lighting
                       E = Type III SSCP Matrix for Part*Lighting
                                S=3    M=3.5    N=7.5

Statistic                       Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda              0.11548010       1.66        33    50.789    0.0503
Pillai's Trace             1.44070585       1.60        33        57    0.0600
Hotelling-Lawley Trace     3.53405102       1.71        33        32    0.0655
Roy's Greatest Root        1.96526620       3.39        11        19    0.0095
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

(b) Monitors

```
MANOVA Test Criteria and F Approximations for the Hypothesis of No Overall Monitors Effect
                          H = Type III SSCP Matrix for Monitors
                        E = Type III SSCP Matrix for Part*Monitors
                                S=3    M=3.5    N=7.5

Statistic                       Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda              0.17515564       1.24        33    50.789    0.2402
Pillai's Trace             1.20749811       1.16        33        57    0.3024
Hotelling-Lawley Trace     2.76321109       1.34        33        32    0.2052
Roy's Greatest Root        1.95066946       3.37        11        19    0.0099
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

(c) Lighting*Monitors

```
                  MANOVA Test Criteria and F Approximations for the
                  Hypothesis of No Overall Lighting*Monitors Effect
                    H = Type III SSCP Matrix for Lighting*Monitors
                  E = Type III SSCP Matrix for Part*Lighting*Monitor
                               S=9    M=0.5    N=34.5

Statistic                       Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda              0.35662331       0.81        99    512.14    0.8953
Pillai's Trace             0.91914140       0.82        99       711    0.8962
Hotelling-Lawley Trace     1.16848727       0.82        99    309.61    0.8783
Roy's Greatest Root        0.46970572       3.37        11        79    0.0007
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

Figure 4.10. The MANOVAs on the reduced visual fatigue data: (a) main effect for Lighting, (b) main effect for Monitors, (c) interaction of Lighting and Monitors.

Roy's Greatest Root is significant for the main effects Lighting and Monitors as well as their interaction (at α=0.05). However, the criterion that was used to judge all MANOVA output for this study is Wilks' Lambda (Johnson, 1998, p. 441). Using this criterion, the main effect for Lighting is significant (p=0.0503), but the main effect for

Monitors and the interaction of Lighting and Monitors was not significant. This finding indicates that the 11 visual fatigue variables – when considered as a single group – were affected systematically by the ambient illumination of the room, but not by the monitors used. The individual visual fatigue questions were analyzed with individual Analyses of Variance (ANOVAs).

4.1.3 Analyses of Variance

To determine which of the reduced visual fatigue variables may have shown significant changes over the experimental session, individual Analyses of Variance (ANOVAs) were performed. Numerous significant main effects were found for both Lighting and Monitors, but no interactions were present.

4.1.3.1 ANOVA of "Watery Eyes"

As shown in Table 4.1, the ANOVA of the "Watery Eyes" question (SVF2) was significant for the main effect of Lighting (p=0.0493). Figure 4.11 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.1 – ANOVA for Visual Fatigue for "Watery Eyes"

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000003	0.00000000		
Within					
Lighting	3	6.02657368	2.00885789	2.97	0.0493
Participant x Lighting	27	18.23475533	0.67536131		
Monitors	3	4.53596190	1.51198730	1.28	0.3013
Participant x Monitors	27	31.90242410	1.18157126		
Lighting x Monitors	9	6.49950149	0.72216683	0.71	0.7013
Participant x Lighting x Monitors	81	82.80152217	1.02224101		
Total	159	150.0007387			

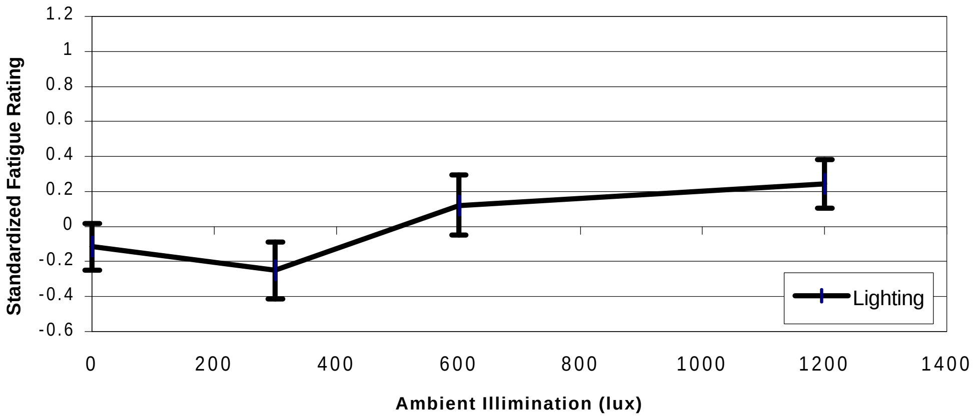

Figure 4.11. The main effect for Lighting on the "Watery Eyes" visual fatigue rating.

A Student Newman Keuls (SNK) post hoc test at α=0.05 did not show significant differences among the mean Lighting levels. However, using the error bars of Figure 4.11, the 300 lux is significantly below the grouping of 600 and 1200 lux and 0 lux below 1200 lux. These observations suggest that brighter lighting conditions lead to a more noticeable level of visual fatigue. Also, the slight (though not significant) elevation for the 0 lux condition over the 300 lux condition may be the result of an experiment artifact. Namely, one participant mentioned to the experimenter that his eyes became watery after the experiment session, at the point when the lights were turned on in the experiment room so the post-sessions surveys could be filled out, but before the questionnaire was completed.

4.1.3.2 ANOVA of "Eyes are Irritated, Gritty, or Burning"

As shown in Table 4.2, the ANOVA of the "Eyes are Irritated, Gritty, or Burning" (SVF3) question was significant for the main effect of Monitors (p=0.0934). Figure 4.12 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.2 – ANOVA for Visual Fatigue for “Irritated, Gritty, or Burning”

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000004	0.00000000		
Within					
Lighting	3	3.50280584	1.16760195	1.36	0.2759
Participant x Lighting	27	23.16995629	0.85814653		
Monitors	3	6.63575342	2.21191781	2.36	0.0934
Participant x Monitors	27	25.27710147	0.93618894		
Lighting x Monitors	9	11.63958840	1.29328760	1.31	0.2431
Participant x Lighting x Monitors	81	79.77418597	0.98486649		
Total	159	149.9993914			

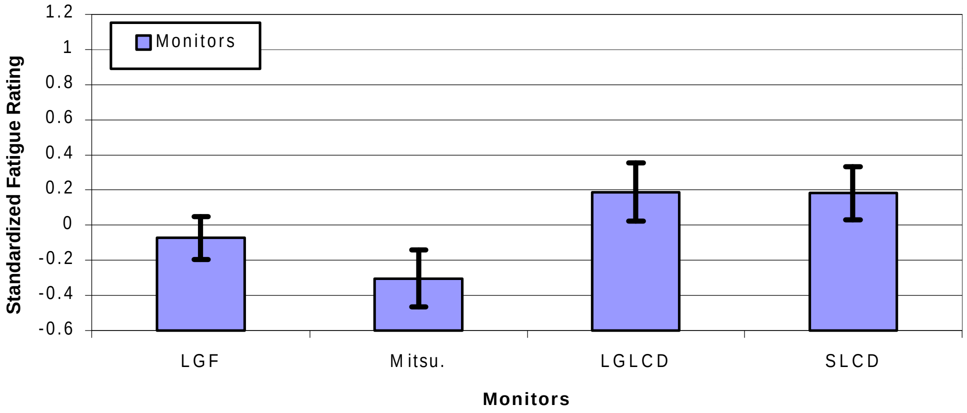

Figure 4.12. The main effect for Monitors on the “Irritated, Gritty, or Burning” visual fatigue rating.

This finding indicates that the two LCD monitors induce more noticeable irritated, gritty, or burning eyes as compared to the two CRTs in this study. Using standard error as a test, the Mitsubishi CRT was associated with the least noticeable symptoms of irritated, gritty, or burning eyes, whereas the two LCD monitors were associated with the most noticeable symptoms of this dimension of visual fatigue.

4.1.3.3 ANOVA of "Pain in or around the Eyeball"

As shown in Table 4.3, the ANOVA of the "Pain in or around the Eyeball" (SVF4) question was significant for the main effect of Monitors (p=0.0092). Figure 4.13 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.3 – ANOVA for Visual Fatigue for "Pain in or around the Eyeball"

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000002	0.00000000		
Within					
Lighting	3	4.47184031	1.49061344	1.43	0.2556
Participant x Lighting	27	28.13056161	1.04187265		
Monitors	3	9.43832982	3.14610994	4.69	0.0092
Participant x Monitors	27	18.12906052	0.67144669		
Lighting x Monitors	9	7.19202881	0.79911431	0.96	0.4816
Participant x Lighting x Monitors	81	67.63719047	0.83502704		
Total	159	134.9990116			

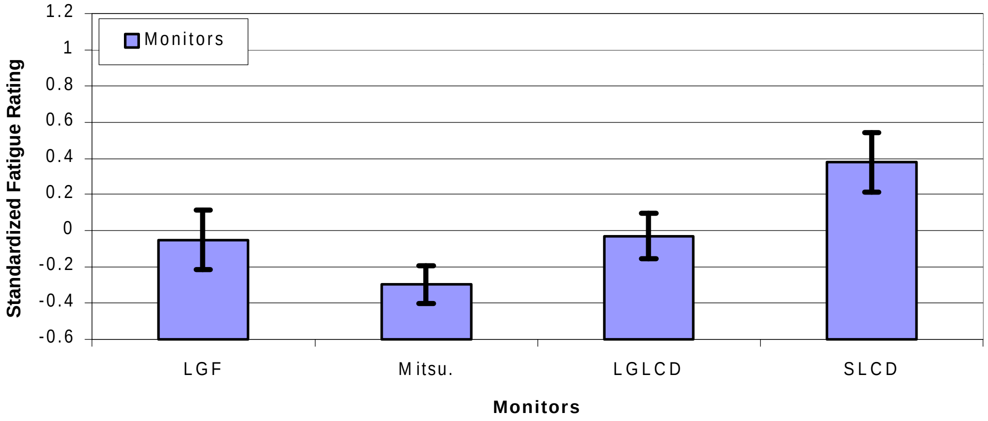

Figure 4.13. The main effect for Monitors on the "Pain in or around the Eyeball" visual fatigue rating.

A Newman Keuls post hoc test at α=0.05 indicated that the LGF, LGLCD, and Samsung LCD monitors were alike, that the LGF, Mitsubishi, and LGLCD monitors were alike, and that the Mitsubishi and SLCD monitors were different from one another. The error bars find this as well and also find that the Mitsubishi monitor was associated with less, and the Samsung LCD monitor significant more, reports of this symptom of visual fatigue when compared to the two LG monitors.

4.1.3.4 ANOVA of "Problems with Line-tracking"

As shown in Table 4.4, the ANOVA of the "Problems with Line-tracking" question (SVF6) was significant for the main effects of Lighting (p=0.0589) and of Monitors (p=0.0066). Figure 4.14 depicts the level differences for the significant effect of Lighting and Figure 4.15 depicts the level differences for Monitors, both graphs including error bars showing +/-1 standard error of the mean.

TABLE 4.4 – ANOVA for Visual Fatigue for "Problems with Line-tracking"

Source	**df**	**Type III SS**	**MS**	**F**	**p**
Between					
Participant	9	0.00000001	0.00000000		
Within					
Lighting	3	7.41489751	2.47163250	2.80	0.0589
Participant x Lighting	27	23.81971776	0.88221177		
Monitors	3	13.29658190	4.43219397	5.05	0.0066
Participant x Monitors	27	23.70824646	0.87808320		
Lighting x Monitors	9	6.04491799	0.67165755	0.90	0.5328
Participant x Lighting x Monitors	81	60.71659626	0.74958761		
Total	159	135.0009579			

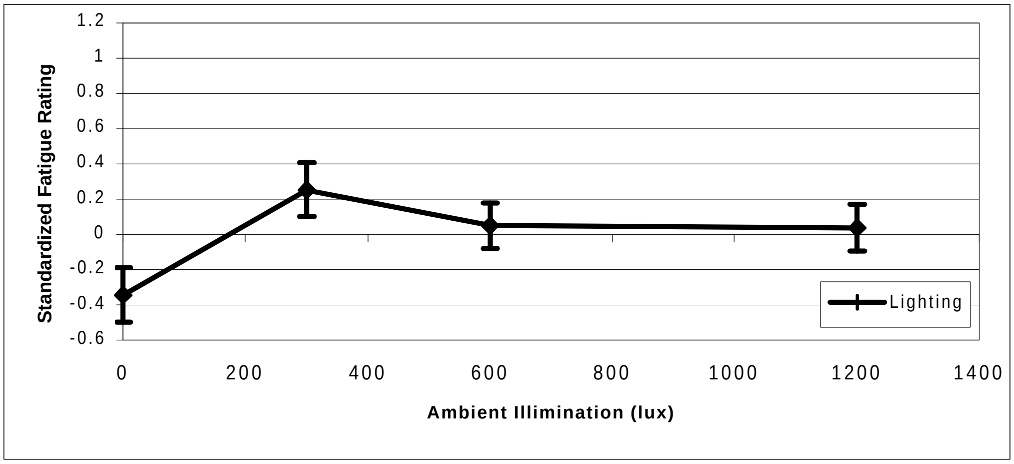

Figure 4.14. The main effect for Lighting on the “Problems with Line-tracking” visual fatigue rating.

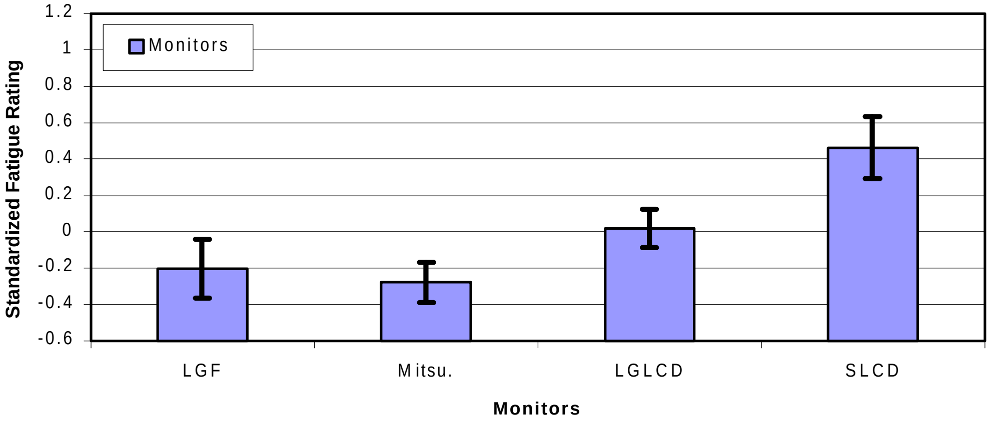

Figure 4.15. The main effect for Monitors on the “Problems with Line-tracking” visual fatigue rating.

A Newman-Keuls post hoc test at α=0.05 for the main effect of Lighting indicated that the 0 lux condition is the best and the 300 lux condition was the worst, with 600 and 1200 lux not being significantly different than either extreme. However, inspection of Figure 4.14 shows that the 0 lux condition was different than the 600 and 1200 lux conditions, finding less noticeable problems with line-tracking. Thus, after sustained work at a VDT workstation, people have less of a problem tracking a line of text across the screen in a dark environment, may have more problems in a dimly lit room, but as the ambient illumination is increased from dim to bright, these problems tend to moderate.

The SNK test on the level means for the main effect of Monitors indicated that the Samsung LCD monitor was associated with reports of more noticeable problems with line-tracking (at α=0.05) when compared to an equal group of the other three monitors. Also, the error bars of Figure 4.15 indicate that the LGLCD monitor caused greater reports of SVF6 symptoms than the Mitsubishi CRT did, with the LGF CRT's mean tending toward that of the Mitsubishi's. Although not significantly different than both CRTs, some indication of a display technology influence can be seen for reports of "Problems with Line-tracking."

4.1.3.5 ANOVA of "Difficulty in Focusing"

As shown in Table 4.5, the ANOVA of the "Difficulty in Focusing" question (SVF7) was significant for the main effect of Monitors (p=0.0002). Figure 4.16 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.5 – ANOVA for Visual Fatigue for "Difficulty in Focusing"

Source	**df**	**Type III SS**	**MS**	**F**	**p**
Between					
Participant	9	0.00000002	0.00000000		
Within					
Lighting	3	0.79228902	0.26409634	0.28	0.8361
Participant x Lighting	27	25.06512083	0.92833781		
Monitors	3	17.72378678	5.90792893	9.50	0.0002
Participant x Monitors	27	16.78370938	0.62161887		
Lighting x Monitors	9	8.08472623	0.89830291	0.89	0.5360
Participant x Lighting x Monitors	81	81.54920081	1.00678026		
Total	159	149.9988331			

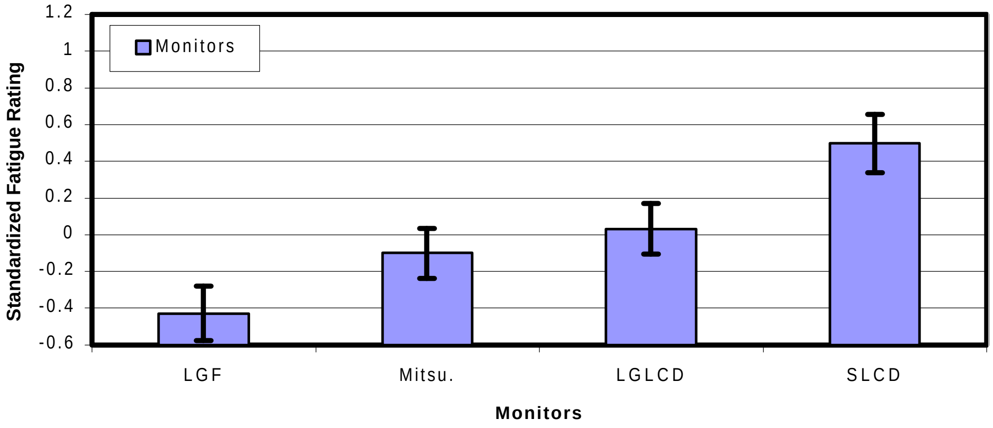

Figure 4.16. The main effect for Monitors on the “Difficulty in Focusing” visual fatigue rating.

Different monitors caused varying amounts of difficulty in the participants’ ability to focus after the experimental session. The level differences for the monitors are somewhat complex. Figure 4.17 depicts the results of the Student Newman Keuls post hoc test (α=0.05).

```
SNK Grouping          Mean      Monitors
           A        0.4980      SLCD

           B        0.0315      LGLCD
           B
      C    B       -0.1005      Mitsu.
      C
      C            -0.4290      LGF

* Means with the same letter are not significantly different.
```

Figure 4.17. The Student Newman Keuls test for the main effect of Monitors for “Difficulty in Focusing”.

Once more, the Samsung LCD was associated with the most noticeable symptoms of SVF7 among the monitors studied, though this time the LG Flatron monitor is the best. Also, as with “Problems with Line-tracking,” the LGLCD monitor was associated with reports of higher visual fatigue symptoms than one of the CRT monitors. Again, although there was no significant display technology influence found since both LCD monitors were not different than both CRTs, some indication exist for its presence.

4.1.3.6 ANOVA of “Foggy Letters”

As shown in Table 4.6, the ANOVA of the “Difficulty in Focusing” question (SVF9) was significant for the main effect of Monitors (p=0.0003). Figure 4.18 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.6 – ANOVA for Visual Fatigue for “’Foggy’ Letters”

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000001	0.00000000		
Within					
Lighting	3	3.58874204	1.19624735	1.05	0.3864
Participant x Lighting	27	30.75318879	1.13900699		
Monitors	3	20.78270070	6.92756690	8.64	0.0003
Participant x Monitors	27	21.64112485	0.80152314		
Lighting x Monitors	9	5.96236696	0.66248522	0.80	0.6194
Participant x Lighting x Monitors	81	67.27240061	0.83052346		
Total	159	150.0005240			

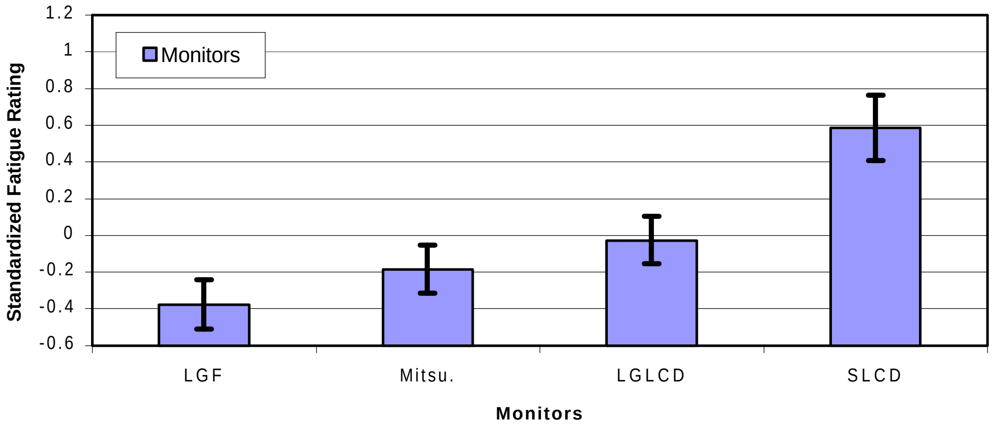

Figure 4.18. The main effect for Monitors on the “’Foggy’ Letters” visual fatigue rating.

As with “Problems with Line-tracking” and “Difficulty in Focusing” the Newman Keuls post hoc test found that the Samsung LCD monitor was associated with greater reports of the visual fatigue symptom "'Foggy' Letters" than the other three monitors. While the SNK range test (at α=0.05) did not show a significant difference between the two CRTs and the LGLCD, the error bars of Figure 4.18 do show that one CRT monitor (in this case, the LGF) is associated with less visually fatigued ratings than the LGLCD, with the other CRT (in this case, the Mitsubishi CRT) tending slightly toward less visual fatigue than the LGLCD. Once more, an indication that CRTs may be associated with lower reports of some symptoms of visual fatigue can be seen in the data.

4.1.3.7 ANOVA of "Glare from Lights"

As shown in Table 4.7, the ANOVA of the "Glare From Lights" question (SVF10) was significant for the main effect of Lighting (p=0.0286). Figure 4.19 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.7 – ANOVA for Visual Fatigue for "Glare From Lights"

Source	**df**	**Type III SS**	**MS**	**F**	**p**
Between					
Participant	9	0.00000004	0.00000000		
Within					
Lighting	3	10.96789631	3.65596544	3.51	0.0286
Participant x Lighting	27	28.10895040	1.04107224		
Monitors	3	2.97877642	0.99292547	0.98	0.4183
Participant x Monitors	27	27.44955189	1.01665007		
Lighting x Monitors	9	1.70703414	0.18967046	0.19	0.9941
Participant x Lighting x Monitors	81	78.78753524	0.97268562		
Total	159	149.9997444			

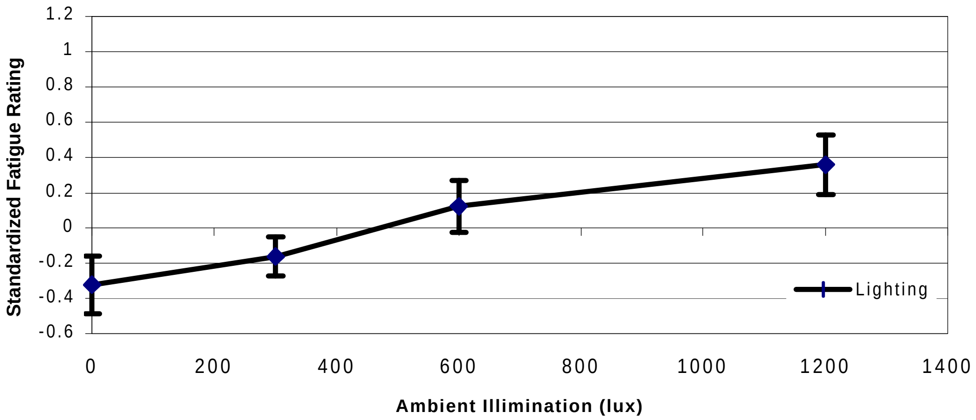

Figure 4.19. The main effect for Lighting on the “Glare From Lights” visual fatigue rating.

The Newman Keuls post hoc test (α=0.05) found that the 0 and 1200 lux conditions were significantly different from one another, with the 1200 lux condition receiving greater reports of noticeable “Glare From Lights”; the 300 and 600 lux conditions were not different from either extreme. Testing level differences using standard error of the means shown in Figure 4.19, a break was found between the 300 and 600 lux conditions; the 0 and 300 lux conditions were associated with less noticeable reports of SVF10 when compared to the 600 and 1200 lux conditions. Both tests indicate that reports of glare from lights are directly proportional to the ambient illumination level. This means that brighter lighting (as measured in lux) makes glare more noticeable to people working for a prolonged period of time at VDT workstations.

4.1.3.8 ANOVA of “Blurry Vision”

As shown in Table 4.8, the ANOVA of the “Blurry Vision” question (SVF11) was significant for the main effect of Monitors (p=0.0618). Figure 4.20 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.8 – ANOVA for Visual Fatigue for “Blurry Vision”

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000003	0.00000000		
Within					
Lighting	3	5.75414761	1.91804920	2.01	0.1365
Participant x Lighting	27	25.78378735	0.95495509		
Monitors	3	8.86917938	2.95639313	2.76	0.0618
Participant x Monitors	27	28.97146302	1.07301715		
Lighting x Monitors	9	4.26298452	0.47366495	0.50	0.8687
Participant x Lighting x Monitors	81	76.35697666	0.94267872		
Total	159	149.9985386			

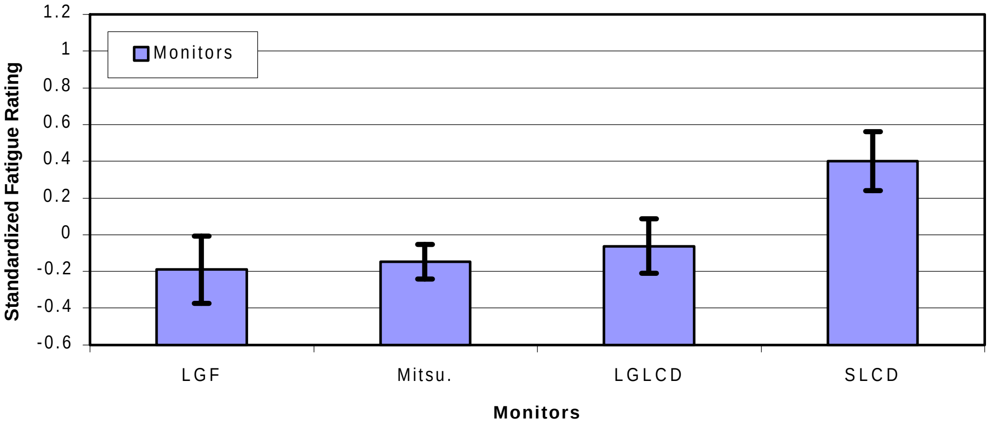

Figure 4.20. The main effect for Monitors on the “Blurry Vision” visual fatigue rating.

A Newman Keuls post test (at α=0.05) did not find any significant differences among the treatment means, though standard errors shown in Figure 4.20 illustrate that the Samsung LCD monitor was associated with greater reports of “Blurry Vision.”

In total, the ANOVA results indicate that the main effect of Lighting affects several aspects of visual fatigue. Ambient illumination affected reports of being sensitive to glare from the lights, line-tracking ability, and watery eyes. In general, greater ambient illumination levels lead to greater reports of these three symptoms of visual fatigue.

The ANOVAs for the main effect of Monitors indicated that the Samsung LCD monitor generated greater reports of visual fatigue symptoms than the other three monitors evaluated. Results for the other three monitors are somewhat muddled. For some questions the LG flat-screen CRT was associated less noticeable symptoms of visual fatigue (e.g., “Difficulty in Focusing” and “'Foggy' Letters”), for other questions it was the Mitsubishi curved-screen CRT (e.g., “Irritated, Gritty, or Burning” and “Pain in or around the Eyeball”). For some visual fatigue symptoms the LGLCD was not significantly different than the CRTs, sometimes it was significantly different than one of them. If there is a conclusion to be drawn from these tests, however, it would be that the two CRTs are quality monitors that are reasonably equitable. The LGLCD monitor is a quality LCD monitor, but its slightly poorer performance for “Irritated, Gritty, or Burning,” “Problems with Line-tracking,” “Difficulty in Focusing,” and “’Foggy’ letters” may indicate that there is a display technology influence on subjective reports of visual fatigue. Namely, that LCDs possibly are more fatiguing on the eyes. However, the effect seen in this study is slight and further investigation is necessary to determine its validity.

4.1.4 Correlational Analysis

The 11 questions of the reduced visual fatigue questionnaire were subjected to a correlational analysis to determine the amount of interrelationship that existed. Table 4.9 presents the matrix of Pearson product moments and their level of significance.

TABLE 4.9 -- Pearson Correlation Matrix for Visual Fatigue Symptoms

	SVF2	SVF3	SVF4	SVF5	SVF6	SVF7	SVF8	SVF9	SVF10	SVF11	SVF17
SVF2	1.0000										
SVF3	0.5394 <0.0001	1.0000									
SVF4	0.3233 <0.0001	0.4977 <0.0001	1.0000								
SVF5	0.3835 <0.0001	0.2899 0.0002	0.3487 <0.0001	1.0000							
SVF6	0.2530 0.0013	0.3763 <0.0001	0.3630 <0.0001	0.4292 <0.0001	1.0000						
SVF7	0.3465 <0.0001	0.3498 <0.0001	0.3461 <0.0001	0.4120 <0.0001	0.5083 <0.0001	1.0000					
SVF8	0.1941 0.0139	0.1854 0.0190	0.1716 0.0300	0.2158 0.0061	0.3402 <0.0001	0.2963 0.0001	1.0000				
SVF9	0.1698 0.0319	0.2913 0.0002	0.1998 0.0113	0.3193 <0.0001	0.4099 <0.0001	0.6499 <0.0001	0.3188 <0.0001	1.0000			
SVF10	0.0903 0.2563	0.1589 0.0448	0.1059 0.1828	0.2999 0.0001	0.2269 0.0039	0.2412 0.0021	0.1649 0.0372	0.3094 <0.0001	1.0000		
SVF11	0.1768 0.0254	0.1762 0.0258	0.0875 0.2714	0.2585 0.0010	0.3662 <0.0001	0.5218 <0.0001	0.3023 0.0001	0.5918 <0.0001	0.2796 0.0003	1.0000	
SVF17	0.1160 0.1441	0.1880 0.0173	0.1109 0.1628	0.3339 <0.0001	0.3662 <0.0001	0.1107 0.1634	0.1639 0.0383	0.2159 0.0061	0.2165 0.0060	0.2246 0.0043	1.0000

Note: values in parentheses are p-values

Noteworthy are two variables that were less well correlated: SVF10: “Glare from Lights” and SVF17: “Mental Fatigue”). This is likely due to their inquiry about somewhat different aspects of the participant’s experience, the former specifically about an artifact of their environment, the latter dealing with a non-visual symptom of visual fatigue.

The variables of the reduced visual fatigue data are very highly and positively correlated with one another. This close interrelationship is a good indication that the 11 symptoms of visual fatigue selected for analysis vary systematically and are mutually supportive of a comprehensive depiction of visual fatigue and work well together in a questionnaire.

4.2 Human Performance

During the experiment data were collected on how long and accurately the participants performed the Office Task Battery (OTB) tasks. Time and error data were analyzed to determine if the ambient illumination, the monitors, and/or some interaction thereof influenced the performance of the participants.

4.2.1 Multivariate Analysis of Variance

Figure 4.21 shows results of the Multivariate Analysis of Variance (MANOVA) tests for the two main effects and one interaction on the performance data.

(a) Lighting

```
MANOVA Test Criteria and F Approximations for the Hypothesis of No Overall Lighting Effect
                          H = Type III SSCP Matrix for Lighting
                        E = Type III SSCP Matrix for Part*Lighting
                                    S=3    M=1    N=10

Statistic                        Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda               0.23016739       2.37        18    62.711    0.0062
Pillai's Trace              0.98858786       1.97        18        72    0.0232
Hotelling-Lawley Trace      2.42928392       2.85        18    38.364    0.0032
Roy's Greatest Root         1.99730124       7.99         6        24    <.0001
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

(b) Monitors

```
MANOVA Test Criteria and F Approximations for the Hypothesis of No Overall Monitors Effect
                          H = Type III SSCP Matrix for Monitors
                        E = Type III SSCP Matrix for Part*Monitors
                                    S=3    M=1    N=10

Statistic                        Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda               0.30383615       1.82        18    62.711    0.0417
Pillai's Trace              0.89229336       1.69        18        72    0.0606
Hotelling-Lawley Trace      1.69016652       1.98        18    38.364    0.0375
Roy's Greatest Root         1.28341259       5.13         6        24    0.0016
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

(c) Lighting*Monitors

```
                MANOVA Test Criteria and F Approximations for the
                Hypothesis of No Overall Lighting*Monitors Effect
                  H = Type III SSCP Matrix for Lighting*Monitors
                E = Type III SSCP Matrix for Part*Lighting*Monitor
                                    S=6    M=1    N=37

Statistic                        Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda               0.56179036       0.87        54    392.12    0.7313
Pillai's Trace              0.53496344       0.88        54       486    0.7119
Hotelling-Lawley Trace      0.62359126       0.86        54    247.87    0.7401
Roy's Greatest Root         0.24203773       2.18         9        81    0.0319
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

Figure 4.21. The MANOVAs on the performance data: (a) main effect for Lighting, (b) main effect for Monitors, (c) interaction of Lighting and Monitors.

Wilk's Lambda is significant (α=0.05) for the main effects of Lighting and Monitors, but not the interaction effect. Thus, performance as a whole (i.e., across all three tasks and both response variables for each task) vary systematically with respect to both the ambient illumination of the experiment room and the monitor used by the participant.

4.2.2 Analyses of Variance

To determine which of the performance measures may have shown differences among the treatments, individual Analyses of Variance (ANOVAs) were performed. No significant results were found for either of the Data Entry or Web Browsing performance variables, but both Word Processing dependent variables were significant for both Lighting and Monitors, with Word Processing Time showed lower p-values.

4.2.2.1 ANOVA for Word Processing Time

As shown in Table 4.10, the ANOVA of the standardized Word Processing Time (SWPT) data was significant for the main effects of Lighting ($p<0.0001$) and of Monitors ($p<0.0001$). Figure 4.22 depicts the level differences for the significant effect of Lighting and Figure 4.23 depicts the level differences for Monitors, both graphs including error bars showing +/-1 standard error of the mean.

TABLE 4.10 – ANOVA for Performance of Word Processing Time

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000001	0.00000000		
Within					
Lighting	3	15. 92139596	5. 30713199	14.80	<0.0001
Participant x Lighting	27	9.68305743	0.35863176		
Monitors	3	9. 85576034	3. 28525345	4. 64	<0.0001
Participant x Monitors	27	19.11210374	0.70785569		
Lighting x Monitors	9	9. 99541194	1. 11060133	1.05	0.4054
Participant x Lighting x Monitors	81	85.43268172	1.05472447		
Total	159	150.0004111			

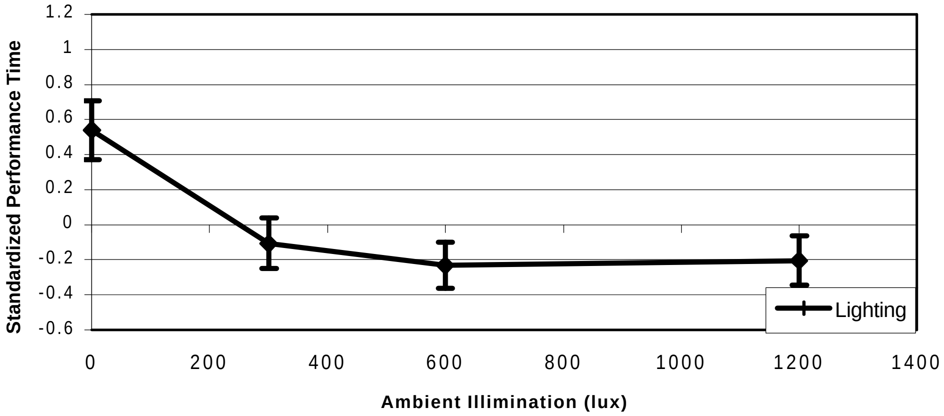

Figure 4.22. The main effect for Lighting on Word Processing Time.

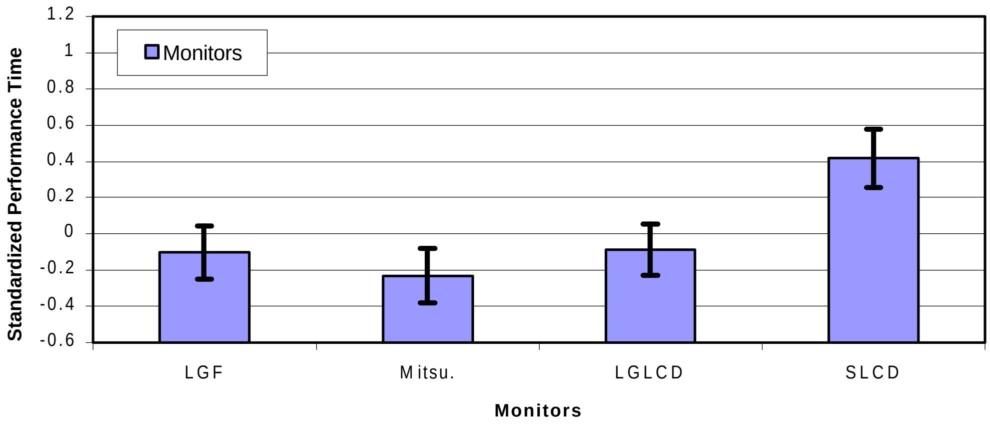

Figure 4.23. The main effect for Monitors on Word Processing Time.

Student Newman Keuls post hoc tests (α=0.05) on the main effects of Lighting and Monitors showed obvious level differences. For Lighting, the 0 lux condition was associated with longer task completion times than an equal grouping of the 300, 600, and 1200 lux conditions. For Monitors, the Samsung LCD was associated with longer task completion times than an equal grouping of the other three monitors. The results show that slower word processing times were caused by being in the dark as well as when participants were using the Samsung LCD monitor.

4.2.2.2 ANOVA for Word Processing Errors

As shown in Table 4.11, the ANOVA of the standardized Word Processing Errors (SWPE) data was significant for the main effects of Lighting (p=0.0443) and of Monitors (p=0.0938). Figure 4.24 depicts the level differences for the significant effect of Lighting and Figure 4.25 depicts the level differences for Monitors, both graphs including error bars showing +/-1 standard error of the mean.

TABLE 4.11 – ANOVA for Performance of Word Processing Error

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000002	0.00000000		
Within					
Lighting	3	4.30441085	1.43480362	3.08	0.0443
Participant x Lighting	27	12.58140349	0.46597791		
Monitors	3	7.83137506	2.61045835	2.36	0.0938
Participant x Monitors	27	29.87971831	1.10665623		
Lighting x Monitors	9	11.53643174	1.28182575	1.24	0.2840
Participant x Lighting x Monitors	81	83.86616788	1.03538479		
Total	159	149.9995073			

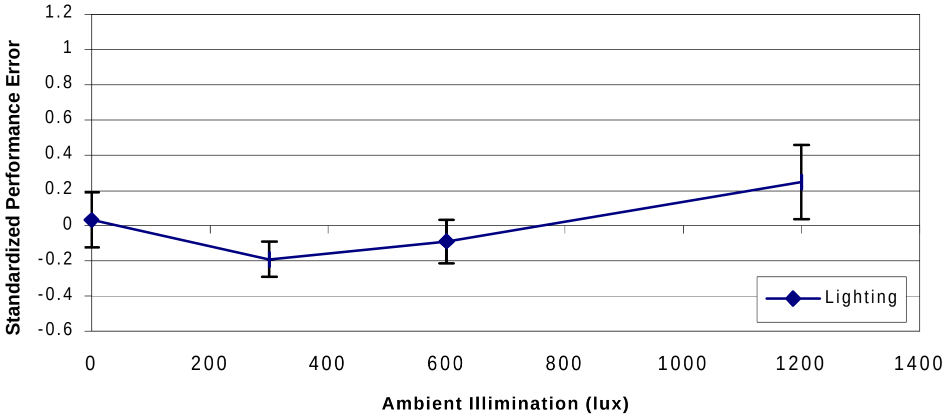

Figure 4.24. The main effect for Lighting on Word Processing Errors.

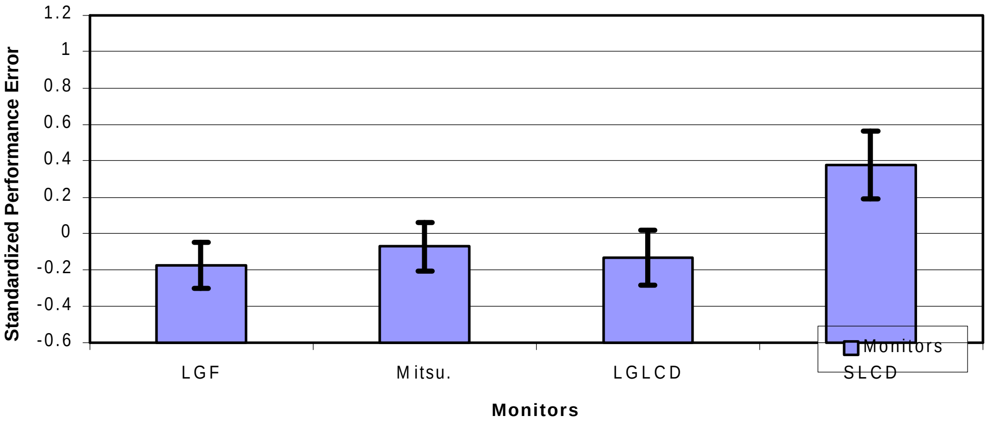

Figure 4.25. The main effect for Monitors on Word Processing Errors.

A Newman Keuls post hoc test at α=0.05 for the main effect of Lighting showed that the 1200 lux condition was associated with more errors than the other three lighting levels and that the 300 lux condition was associated with less errors when compared to the other three lighting conditions. The U-shaped curve of Figure 4.24 depicts how the two extremes of Lighting caused more errors in the word processing task. This is reasonable, since the dark condition is somewhat difficult for the eyes to adjust to, as well as to be able to see the keyboard, and the 1200 lux condition was very bright. Ambient illumination of 300 or 600 lux was found to be the best for the performance measure of Word Processing Errors.

Although the Newman Keuls post hoc test was not significant (α=0.05) for the main effect of Monitors, Figure 4.25 shows the same level differences found for Word Processing Time – namely, that the Samsung LCD monitor is associated with higher error rates than an equal grouping of the other three monitors.

How the monitors affected word processing performance is clear: the Samsung LCD monitor was associated with longer task times and more errors for the Word Processing task. The affect of ambient illumination is less clear, but indicates that the extreme conditions of 0 and 1200 lux cause lower performance; specifically, the dark condition causing slower typing, the very bright condition causing more errors.

4.2.3 *Correlational Analysis*

A correlational analysis was performed on the six performance variables to determine the amount of interrelationship that existed between them. Table 4.12 presents the matrix of Pearson product moments and their significant level.

TABLE 4.12 – Pearson Correlation Matrix for Performance

	WBT	WBE	DET	DEE	WBT	WBE
WBT	1.0000					
WBE	0.2336 (0.0030)	1.0000				
DET	0.4478 (<0.0001)	0.2846 (0.0003)	1.0000			
DEE	0.3996 (<0.0001)	0.3299 (<0.0001)	0.5196 (<0.0001)	1.0000		
WBT	0.1442 (0.0689)	0.0889 (0.2639)	0.1708 (0.0309)	0.0957 (0.2285)	1.0000	
WBE	-0.0028 (0.9723)	-0.0166 (0.8351)	-0.0691 (0.3853)	-0.0061 (0.9394)	-0.0056 (0.9442)	1.0000

Note: values in parentheses are p-values

Almost all of the interrelationship of the performance variables exists between the Word Processing and Data Entry tasks. This could be the result of a marked difference between the Web Browsing task and the other two tasks, both in terms of keyboard/mouse use, as well as the fact that the Web Browsing task was more dynamic (i.e., due to the changing of page appearances during navigation and scrolling when searching for the target word) on the screen. It could also be that the Web Browsing task was less well controlled at the trial level than the other two tasks. Thus it could either be that the Web Browsing task reflects a different type of performance or the task was not rigid enough. However, the Word Processing and Data Entry tasks seem to complement each other well and were fairly robust.

4.3 Subjective Image Quality

In addition to the subjective ratings of visual fatigue experience and the objective measures of performance, participants were asked to rate the perceived quality of their monitor after every experimental session. Found in Appendix C, this survey first asked for an overall rating of the monitor and then inquired about seven specific dimensions of the monitor’s image quality. The following analyses seek to determine if the survey’s questions need to be removed (as was done with the visual fatigue questionnaire) and then a series of multivariate and univariate statistical analyses were performed to find out if participants’ responses systematically varied due to the ambient illuminations they were exposed to during the session or due to the monitor they used.

4.3.1 Subjective Image Quality Survey Reduction

The Standardized Subjective Image Quality (SSIQ) questions were initially subjected to PCA and FA methods to determine if any questions in the survey contributed little to no variance to the survey as a whole. Figure 4.26 lists the eigenvalues and eigenvectors of the PCA, Figure 4.27 lists the factor pattern from the FA, and Figure 4.28 shows the scree plot of the eigenvalues from both analyses.

```
             Eigenvalues of the Covariance Matrix

       Eigenvalue    Difference    Proportion    Cumulative

1      4.05275975    3.24241438        0.5579        0.5579
2      0.81034537    0.17509434        0.1116        0.6695
3      0.63525103    0.14494186        0.0874        0.7569
4      0.49030916    0.04056719        0.0675        0.8244
5      0.44974198    0.07833795        0.0619        0.8863
6      0.37140402    0.10579984        0.0511        0.9375
7      0.26560418    0.07685046        0.0366        0.9740
8      0.18875372                      0.0260        1.0000

                          Eigenvectors

             Prin1     Prin2     Prin3     Prin4     Prin5

 SSIQ1   -.421965  0.119909  0.043135  0.239889  0.089115
 SSIQ2   0.369728  -.384361  0.342723  0.217999  -.269912
 SSIQ3   0.393438  -.202789  0.199869  -.065366  -.379465
 SSIQ4   0.359092  0.077496  -.711192  -.199979  0.121386
 SSIQ5   0.407260  0.079360  -.124900  -.289118  -.014901
 SSIQ6   0.319614  0.053401  0.444321  -.115035  0.808468
 SSIQ7   0.276411  -.056209  -.272067  0.854774  0.193808
 SSIQ8   0.238934  0.882298  0.218855  0.152330  -.262818
```

Figure 4.26. The eigenvalues and eigenvectors from the PCA of the subjective image quality data.

```
                          The FACTOR Procedure
               Initial Factor Method: Principal Components

                            Factor Pattern

                               Factor1

                SSIQ1         -0.86965
                SSIQ2          0.76465
                SSIQ3          0.81168
                SSIQ4          0.74201
                SSIQ5          0.84007
                SSIQ6          0.70459
                SSIQ7          0.65875
                SSIQ8          0.49302
```

Figure 4.27. The factor pattern from the FA of the subjective image quality data.

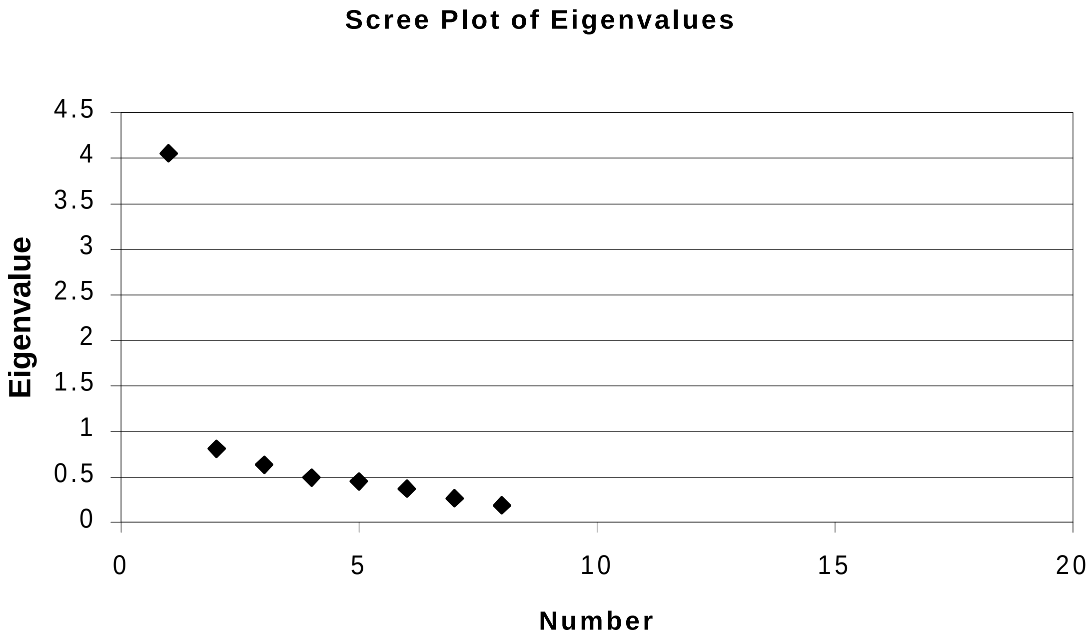

Figure 4.28. The Scree plot of the eigenvalues from the PCA and FA of the subjective image quality data.

Shown in Figure 4.28 (and like the visual fatigue data) the first eigenvalue is relatively large. Thus, one variable set was recommended. Inspection of the first principal component reveals all eight variables are associated with it; the same is true of the first factor. (The negative values for SSIQ1 is due to the fact that better ratings were larger for SSIQ1 while smaller ratings for SSIQ2-8 were better.) One group of variables, consisting of all eight standardized subjective image quality variables, was retained for analysis.

4.3.2 Multivariate Analysis of Variance

Figure 4.29 shows results of the Multivariate Analysis of Variance (MANOVA) tests for the two main effects and one interaction effect on the whole of the standardized subjective image quality data.

(a) Lighting

```
MANOVA Test Criteria and F Approximations for the Hypothesis of No Overall Lighting Effect
                          H = Type III SSCP Matrix for Lighting
                        E = Type III SSCP Matrix for Part*Lighting
                                    S=3    M=2    N=9

Statistic                        Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda               0.14190434       2.35        24    58.607    0.0042
Pillai's Trace              1.36928902       2.31        24        66    0.0040
Hotelling-Lawley Trace      2.98158392       2.37        24    36.661    0.0092
Roy's Greatest Root         1.63830862       4.51         8        22    0.0024
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

(b) Monitors

```
MANOVA Test Criteria and F Approximations for the Hypothesis of No Overall Monitors Effect
                          H = Type III SSCP Matrix for Monitors
                        E = Type III SSCP Matrix for Part*Monitors
                                   S=3    M=2    N=9

Statistic                        Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda               0.05616288       4.15        24    58.607    <.0001
Pillai's Trace              1.17228817       1.76        24        66    0.0365
Hotelling-Lawley Trace     12.83767542      10.18        24    36.661    <.0001
Roy's Greatest Root        12.52962758      34.46         8        22    <.0001
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

(c) Lighting*Monitors

```
                  MANOVA Test Criteria and F Approximations for the
                  Hypothesis of No Overall Lighting*Monitors Effect
                    H = Type III SSCP Matrix for Lighting*Monitors
                  E = Type III SSCP Matrix for Part*Lighting*Monitor
                                  S=8    M=0    N=36

Statistic                        Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda               0.47902481       0.82        72     457.7    0.8533
Pillai's Trace              0.65191013       0.80        72       648    0.8839
Hotelling-Lawley Trace      0.84285023       0.85        72    280.01    0.7950
Roy's Greatest Root         0.49525402       4.46         9        81    <.0001
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

Figure 4.29. The MANOVAs for the subjective image quality data: (a) main effect for Lighting, (b) main effect for Monitors, (c) interaction of Lighting and Monitors.

Using Wilk’s Lambda, the main effects for Lighting (p=0.0042) and for Monitors (p<0.0001) were significant. Their interaction effect was not significant (p=0.8533). Therefore, the entire subjective image quality survey systematically varied due to changes in the ambient illumination of the experiment room and according to the monitor the participants used.

4.3.3 Analyses of Variance

To determine which of the subjective image quality questions may have shown differences among the treatments, individual Analyses of Variance (ANOVAs) were performed. Significant results were found for all eight questions, with the first five questions being significant only for the main effect of Monitors, the eighth question only significant for the main effect of Lighting, and the sixth and seventh question significant for both main effects. No interactions were found.

4.3.3.1 ANOVA for the "Overall" Rating

As shown in Table 4.13, the ANOVA of the "Overall" subjective image quality question (SSIQ1) was significant for the main effect of Monitors (p<0.0001). Figure 4.30 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.13 – ANOVA for Subjective Image Quality for "Overall" Rating

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000005	0.00000001		
Within					
Lighting	3	0.65978222	0.21992741	0.51	0.6817
Participant x Lighting	27	11.74459480	0.43498499		
Monitors	3	50.16830673	16.72276891	21.06	<0.0001
Participant x Monitors	27	21.43857439	0.79402127		
Lighting x Monitors	9	2.85554697	0.31728300	0.41	0.9279
Participant x Lighting x Monitors	81	63.13236358	0.77941190		
Total	159	149.9991687			

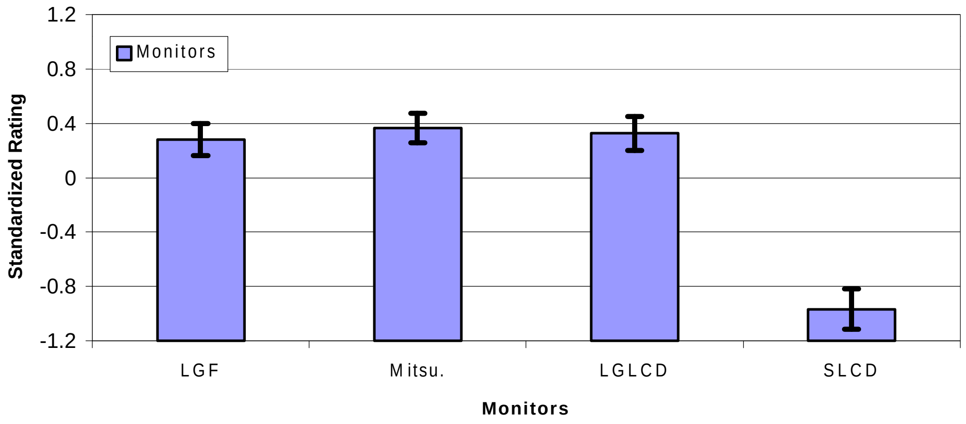

Figure 4.30. The main effect for Monitors on “Overall” Rating.

A lower rating for the “Overall” subjective image quality question was worse, thus Figure 4.30 shows that the Samsung LCD monitor received the lowest Overall ratings. This is confirmed by a Newman Keuls post hoc test that found the SLCD monitor to be significantly worse (at α=0.05) than the other three monitors, which were not different from one another. The poorer visual fatigue ratings and performance of the SLCD monitor is corroborated here in the “Overall” ratings.

4.3.3.2 ANOVA for the “Contrast” Rating

As shown in Table 4.14, the ANOVA of the “Contrast” subjective image quality question (SSIQ2) was significant for the main effect of Monitors ($p<0.0001$). Figure 4.31 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.14 – ANOVA for Subjective Image Quality for the “Contrast” Rating

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000003	0.00000000		
Within					
Lighting	3	0.97616456	0.32538819	0.51	0.6757
Participant x Lighting	27	17.07140485	0.63227425		
Monitors	3	28.47991724	9.49330575	10.99	<0.0001
Participant x Monitors	27	23.31374093	0.86347189		
Lighting x Monitors	9	2.22971970	0.24774663	0.26	0.9839
Participant x Lighting x Monitors	81	77.92964529	0.96209439		
Total	159	150.0005926			

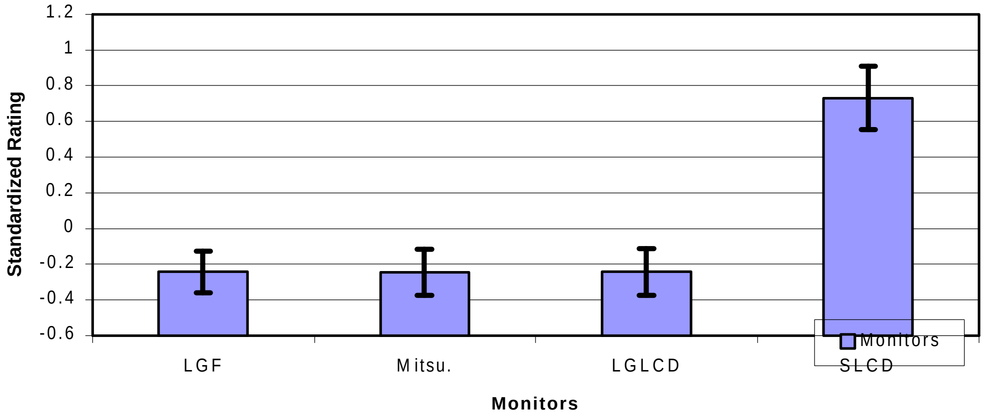

Figure 4.31. The main effect for Monitors on the “Contrast” rating.

As depicted in Figure 4.31, the Samsung LCD monitor had markedly worse ratings (greater ratings of insufficient contrast); this is confirmed by a Newman Keuls test and the standard error of the mean error bars, both of which show the SLCD monitor to have been given lower ratings with respect to contrast than the equal grouping of the LGF, Mitsubishi, and LGLCD monitors.

4.3.3.3 ANOVA for the "Sharpness" Rating

As shown in Table 4.15, the ANOVA of the "Sharpness" subjective image quality question (SSIQ3) was significant for the main effect of Monitors (p=0.0006). Figure 4.32 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.15 – ANOVA for Subjective Image Quality for the "Sharpness" Rating

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000002	0.00000000		
Within					
Lighting	3	1.12468414	0.37489471	0.68	0.5719
Participant x Lighting	27	14.88535494	0.55130944		
Monitors	3	33.41793753	11.13931251	7.94	0.0006
Participant x Monitors	27	37.88759750	1.40324435		
Lighting x Monitors	9	2.63544542	0.29282727	0.39	0.9342
Participant x Lighting x Monitors	81	60.04919945	0.74134814		
Total	159	150.0002190			

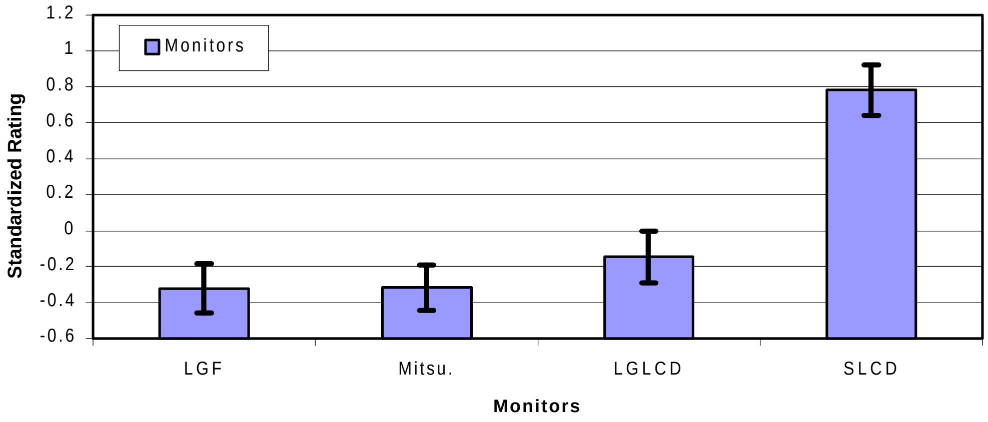

Figure 4.32. The main effect for Monitors on the "Sharpness" rating.

A Student Newman Keuls test found that the Samsung LCD monitor was rated as having less sharpness than the equal group of the other three monitors. This finding is also depicted in Figure 4.32's error bars.

4.3.3.4 ANOVA for the "Color" Rating

As shown in Table 4.16, the ANOVA of the "Color" subjective image quality question (SSIQ4) was significant for the main effect of Monitors (p<0.0001). Figure 4.33 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.16 – ANOVA for Subjective Image Quality for the "Color" Rating

Source	**df**	**Type III SS**	**MS**	**F**	**p**
Between					
Participant	9	0.00000002	0.00000000		
Within					
Lighting	3	0.82543380	0.27514460	0.46	0.7145
Participant x Lighting	27	16.25223743	0.60193472		
Monitors	3	52.69617009	17.56539003	37.57	<0.0001
Participant x Monitors	27	12.62263724	0.46750508		
Lighting x Monitors	9	2.95924739	0.32880527	0.41	0.9253
Participant x Lighting x Monitors	81	64.64498577	0.79808624		
Total	159	150.0007117			

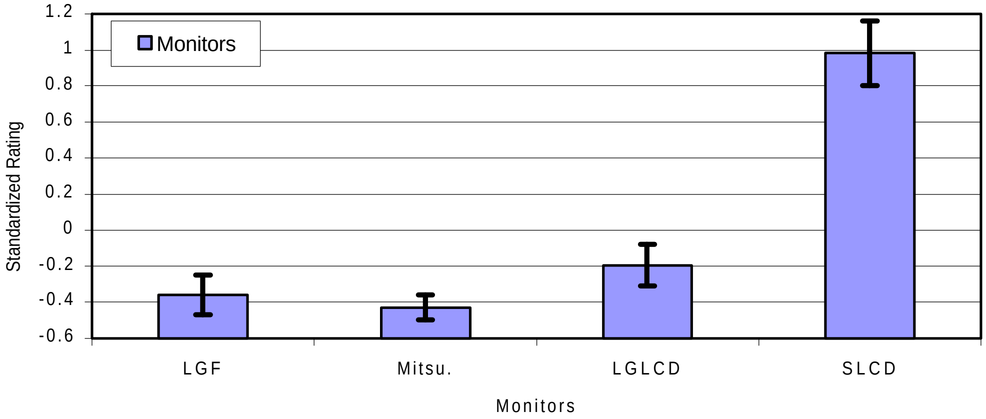

Figure 4.33. The main effect for Monitors on the “Color” rating.

As with the other dimensions of image quality presented so far, a Student Newman Keuls test found the Samsung LCD to be significantly worse (α=0.05) than the other three monitors for the “Color” question (SSIQ4). But while the SNK test did not show a break between the two CRTs and the LGLCD, Figure 4.33 found the LGLCD monitor was rated worse than the Mitsubishi monitor with respect to strange or washed-out colors, and almost so for the LG Flatron monitor. With the Samsung LCD monitor being rated much worse than both CRTs, color quality may be a dimension where a display technology influence is present.

4.3.3.5 ANOVA for the “Brightness” Rating

As shown in Table 4.17, the ANOVA of the “Brightness” subjective image quality question (SSIQ5) was significant for the main effect of Monitors (p<0.0001). Figure 4.34 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.17 – ANOVA for Subjective Image Quality for the “Brightness” Rating

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000004	0.00000000		
Within					
Lighting	3	2.85181441	0.95060480	1.68	0.1940
Participant x Lighting	27	15.24537127	0.56464338		
Monitors	3	43.50342881	14.50114294	16.49	<0.0001
Participant x Monitors	27	23.73950312	0.87924086		
Lighting x Monitors	9	9.64112902	1.07123656	1.58	0.1361
Participant x Lighting x Monitors	81	55.01891298	0.67924584		
Total	159	150.0001596			

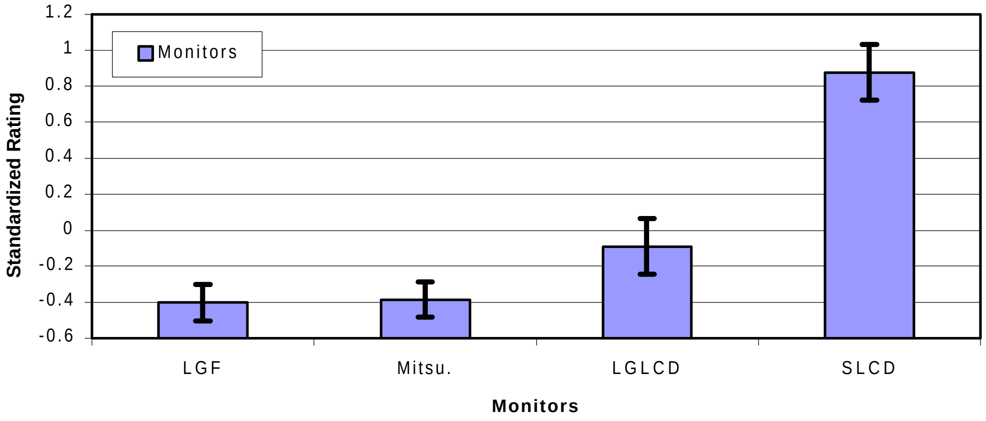

Figure 4.34. The main effect for Monitors on the “Brightness” rating.

A Newman Keuls post hoc test showed the Samsung LCD monitor was rated significantly (at α=0.05) worse with regard to its brightness varying across the screen than the equal group of the other three monitors. Testing level differences using standard error of the mean (as shown in Figure 4.34’s error bars), a difference was found between display technologies. The LGLCD monitor’s ratings fall between the those for the SLCD and for the two CRT monitors. Brightness variation across the screen, though usually associated with CRT monitors, may be another display technology effect.

4.3.3.6 ANOVA for the "Sizing" Rating

As shown in Table 4.18, the ANOVA of the "Sizing" subjective image quality question (SSIQ6) was significant for the main effect of Lighting (p=0.0133) and for the main effect of Monitors (p=0.0164). Figure 4.35 depicts the level differences for the significant effect of Lighting and Figure 4.36 depicts the level differences for Monitors, both graphs including error bars showing +/-1 standard error of the mean.

TABLE 4.18 – ANOVA for Subjective Image Quality for the "Sizing" Rating

Source	**df**	**Type III SS**	**MS**	**F**	**p**
Between					
Participant	9	0.00000002	0.00000000		
Within					
Lighting	3	7.48220663	2.49406888	4.30	0.0133
Participant x Lighting	27	15.67446107	0.58053560		
Monitors	3	16.35120080	5.45040027	4.08	0.0164
Participant x Monitors	27	36.08779276	1.33658492		
Lighting x Monitors	9	3.10463723	0.34495969	0.50	0.8730
Participant x Lighting x Monitors	81	56.29918466	0.69505166		
Total	159	134.9994832			

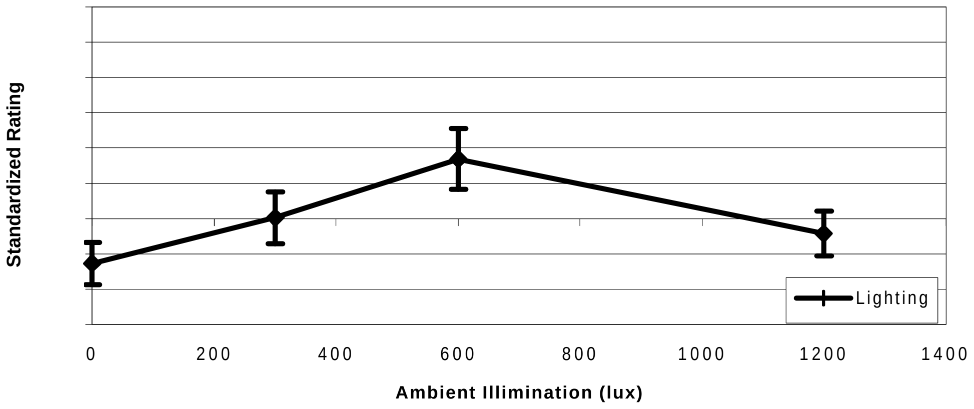

Figure 4.35. The main effect for Lighting on the “Sizing” rating.

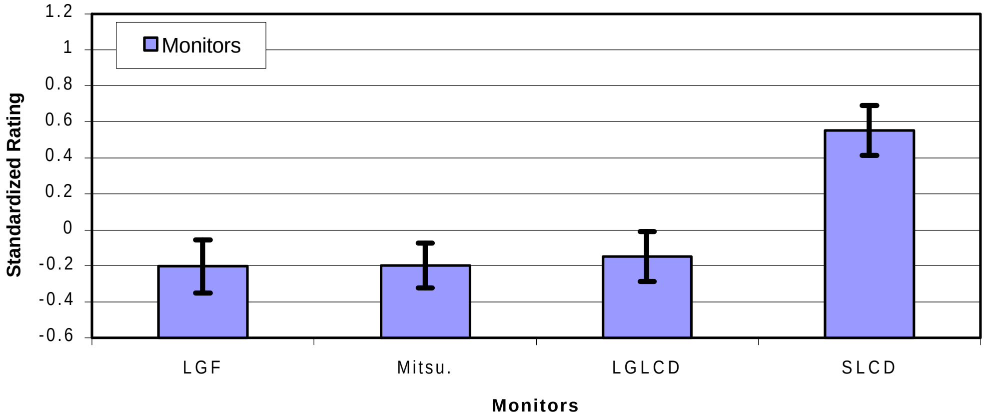

Figure 4.36. The main effect for Monitors on the “Sizing” rating.

A Newman Keuls test found level differences (at α=0.05) were present among the ambient illumination conditions, with the 600 lux condition being worse, in terms of the “Sizing” question, than both the 0 and 1200 lux conditions. Figure 4.35 shows how the sizing anomalies were perceived by the participants over the range of ambient illumination. Testing level differences with standard error found the 600 lux condition significantly worse than an equal grouping of the other three lighting levels.

A Newman Keuls test of the main effect of Monitors found that the Samsung LCD was rated has having more problems with sizing compared to an equal grouping of the other three monitors. This finding is depicted in Figure 4.36.

4.3.3.7 ANOVA for the "Temporal" Rating

As shown in Table 4.19, the ANOVA of the "Temporal" (which includes both flicker and jitter) subjective image quality question (SSIQ7) was significant for the main effect of Lighting (p=0.0584) and for the main effect of Monitors (p=0.0001). Figure 4.37 depicts the level differences for the significant effect of Lighting and Figure 4.38 depicts the level differences for Monitors, both graphs including error bars showing +/-1 standard error of the mean.

TABLE 4.19 – ANOVA for Subjective Image Quality for the "Temporal" Rating

Source	**df**	**Type III SS**	**MS**	**F**	**p**
Between					
Participant	9	0.00000003	0.00000000		
Within					
Lighting	3	3.17132302	1.05710767	2.81	0.0584
Participant x Lighting	27	10.15486106	0.37610597		
Monitors	3	31.29408947	10.43136316	10.08	0.0001
Participant x Monitors	27	27.95013680	1.03519025		
Lighting x Monitors	9	3.17917944	0.35324216	0.65	0.7540
Participant x Lighting x Monitors	81	44.25274227	0.54633015		
Total	159	120.0023321			

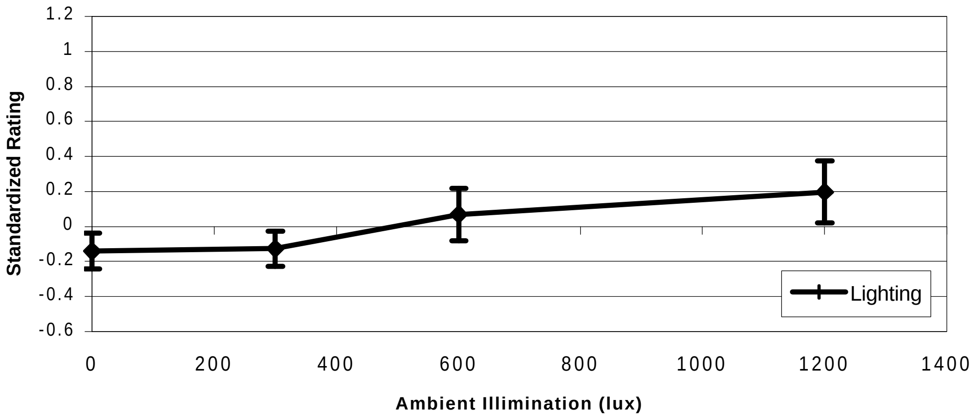

Figure 4.37. The main effect for Lighting on the “Temporal” rating.

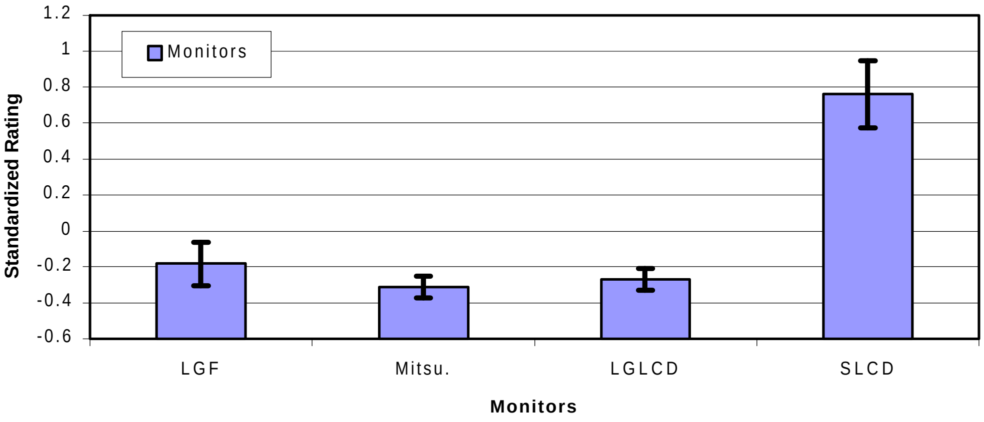

Figure 4.38. The main effect for Monitors on the “Temporal” rating.

The Newman Keuls post hoc test for the main effect of Lighting (at α=0.05) found no significant level differences. However, inspection of Figure 4.37’s error bars found that ratings were higher for noticing temporal distortions, such as flicker and jitter, in the brightest condition of 1200 lux relative to the 0 and 300 lux conditions.

The SNK test on the Monitors main effect found the Samsung LCD monitor to be significantly worse (α=0.05) with respect to temporal distortion in comparison with an equal grouping of the other three monitors. This effect is illustrated in Figure 4.38 and is corroborated by its error bars.

4.3.3.8 ANOVA for the “Glare” Rating

As shown in Table 4.20, the ANOVA of the “Glare” subjective image quality question (SSIQ8) was significant for the main effect of Lighting (p=0.0079). Figure 4.39 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean.

TABLE 4.20 – ANOVA for Subjective Image Quality for the “Glare” Rating

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000005	0.00000001		
Within					
Lighting	3	11.84848586	3.94949529	4.86	0.0079
Participant x Lighting	27	21.95025700	0.81297248		
Monitors	3	9.76248423	3.25416141	2.20	0.1112
Participant x Monitors	27	39.94547423	1.47946201		
Lighting x Monitors	9	6.57252015	0.73028002	0.99	0.4571
Participant x Lighting x Monitors	81	59.92101515	0.73976562		
Total	159	150.0002367			

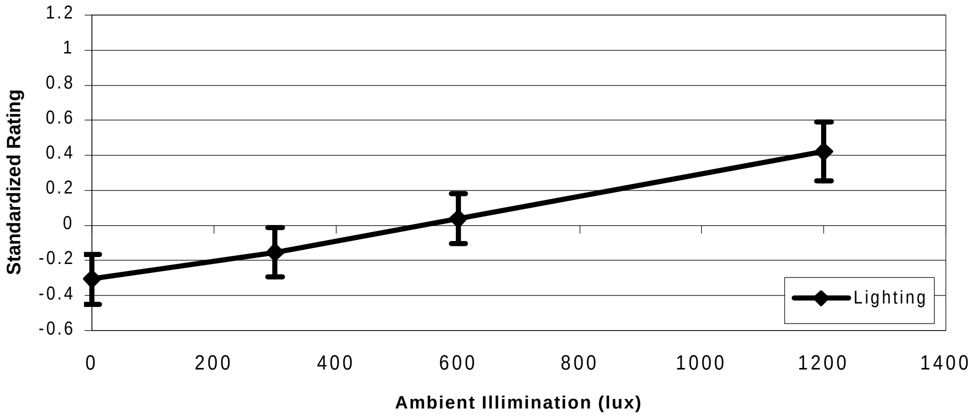

Figure 4.39. The main effect for Lighting on the “Glare” rating.

A Newman Keuls range test found that the 0, 300, and 600 lux condition fell into an equal grouping and the 600 and 1200 lux conditions fell into another, with 1200 being significantly worse than the 0 and 300 lux conditions (α=0.05). This trend can be seen in Figure 4.39 where subjective reports of bothersome screen reflections increased in direct proportion with ambient illumination, the error bars test also finding that the 600 lux condition was worse than 0 lux.

In general, the results of the subjective image quality data point to the Samsung LCD monitor’s poor overall subjective experience. Participants rated it poorer than the other three monitors in all categories where a Monitors effect was present. Since the LGLCD monitor was grouped with the CRT monitors according to the Student Newman Keuls tests, it is difficult to conclude any display technology influence on subjective image quality. However, using the standard error of the mean error bars in Figures 4.33 (Color quality) and Figure 4.34 (Brightness variation), this test found that the LGLCD monitor is slightly poorer in these two areas than the two CRTs. As a result, it may be that LCD monitors are judged poorer in terms of color rendering and brightness variation over the screen.

For ambient illumination, greater lighting caused higher reports of temporal anomalies (flicker and jitter) and bothersome glare. It also produced an inverted-U shape curve for sizing anomalies, with the 600 lux condition being rated worse than the illumination extremes.

In terms of subjective image quality, participants preferred the dimmer lighting conditions of 0 and 300 lux, but made their distinctions more based on the monitor, where they disliked the Samsung LCD compared to the other three monitors they used.

4.3.4 Correlational Analysis

The eight questions of the augmented subjective image quality survey were subjected to a correlational analysis to determine the amount of interrelationship that existed. Table 4.21 presents the matrix of Pearson product moments and their level of significance.

TABLE 4.21 -- Pearson Correlation Matrix for Subjective Image Quality

	Overall	Contrast	Sharp.	Color	Bright.	Sizing	Tempor.	Glare
Overall	1.0000							
Contrast	-0.6802 (<0.0001)	1.0000						
Sharpness	-0.6743 (<0.0001)	0.6396 (<0.0001)	1.0000					
Color	-0.6628 (<0.0001)	0.4014 (<0.0001)	0.4745 (<0.0001)	1.0000				
Brightness	-0.6690 (<0.0001)	0.5372 (<0.0001)	0.6622 (<0.0001)	0.6344 (<0.0001)	1.0000			
Sizing	-0.5583 (<0.0001)	0.4949 (<0.0001)	0.4993 (<0.0001)	0.3780 (<0.0001)	0.5392 (<0.0001)	1.0000		
Temporal	-0.4515 (<0.0001)	0.4670 (<0.0001)	0.4565 (<0.0001)	0.4916 (<0.0001)	0.4574 (<0.0001)	0.3715 (<0.0001)	1.0000	
Glare	-0.3458 (<0.0001)	0.2155 (0.0062)	0.2988 (0.0001)	0.3109 (<0.0001)	0.4038 (<0.0001)	0.3431 (<0.0001)	0.2599 (0.0009)	1.0000

Note: values in parentheses are p-values

The negative correlations between the “Overall” variable and the other variables is due to its scaling, with a greater value being associated with a better rating of image quality, while the opposite is true for the other seven variables.

The high degree of absolute correlation among the variables is encouraging, confirming that the eight questions worked well together to ascertain a comprehensive understanding of the subjective experience of the participants. Importantly, there is high correlation between the seven image quality dimension questions and the “Overall” rating. These questions were added to an established rating scale for this experiment and the high correlation is confirmation that they do reflect image quality judgments.

4.4 Contrast Sensitivity

Using the VisTech Contrast Sensitivity Test System, participants’ contrast sensitivities were measured at spatial frequencies of 1.5, 3.0, 6.0, 12.0, and 18.0 cycles/degree (c/deg) before and after each experimental session. Differences were analyzed to determine if shifts in contrast sensitivity occurred as a result of completing the task sessions.

4.4.1 Multivariate Analysis of Variance

Figure 4.40 shows results of the Multivariate Analysis of Variance (MANOVA) tests for the two main effects and one interaction effect on the whole of the standardized contrast sensitivity data.

(a) Lighting

```
MANOVA Test Criteria and F Approximations for the Hypothesis of No Overall Lighting Effect
                          H = Type III SSCP Matrix for Lighting
                        E = Type III SSCP Matrix for Part*Lighting
                                  S=3    M=0.5    N=10.5

Statistic                        Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda               0.58447035       0.91        15    63.894    0.5523
Pillai's Trace              0.44559924       0.87        15        75    0.5967
Hotelling-Lawley Trace      0.65984042       0.97        15    38.495    0.4984
Roy's Greatest Root         0.57212603       2.86         5        25    0.0355
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

(b) Monitors

```
MANOVA Test Criteria and F Approximations for the Hypothesis of No Overall Monitors Effect
                          H = Type III SSCP Matrix for Monitors
                        E = Type III SSCP Matrix for Part*Monitors
                                   S=3    M=0.5    N=10.5

Statistic                        Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda               0.23937978       2.89        15    63.894    0.0016
Pillai's Trace              0.94659072       2.30        15        75    0.0094
Hotelling-Lawley Trace      2.43993067       3.60        15    38.495    0.0007
Roy's Greatest Root         2.11924638      10.60         5        25    <.0001
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

(c) Lighting x Monitors

```
            MANOVA Test Criteria and F Approximations for the
            Hypothesis of No Overall Lighting*Monitors Effect
             H = Type III SSCP Matrix for Lighting*Monitors
            E = Type III SSCP Matrix for Part*Lighting*Monitor
                        S=5    M=1.5    N=37.5

Statistic                        Value    F Value    Num DF    Den DF    Pr > F

Wilks' Lambda               0.70795818       0.62        45    347.54    0.9742
Pillai's Trace              0.32853466       0.63        45       405    0.9696
Hotelling-Lawley Trace      0.36356596       0.61        45    226.49    0.9750
Roy's Greatest Root         0.15070218       1.36         9        81    0.2219
NOTE: F Statistic for Roy's Greatest Root is an upper bound.
```

Figure 4.40. The MANOVAs for the contrast sensitivity data: (a) main effect for Lighting, (b) main effect for Monitors, (c) interaction of Lighting and Monitors.

Using Wilk's Lambda, the main effect for Monitors was significant (p=0.0016). No interaction effect was present. Therefore, shifts contrast sensitivity as a whole varied systematically based on the monitor used in the experiment session.

4.4.2 Analyses of Variance

To determine which spatial frequencies of contrast sensitivity showed significant changes over the experimental session, individual Analyses of Variance (ANOVAs) were performed. 1.5 and 3.0 cycles/degree were not significant.

4.4.2.1 ANOVA for Contrast Sensitivity of 6.0 c/deg

As shown in Table 4.22, the ANOVA for the standardized contrast sensitivity data at 6.0 c/deg (SCS3) was significant for the main effect of Lighting (p=0.0546). Figure 4.41 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean; Figure 4.42 shows the same significant effect, but with unstandardized data.

TABLE 4.22 – ANOVA for Contrast Sensitivity of 6.0 c/deg

Source	**df**	**Type III SS**	**MS**	**F**	**p**
Between					
Participant	9	0.00000008	0.00000001		
Within					
Lighting	3	8.7076601	2.90255337	2.88	0.0546
Participant x Lighting	27	27.25700693	1.00951878		
Monitors	3	2.22043410	0.74014470	0.82	0.4962
Participant x Monitors	27	24.48416111	0.90682078		
Lighting x Monitors	9	7.1626408	0.79584898	0.80	0.6136
Participant x Lighting x Monitors	81	80.16850596	0.98973464		
Total	159	150.0004091			

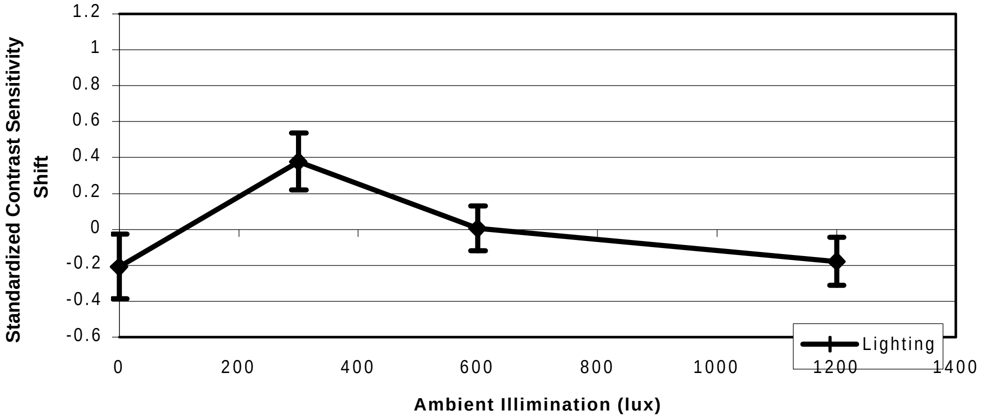

Figure 4.41. The main effect for Lighting on standardized contrast sensitivity data at 6.0 c/deg.

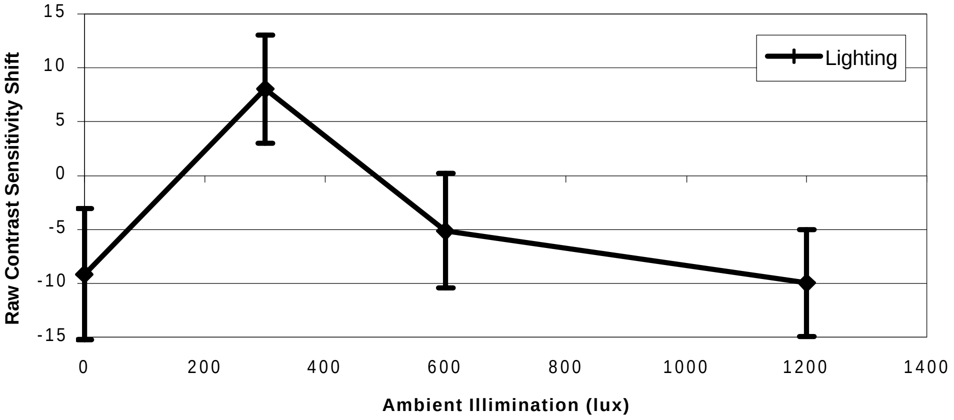

Figure 4.42. The main effect for Lighting on unstandardized contrast sensitivity data at 6.0 c/deg.

Although a Newman Keuls post hoc test (α=0.05) was not significant for level differences, the standard error of the mean error bars of Figure 4.41 show that the 300 lux condition resulted in the least downward shift in contrast sensitivity at 6.0 c/deg. In fact, the raw contrast sensitivity data of Figure 4.42 show that some degree of contrast sensitivity was gained at in 300 lux. Consequently, an ambient illumination of 300 lux during the experiment had the most beneficial effect on participants' contrast sensitivity at 6.0 c/deg.

4.4.2.2 ANOVA for Contrast Sensitivity of 12.0 c/deg

As shown in Table 4.23, the ANOVA for the standardized contrast sensitivity data at 12.0 c/deg (SCS4) was significant for the main effect of Monitors (p=0.0261). Figure 4.43 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean; Figure 4.44 shows the same significant effect, but with unstandardized data.

TABLE 4.23 – ANOVA for Contrast Sensitivity of 12.0 c/deg

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000008	0.00000001		
Within					
Lighting	3	3.25356475	1. 08452158	1.06	0.3834
Participant x Lighting	27	27.68823994	1.02549037		
Monitors	3	8. 85061068	2. 95020356	3.60	0.0261
Participant x Monitors	27	22.11470374	0.81906310		
Lighting x Monitors	9	4. 23558037	0. 47062004	0. 45	0.9005
Participant x Lighting x Monitors	81	83.85668672	1.03526774		
Total	159	149.9993863			

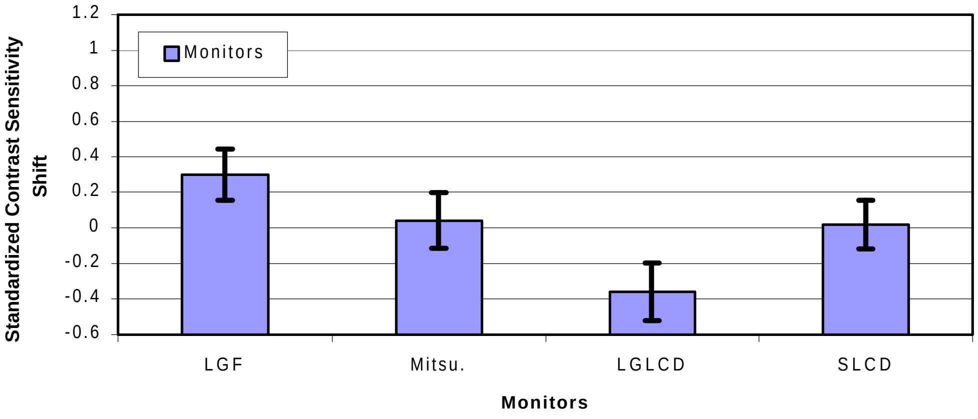

Figure 4.43. The main effect for Monitors on standardized contrast sensitivity data at 12.0 c/deg.

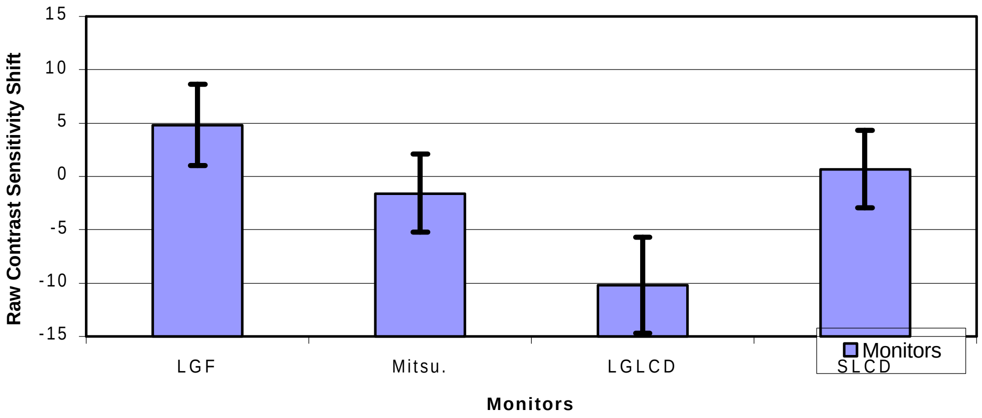

Figure 4.44. The main effect for Monitors on unstandardized contrast sensitivity data at 12.0 c/deg.

A Newman Keuls test found that the two groups of the LGF, Mitsubishi, and SLCD monitor and the Mitsubishi, SLCD, and LGLCD monitors were the same as one another, but that the extremes of the LGF and LGLCD monitors were significantly different. This difference is reflected in Figure 4.43. The raw contrast sensitivity data shown in Figure 4.44 also reflect this finding, but show that contrast sensitivities improved slightly for the LGF monitor while they fell significantly for the LGLCD monitor.

4.4.2.3 ANOVA for Contrast Sensitivity of 18.0 c/deg

As shown in Table 4.24, the ANOVA for the standardized contrast sensitivity data at 18.0 c/deg (SCS5) was significant for the main effect of Monitors (p=0.0136). Figure 4.45 depicts the level differences for this significant effect with error bars showing +/-1 standard error of the mean; Figure 4.46 shows the same significant effect, but with unstandardized data.

TABLE 4.24 – ANOVA for Contrast Sensitivity of 18.0 c/deg

Source	df	Type III SS	MS	F	p
Between					
Participant	9	0.00000003	0.00000000		
Within					
Lighting	3	0.39974975	0. 13324992	0.12	0.9498
Participant x Lighting	27	30.95884745	1.14662398		
Monitors	3	10.62307995	3. 54102665	4.28	0.0136
Participant x Monitors	27	22.36383626	0.82829023		
Lighting x Monitors	9	4. 68338304	0. 52037589	0.52	0.8657
Participant x Lighting x Monitors	81	80.97277963	0.99966395		
Total	159	150.0016761			

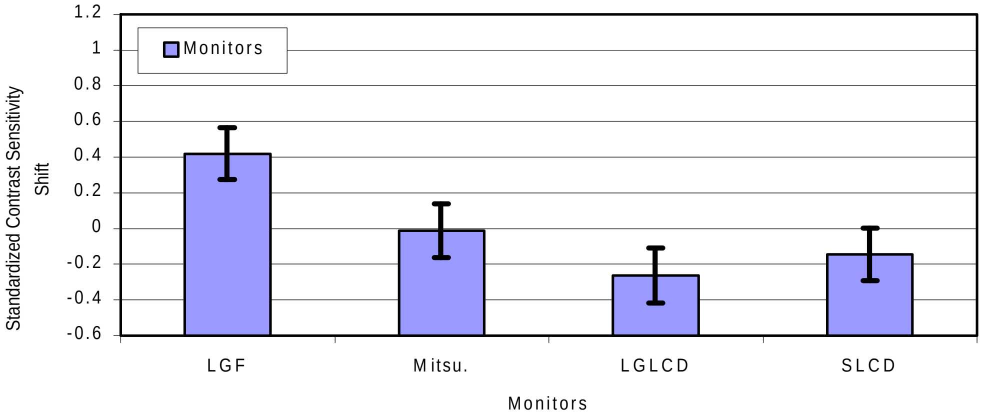

Figure 4.45. The main effect for Monitors on standardized contrast sensitivity data at 18.0 c/deg.

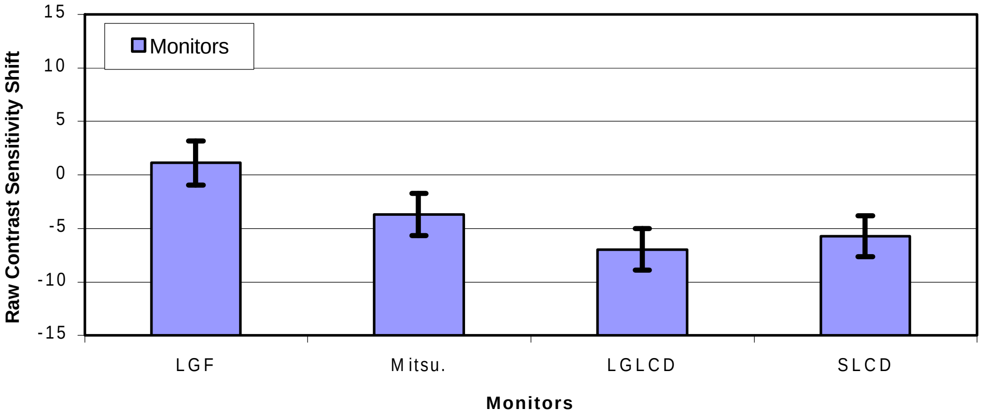

Figure 4.46. The main effect for Monitors on unstandardized contrast sensitivity data at 18.0 c/deg.

A Newman Keuls test on the level means for the four monitors showed that the LGF monitor was the better than the other three monitors with respect to loss of contrast sensitivity at 18.0 cycles/degree. This difference can be seen in Figure 4.45, while Figure 4.46 shows that participants' contrast sensitivity at this spatial frequency actually improved slightly for the LG Flatron monitor, while fell for the other three monitors.

Surprisingly, no significant loss in contrast sensitivity was found for either the 1.5 or 3.0 cycles/degree spatial frequencies. It had been supposed that adaptation to the periodic stimulus of lines of text on the screen would cause a desensitization for these frequencies, but none seem to be present.

In terms of ambient illumination, only the 6.0 cycles/degree spatial frequency showed any significance for Lighting. It found that the 300 lux condition is the best in terms of minimizing contrast sensitivity loss over an intense work session. 300 lux actually was associated with increased sensitivity, but the other three lighting levels caused sensitivity loss.

Finally, some task-induced myopia may have been present due to the monitors used. The 12.0 and 18.0 c/deg spatial frequencies showed main effects for Monitors. Particularly, the LG Flatron monitor performed significantly better than the other three monitors in minimizing this shift, actually causing a slight increase in contrast sensitivity at these two frequencies. This effect is probably not due to display technology since the two LCDs did not induce similar shifts for these two spatial frequencies. However, it is possible that the flat-screen of the LGF may have been responsible for this effect since it was the only monitor to use that technology, but a more complete study is required to make such a conclusion.

4.4.3 Correlational Analysis

A matrix of Pearson product moments and their corresponding p-values was calculated for the interrelationships of the five spatial frequencies of the contrast sensitivity test. The results of this correlational analysis are presented below in Table 4.25.

TABLE 4.25 -- Pearson Correlation Matrix for Contrast Sensitivity

c/deg	1.5	3.0	6.0	12.0	18.0
1.5	1.0000				
3.0	0.0512 (0. 5206)	1.0000			
6.0	0.1194 (0.1326)	-0.0187 (0.8147)	1.0000		
12.0	-0.0137 (0.8633)	0.1486 (0.0607)	0.0549 (0.4906)	1.0000	
18.0	0.0456 (0.5667)	-0.0080 (0.9204)	0.0374 (0.6387)	0.0687 (0.3878)	1.0000

Note: values in parentheses are p-values

No significant correlations among the five tested spatial frequencies existed. It seems that the spatial frequencies tested were substantially different from one another and, consequently, that they likely do not overlap concerning the aspect of visual performance they describe. It is assumed that this was probably done by the designers of the eye test.

4.5 Correlations Among Data Sets

In an effort to determine if there existed any relationships among the visual fatigue experience, performance, subjective ratings of image quality, and shifts in contrast sensitivity, a correlational analysis of all of the significant variables from the previous analyses was conducted. The results, with the intra-data set correlations removed, are presented in Table 4.26. (The correlations for all variables can be found in Appendix E.) Although there are numerous significant correlations present in this large matrix, the overall trends are the important features to draw from the table.

The first noteworthy feature is ratings of visual fatigue and performance are not strongly correlated. Likely this is due to participants being able to overcome their fatigue and perform consistently over the 75 minute experiment sessions. Also, it may be that participants were able to overcome poor image quality and perform reasonably well, though there is some correlation between Word Processing Time and the subjective image quality ratings.

With regard to subjective ratings of visual fatigue and subjective image quality, these variables are strongly correlated, with the vast majority of the 88 correlations being significant (69 of 88 at $p<=0.10$). This indicates that the treatment conditions that participants rated as having poor image quality tended to be visually fatiguing.

Finally, there was little correlation between shifts in contrast sensitivity and subjective ratings of visual fatigue or image quality. Thus it seems as though changes in contrast sensitivity are not a good corroborating measure of either.

TABLE 4.26 – Pearson Correlation Matrix Among Data Sets

	SVF2	SVF3	SVF4	SVF5	SVF6	SVF7	SVF8	SVF9	SVF10	SVF11	SVF17	SWPT	SWPE	SSIQ1	SSIQ2	SSIQ3	SSIQ4	SSIQ5	SSIQ6	SSIQ7	SSIQ8
SWPT	-0.0394	0.0498	0.2111 (0.0074)	-0.0042	0.0649	0.0846	0.0924	0.1202	-0.0669	0.1034	0.1520 (0.0551)										
SWPE	0.0916	0.1914 (0.0153)	0.1242	0.0574	0.1485 (0.0608)	0.1010	-0.0055	0.0998	0.0566	0.1196	0.0792										
SSIQ1	-0.1054	-0.2237 (0.0045)	-0.2824 (0.0003)	-0.1902 (0.0160)	-0.3083 (<.0001)	-0.4742 (<.0001)	-0.1664 (0.0355)	-0.5550 (<.0001)	-0.1370 (0.0840)	-0.3676 (<.0001)	-0.1088	-0.2354 (0.0027)	-0.0770								
SSIQ2	0.0548	0.1426 (0.0720)	0.2504 (0.0014)	0.1551 (0.0502)	0.3404 (<.0001)	0.3700 (<.0001)	0.1698 (0.0318)	0.3866 (<.0001)	0.0875	0.2685 (0.0006)	0.1198	0.3031 (<.0001)	0.1817 (0.0215)								
SSIQ3	0.1741 (0.0277)	0.1536 (0.0524)	0.3011 (0.0001)	0.2314 (0.0032)	0.3999 (<.0001)	0.3675 (<.0001)	0.1856 (0.0188)	0.3778 (<.0001)	0.1692 (0.0325)	0.2243 (0.0044)	0.1504 (0.0577)	0.2444 (0.0018)	0.1157								
SSIQ4	0.1866 (0.0182)	0.1943 (0.0138)	0.2390 (0.0023)	0.1891 (0.0166)	0.2479 (0.0016)	0.3890 (<.0001)	0.1207	0.3732 (<.0001)	0.1086	0.2416 (0.0021)	0.0585	0.1346 (0.0897)	0.0588								
SSIQ5	0.1868 (0.0180)	0.1121	0.1610 (0.0419)	0.1925 (0.0147)	0.3217 (<.0001)	0.3478 (<.0001)	0.2082 (0.0082)	0.4553 (<.0001)	0.1862 (0.0184)	0.2442 (0.0019)	0.2282 (0.0037)	0.0795	-0.0261								
SSIQ6	0.1515 (0.0559)	0.0963	0.0829	0.1378 (0.0824)	0.2685 (0.0006)	0.2181 (0.0056)	0.2793 (0.0003)	0.3252 (<.0001)	0.1841 (0.0198)	0.3645 (<.0001)	0.1443 (0.0687)	0.0746	0.0898								
SSIQ7	0.2330 (0.0030)	0.1696 (0.0320)	0.1636 (0.0387)	0.0927	0.2803 (0.0003)	0.1976 (0.0123)	0.3414 (<.0001)	0.2016 (0.0106)	0.0833	0.1634 (0.0390)	0.0596	0.0910	0.0859								
SSIQ8	0.1301	0.0312	0.1122	0.1513 (0.0562)	0.1316 (0.0971)	0.2018 (0.0105)	0.1480 (0.0617)	0.1771 (0.0250)	0.2943 (0.0002)	0.0534	0.0601	-0.0877	-0.1588 (0.0449)								
SCS3	-0.0506	0.0364	0.0966	-0.0618	0.0840	0.1181	-0.0366	-0.0377	-0.0924	0.1048	-0.0479	-0.0019	-0.0391	-0.0112	-0.0161	0.0133	0.0714	-0.0713	-0.0271	0.0439	0.0177
SCS4	-0.0555	-0.0189	0.0638	-0.1232	-0.1519 (0.0552)	-0.1457 (0.0661)	-0.1001	-0.1320 (0.0960)	-0.1267	-0.2339 (0.0029)	-0.0931	0.0475	-0.0960	-0.0363	-0.0353	0.0604	0.0373	-0.0542	-0.1025	-0.0179	-0.0008
SCS5	-0.1822 (0.0211)	-0.0838	-0.0803	-0.0406	-0.0099	-0.1290	-0.0225	-0.1206	0.1029	-0.0849	-0.0735	-0.0950	-0.0630	0.0337	0.0558	0.0270	-0.1573 (0.0470)	-0.0366	-0.0088	-0.0238	-0.1259

Note: values in parentheses are p-values

SVF2: watery eyes
SVF3: eyes are irritated, gritty, or burning
SVF4: pain in or around the eyeball
SVF5: heaviness of the eyes
SVF6: problems with line-tracking
SVF7: difficulty in focusing
SVF8: "shivering/jumping" text
SVF9: "foggy" letters
SVF10: glare from lights
SVF11: blurry vision
SVF17: mental fatigue
SWPT: Word Processing Time
SWPE: Word Processing Errors
SSIQ1: Overall
SSIQ2: Contrast
SSIQ3: Sharpness
SSIQ4: Color
SSIQ5: Brightness Variation
SSIQ6: Sizing
SSIQ7: Temporal (Flicker/Jitter)
SSIQ8: Glare
SCS3: 6.0 c/deg
SCS4: 12.0 c/deg
SCS5: 18.0 c/deg

4.6 Regression Analysis

In an effort to develop a model that might be capable of predicting a workspace's tendency to induce visual fatigue, a regression analysis of this study's data was undertaken. The analysis used monitor type (MonType: CRT=1 and LCD=2) and Ambient Illumination (AmbIll: measured in lux) as its regressors and an additive combination of the 11 standardized visual fatigue variables as the dependent variable. (Weighted sums of the standardized visual fatigue variables using the PCA's "Prin1" eigenvector and the FA's "Factor1" factor pattern were also considered in the analysis, but discarded due to less explanation of the data's variance.) Equation 4.1 gives the relationship developed by the regression analysis.

$$\text{Standardized VF Rating} = -7.12+3.97*\text{MonType}+0.00221*\text{AmbIll} \qquad \textbf{(Eq. 4.1)}$$

The equation shows that much more visual fatigue will be reported for CRT monitors than for LCD monitors and that reports of visual fatigue will increase as the ambient illumination of the workplace increases. However, given the relative values of the coefficients for the type of monitor and ambient illumination, this analysis found that below average reports of visual fatigue (i.e., below 0 for standardized ratings) can only be achieved with a CRT monitor, regardless of which ambient illumination level used in this study is chosen for calculation.

The results of the regression analysis suggest that a CRT monitor is less visually fatiguing than an LCD monitor and that greater ambient illumination leads to higher reports of visual fatigue. While this model generally does support the findings discussed in Section 4.1, the model only accounts for 12.63% of the data's variance (r^2=0.1263). This again points to a limitation of this research with respect to the monitors used – only two monitors from each display technology group were used. In addition to this not being a representative sample in and of itself, the two CRT monitors used have different pixel structure technologies and the consistent poor results of the Samsung LCD monitor suggest that these four monitors are not a comprehensive reflection of the two display technologies.

This limitation may partially explain why so little of the data’s total variance was accounted for by the regression model. Also, since visual fatigue as measured in this study is a subjective experience, it is not likely that an equation will ever adequately explain a large portion of the data. Thus, this model is offered as partial support for the conclusion that there may be a display technology influence on visual fatigue, as well as a stepping stone for future research.

5.0 DEVELOPMENTS, FUTURE RESEARCH, AND CONTRIBUTIONS

The results of this research are far-ranging, but do not exist in isolation from one another. Taken in groups and as a whole the results can be extended into new developments for the field of human factors research, offer new avenues of study, and contribute to the discipline of the practitioning human factors community.

5.1 Developments

This dissertation has made several developments in the area of research into visual fatigue research at VDT workstations, as well as research into visual displays in general. The three major developments are: a comprehensive questionnaire for evaluating the subjective experience of visual fatigue; a task battery representative of office work that can be used in visual fatigue, and other VDT workstation, research; and the extension of an existing subjective image quality rating metric into one that can seek specific information about a visual display's characteristics.

5.1.1 Comprehensive Visual Fatigue Questionnaire

The most significant development of this research is related to characterizing the subjective experience of visual fatigue. Numerous methods for evaluating the nebulous concept of visual fatigue – and whether people are experiencing it – have been proposed and employed in previous experiments. Chief among these method has been the use of surveys, but they have lacked consistency. This study took a large number of surveys under consideration and chose 17 factors that were commonly used, combining them into a single questionnaire for use in this study. After analysis of the data generated by this questionnaire, a reduced set of 11 factors that were found to be the most consistent predictors of visual fatigue. These 11 factors are:

- watery eyes
- eyes are irritated, gritty, or burning
- pain in or around the eyeball
- heaviness of the eyes
- problems with line-tracking
- difficulty in focusing
- "shivering/jumping" text
- "foggy" letters
- glare from lights
- blurry vision
- mental fatigue

The only alteration that is suggested to improve the 11-question questionnaire is to add more explicit instructions for participants to rate how they felt *immediately* after the end of the experiment session. For instance, if the experiment was performed in the dark and then the lights are turned on to complete the questionnaire, an asthenopic symptom such as watery eyes may be induced that should not be reported in the visual fatigue questionnaire. A good solution to this problem may be to have participants fill-out the survey on the computer upon completion of the experimental session.

5.1.2 Office Task Battery

The task set used to fatigue the participants during the experiment session was one designed for this experiment. Although similar tasks have been used together, what constituted the "word processing" task, the "data entry" task, and the "Web browsing" task was developed for this research.

The word processing task was successful as used in this study, achieving significant results for both the time and error performance variables. Using three, four, and five letter word sets from web pages designed for Scrabble players, a simple program was written to generate the task trials. The time-intensive portion of the task development came in formatting the special words.

A somewhat more sophisticated program probably could do this with greater ease.

The data entry task did not achieve significance for either performance variable. One reason for this may have been that the trials were too long, resulting in relatively few trials being completed in the 25 minute period. Fewer data points for entry per trial would have allowed more trials to be completed in the 25 minute period and, perhaps, more accurately reflected performance on this task. Generation of the task trials was quite easy. A simple program was written to generate random numbers and a spreadsheet was used to neatly table those numbers.

The Web browsing generated no significant results for the performance variables. This may have been due to a large degree of inter-trial variability, which, in turn, is attributable to the Web's ever-changing nature. The generation of the task trials was by far the most difficult of the OTB. Due to the Web's constant flux, the trials had to be developed nearly at the last minute. Furthermore, World Wide Web pages typically take advantage of their multimedia capabilities and finding pages that contained mostly text was a challenge. Combine that with trying to find pages that were of reasonably equal length and not too difficult to link to (to minimize trial inhomogeneity), and the approximate time to develop one trial was 30 to 40 minutes; a large time investment, at the last minute, when developing nearly 100 trials. With the additional threat of network downtime during the experiment, the Web browsing task, as designed for this experiment, is impracticable.

5.1.3 Augmented Subjective Image Quality Survey

The third major development of this dissertation research has been the augmentation of a well-established subjective rating scale. This scale, a nine-point Likert scale with adjective anchors for each point, has been used extensively in subjective ratings of visual display image quality. This current research has shown that the addition of ratings scales for seven image quality dimensions was well correlated with this established scale and can detect fine differences in subjective ratings of different monitors.

5.2 Future Research Possibilities

While this dissertation research was large in scope, it could not be expected to resolve all of the unanswered research questions in the area of visual fatigue. Even for the topics that were investigated, the research is not yet complete. Two major areas need further research.

First, the OTB needs refining. While it worked well for this project, issues such as the proper trial size for the Data Entry task need to be explored in further human factors research. Also, several issues for the Web Browsing task remain, such as trial inhomogeneity and dealing with the vagaries of the Internet (e.g., ever-changing web pages and network downtime).

Second, a larger effort needs to be made to evaluate monitors representing the three display technologies used in this study. Due to the use of ambient illumination as an independent variable in this experiment, only four monitors could be used. Future research that concentrates on display technologies could test more monitors. That research probably should use more than one monitor representing each technology. As the poor performance of the Samsung LCD monitor showed in this research, investigators need to be sure that differences are due to the technology itself and not due to a poor display. Also, when comparing CRT displays, an effort should be made to compare monitors that use the same pixel structure technology (e.g., shadow mask, slot mask, Trinitron, etc.) so as to control this confounding effect.

Lastly, the predictive model of visual fatigue developed in this research should be expanded. While this study’s data did not generate a robust model, future research may be able to. Such a model would be a very beneficial tool for the human factors/ergonomics community, allowing them to quickly, easily, and cheaply evaluate VDT workstation design with respect to visual fatigue.

5.3 Contributions

Computer use keeps growing. The workplace is becoming more electronic all the time and with the cheap cost of personal computers and access to the Internet, the time an average person spends in front of a computer is not only becoming greater, but is taking up a larger fraction of the day. With this current societal trend, it is incumbent upon researchers to learn more about how this use affects computer users. Human factors researchers in particular need to understand and quantify these effects. This research has striven to both understand and quantify the visual fatigue experience.

It was intended that this research extend previous research into visual fatigue; building on the knowledge base in this area and adding another supporting element to the body of research. While the research itself contributed another sound study to the area of visual fatigue, perhaps its greatest benefit is the development of a comprehensive survey that can be used as a standardized metric for visual fatigue studies. Hopefully this will help the research community by providing a single yardstick to measure visual fatigue and compare future studies to one another.

It was further hoped that this research would begin an effort to standardize another important feature of visual fatigue research – namely the visually fatiguing work participants perform. The development of the Office Task Battery (OTB), while still not fully refined, offers a measurable set of tasks that are grounded in real-world work performed at VDT workstations.

This research also contributed in the area of subjective image quality measurement. Using a well-established overall metric for image quality judgments as its basis, the addition of seven dimensions of image quality was used to help distinguish between fine differences of the various displays used in this study. It is hoped that this development will aid future research into comparisons visual displays.

Lastly, beyond a general extension of visual fatigue research and the consolidation of a questionnaire and task set, this research hoped to contribute to an undefined branch of this field, specifically into how various display technologies might affect visual fatigue. We are on the cusp of a shift in visual displays – from the standard bearer curved-screen CRT to “flat” and “thin” technologies. How this shift might affect computer users is an important engineering issue. Accordingly, having a sound research base for the design of VDT workstations is a meaningful and important topic to investigate. It is anticipated that this research will be the cornerstone for future investigations into this issue.

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APPENDIX A:

The Informed Consent Form

Title of Project: Display Technology Influences on Visual Fatigue at VDT Workstations

Principle Investigator: Aaron Bangor

I. THE PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study about visual display quality under various illumination conditions. This study involves experimentation for the purpose of measuring how different types of computer monitors perform under various illumination conditions and how people respond to working with those monitors.

II. PROCEDURES

Should you choose to participate in this study the following procedures will be used. You will be given a vision test for acuity and contrast sensitivity. Following this exam you will be given a questionnaire to fill out. Once this is done, you will be seated at a computer workstation and asked to perform various tasks on the computer that represent types of work done in an office environment. These tasks will last 75 minutes. At the end of that 75 minutes you will be given a second contrast sensitivity test and asked to fill out two other surveys. This procedure will be followed for 15 more sessions.

In order to participate in this experiment it is necessary that you meet all of the conditions listed below:

1) you have a corrected visual acuity of 20/30 or better,
2) you are free from ocular (eye) diseases,
3) you are between 18 and 40 years of age, and

III. RISKS OF THIS PROJECT

The risk that you will be exposed to in this study is related to using a personal computer. You are not exposing yourself to any additional risk by participating in this study. You understand and are familiar with using a personal computer and have not had any problems with them.

IV BENEFITS OF THIS PROJECT

Your participation in this experiment will provide information regarding how different monitors and lighting conditions may influence the use of a personal computer. No guarantee of benefits has been made to encourage you to participate, other than the compensation specified in Section VI of this form. You may receive a hard copy summary of this research upon its completion by leaving a self-addressed envelope or a soft copy summary if you leave your e-mail address and a preferred format (e.g., ASCII, .pdf, Word, etc.) with the investigator.

V EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of your specific contribution to this study will be kept strictly confidential. At no time will the researchers release the results of the study containing your name to anyone other than individuals working on this project without your written consent. The information you provide will have your name removed and only a participant number will identify you during analyses and any written reports of the research.

VI COMPENSATION

Your compensation for participating in this study is that which you agreed upon with your temp agency.

VII FREEDOM TO WITHDRAW

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

There may be the following circumstances under which the investigator may determine that you should not continue as a participant of this project:

1) your corrected vision is not 20/30 or better
2) you have an eye disease
3) you are not between the ages of 18 and 40 years.
4) you have missed work sessions that could not be made-up

Should the investigator determine that the experiment will not continue, you will be compensated for the portion of the session completed.

VIII APPROVAL OF RESEARCH

This research has bee approved, as required, by the Institutional Review Board (IRB) for projects involving human participants at Virginia Polytechnic Institute and State University and by the Department of Industrial and Systems Engineering.

IX PARTICIPANT'S RESPONSIBILITIES

I know of no reason I cannot participate in this study. I have corrected vision of 20/30 or better, am free of eye disease, and am between the ages of 18 and 40 years. I will follow the instructions of the investigator and will participate in the experiment to the best of my ability.

I will attend every session as scheduled by the experimenter. I will be in the lab on time; at the most 15 minutes late. If, for some reason, I can not be present on time, I will call to inform the investigator of this at: 540-231-8748.

X PARTICIPANT'S PERMISSION

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

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

Participant Signature

____
Signature Date

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

Aaron Bangor, Principal Investigator - 552-5067; abangor@vt.edu
Dr. Robert Beaton, Dissertation Committee Chair - 231-8748; bobb@vt.edu
H. T. Hurd, IRB Chair Research Division - 231-9359

APPENDIX B:

(Developed from: Aarås et al. (1998); Chi and Lin, 1998; Conlon et al., 1999; Dillon and Emurian, 1995; Jaschinski, Heuer, and Kylian, 1999; Matthews and Desmond, 1998; and Watten, Lie, and Magnussen, 1992)

Visual Fatigue Questionnaire

Participant #:_______

INSTRUCTIONS: To respond to each of the following categories, make a vertical mark across the dashed line. You can make your mark at any point from the left to right endpoints.

Do you notice any of the following symptoms affecting you right now?

Dry Eyes:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Watery Eyes:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Eyes are Irritated, Gritty, or Burning:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Pain in or around the Eyeball:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Heaviness of the Eyes:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Problems with Line-tracking:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Difficulty in Focusing:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

"Shivering/Jumping" Text:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

"Foggy" Letters:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Glare From Lights:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Blurry Vision:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Double Vision:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Headache:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Neck Pain:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Dizziness:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Nausea:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

Mental Fatigue:
|----------+----------+----------+----------|----------+----------+----------+----------|
Not noticeable at all Somewhat noticeable Extremely noticeable

APPENDIX C:

(Developed from: (Menozzi, Napflin, and Krueger, 1999; Toms and Cone, 1995; Hunter, 1988)

Subjective Image Quality Survey

Participant #:_______

Check the box that best expresses your opinion about each question.

How would you describe the **OVERALL** quality of the monitor's image?

☐	☐	☐	☐	☐	☐	☐	☐	☐
Worst Imaginable	Awful	Poor	Marginal	Passable	OK	Good	Excellent	Best Imaginable

For each category, make a vertical mark across the dashed line. You can make your mark at any point from the left to right endpoints.

While using the computer during **ONLY** this past session, did you notice any of the following?

Contrast of text and icons was insufficient to see well

|----------+----------+----------+----------|----------+----------+----------+----------|

Not noticeable at all Somewhat noticeable Extremely noticeable

Image was not sharp – details were not seen and the screen lacked overall clarity

|----------+----------+----------+----------|----------+----------+----------+----------|

Not noticeable at all Somewhat noticeable Extremely noticeable

Colors looked strange (for instance, reds had an orange or purple tinge to them) or washed out (for instance, reds looked pinkish)

|----------+----------+----------+----------|----------+----------+----------+----------|

Not noticeable at all Somewhat noticeable Extremely noticeable

Brightness varied at different locations of the screen (not from the lights)

|----------+----------+----------+----------|----------+----------+----------+----------|

Not noticeable at all Somewhat noticeable Extremely noticeable

Text, icons, and other characters looked incorrectly sized (too large or too small compared to the rest of the screen) or looked distorted

|----------+----------+----------+----------|----------+----------+----------+----------|

Not noticeable at all Somewhat noticeable Extremely noticeable

The whole screen flickered (brightness flashed really quickly) or jittered (jumped around)

|----------+----------+----------+----------|----------+----------+----------+----------|

Not noticeable at all Somewhat noticeable Extremely noticeable

Screen reflections were bothersome

|----------+----------+----------+----------|----------+----------+----------+----------|

Not noticeable at all Somewhat noticeable Extremely noticeable

APPENDIX D:

Participants' Task Instructions

Word Processing Task

When the experimenter tells you that you may begin, click the "Start Task" button at the bottom of this window. You will be shown a set of three, four, and five letter words arranged randomly, but with three of each on a line, for a total of nine words per line; there will be ten lines per page. Additionally, one word out of each line will be formatted either in **bold**, *italics*, or underlined. Your task is to transfer these words, in order and with the appropriate formatting, to a document in Microsoft Word. To do this, double-click on the "Microsoft Word" icon on the desktop. Do so now. You may adjust the size and location of the Word window to your liking. After that you can switch from this window to Microsoft Word by clicking on the Word window and then clicking on this window to return again.

When you are transferring the text, you may format each special word as you go, when you reach the end of the line, or at the end of each page. Also, you can either use the formatting toolbar¹s icons or the Apple-B, Apple-I, or Apple-U key combinations to bold, italicize, or underline those words, respectively, so long as you do so before moving on to the next page -- you won't be able to go back.

When you are finished transferring all of the words, with formatting, from the this window to Microsoft Word, click on the "Next Word Set" button to go to a wait screen. While on the wait screen, go back to Word and insert a page break after the set of words. Begin the second set of words by clicking on the "Next Word Set" button on the wait screen and typing the new word set below the page break on the new page in Word.

When the experimenter tells you the word processing task is over, immediately stop entering any text into the Word window, return to this window and click on the "Stop Word Processing" button. Finally, go back to Word and save the text to the "Experiment Files" folder, naming the file "Word".

You will be measured on the time to transfer each set of words and the number of typing and formatting errors that you make.

Data Entry Task

REMINDER: Save the Microsoft Word document to the "Experiment Files" folder, naming it "Word". Quit Microsoft Word.

When the experimenter tells you that you may begin, click the "Start Task" button in this window. You will be shown a table of numbers. Your task is to transfer these numbers in order and including the column headers and any decimal points and commas to a document in Microsoft Excel. To do this, close Word and then double-click on the "Microsoft Excel" icon on the desktop. Do so now. You may adjust the size and location of the Excel window to your liking. You can switch between windows as you did in the word processing task -- by clicking on the desired window to make it active. When you are in Excel enter the numbers from this window -- one number per cell.

When you are finished transferring all of the numbers from this window to Excel, click on the "Next Data Set" button to go to a wait screen. While on the wait screen, go back to Excel and insert a page break after the set of numbers. Begin the second data set by clicking on the "Next Data Set" button on the wait screen and entering the new data set below the page break on the new page in Excel. When you begin the next set of numbers in the Excel window, be sure to skip at least one line to separate the new set of numbers from the previous set.

When the experimenter tells you the session is over, immediately stop entering any numbers into the Excel window, return to this window and click on the "Stop Data Entry" button. Finally, go back to Excel and save the file to the "Experiment Files" folder, naming the file "Excel".

You will be measured on the time to transfer each set of numbers and the number of incorrect numbers that you enter into the spreadsheet.

Web Browsing Task

REMINDER: Save the Microsoft Excel document to the "Experiment Files" folder, naming it "Excel". Quit Microsoft Excel.

When the experimenter tells you that you may begin, click the "Start Task" button in this window. You will be shown a list of steps about how to reach a specific web page. The first will be an address to begin at, followed by a series of links you should click on. Follow these steps to find the page of interest it should contain mostly text. To do this, close Excel and then double-click on the “Browser” icon on the desktop. Enter the starting address in the "Address" bar and then begin browsing.

Once you have reached the target page, you will need to use your eyes to search for the target word you were given in this window. DO NOT use the browser's "Find" feature to search for you. Your task will be to locate the exact number of times that target word appears on the web page. Any instance of this word, whether it is text or part of a graphic, should be counted. However, it must be the word itself and not part of another word. For example if the target word is "the" you should not count "there" as an instance of the word "the." You should NOT read the page. When you have finished searching the page and have a count of the target word, return to this window and enter it into the "Target Word Count" box and then click on the "Next Web Search" button.

When the experimenter tells you the session is over, immediately stop entering any numbers into the browser window, return to this window and click on the "Stop Web Browsing" button.

You will be measured on the time needed to determine the target word count and how far off your count was from the actual count.

APPENDIX E:

SAS Output for the Correlational Analysis Including All Dependent Variables

```
                                 The CORR Procedure

                      Pearson Correlation Coefficients, N = 160
                              Prob > |r| under H0: Rho=0

              SVF2         SVF3         SVF4         SVF5         SVF6         SVF7         SVF8         SVF9

SVF2       1.00000      0.53935      0.32334      0.38350      0.25295      0.34650      0.19412      0.16977
                         <.0001       <.0001       <.0001       0.0013       <.0001       0.0139       0.0319

SVF3       0.53935      1.00000      0.49774      0.28990      0.37633      0.34979      0.18535      0.29128
            <.0001                    <.0001       0.0002       <.0001       <.0001       0.0190       0.0002

SVF4       0.32334      0.49774      1.00000      0.34869      0.36298      0.34607      0.17159      0.19982
            <.0001       <.0001                    <.0001       <.0001       <.0001       0.0300       0.0113

SVF5       0.38350      0.28990      0.34869      1.00000      0.42921      0.41196      0.21581      0.31933
            <.0001       0.0002       <.0001                    <.0001       <.0001       0.0061       <.0001

SVF6       0.25295      0.37633      0.36298      0.42921      1.00000      0.50834      0.34012      0.40992
            0.0013       <.0001       <.0001       <.0001                    <.0001       <.0001       <.0001

SVF7       0.34650      0.34979      0.34607      0.41196      0.50834      1.00000      0.29633      0.64986
            <.0001       <.0001       <.0001       <.0001       <.0001                    0.0001       <.0001

SVF8       0.19412      0.18535      0.17159      0.21581      0.34012      0.29633      1.00000      0.31881
            0.0139       0.0190       0.0300       0.0061       <.0001       0.0001                    <.0001

SVF9       0.16977      0.29128      0.19982      0.31933      0.40992      0.64986      0.31881      1.00000
            0.0319       0.0002       0.0113       <.0001       <.0001       <.0001       <.0001

SVF10      0.09028      0.15886      0.10585      0.29993      0.22690      0.24122      0.16485      0.30939
            0.2563       0.0448       0.1828       0.0001       0.0039       0.0021       0.0372       <.0001

SVF11      0.17676      0.17622      0.08748      0.25846      0.36616      0.52178      0.30225      0.59176
            0.0254       0.0258       0.2714       0.0010       <.0001       <.0001       0.0001       <.0001

SVF17      0.11601      0.18796      0.11086      0.33388      0.36618      0.11072      0.16392      0.21594
            0.1441       0.0173       0.1628       <.0001       <.0001       0.1634       0.0383       0.0061

SWPT      -0.03938      0.04982      0.21110     -0.00416      0.06490      0.08463      0.09236      0.12016
            0.6210       0.5315       0.0074       0.9583       0.4149       0.2873       0.2454       0.1301

SWPE       0.09159      0.19144      0.12421      0.05741      0.14855      0.10105     -0.00550      0.09975
            0.2494       0.0153       0.1176       0.4709       0.0608       0.2036       0.9450       0.2095

SDET      -0.03937      0.04653      0.10439     -0.05865     -0.03397      0.07972     -0.05229      0.16147
            0.6211       0.5591       0.1890       0.4613       0.6698       0.3163       0.5114       0.0414

SDEE      -0.04142      0.02242      0.06155      0.05488      0.02301     -0.04736     -0.08533      0.00305
            0.6031       0.7784       0.4394       0.4907       0.7727       0.5520       0.2833       0.9694

SWBT       0.02699     -0.03147      0.01756     -0.01557      0.09758      0.04285      0.05942      0.10384
            0.7347       0.6928       0.8256       0.8451       0.2196       0.5906       0.4554       0.1913

SWBE      -0.21913     -0.18066     -0.08470     -0.13133      0.04191      0.00463      0.17461     -0.02718
            0.0054       0.0222       0.2869       0.0978       0.5988       0.9536       0.0272       0.7330
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SSIQ1	-0.10536	-0.22373	-0.28243	-0.19016	-0.30826	-0.47424	-0.16639	-0.55505
	0.1849	0.0045	0.0003	0.0160	<.0001	<.0001	0.0355	<.0001
SSIQ2	0.05484	0.14262	0.25040	0.15510	0.34045	0.36996	0.16978	0.38660
	0.4910	0.0720	0.0014	0.0502	<.0001	<.0001	0.0318	<.0001
SSIQ3	0.17407	0.15362	0.30111	0.23144	0.39995	0.36745	0.18558	0.37781
	0.0277	0.0524	0.0001	0.0032	<.0001	<.0001	0.0188	<.0001
SSIQ4	0.18657	0.19430	0.23896	0.18913	0.24788	0.38903	0.12072	0.37321
	0.0182	0.0138	0.0023	0.0166	0.0016	<.0001	0.1284	<.0001
SSIQ5	0.18676	0.11213	0.16103	0.19254	0.32173	0.34784	0.20821	0.45534
	0.0180	0.1580	0.0419	0.0147	<.0001	<.0001	0.0082	<.0001
SSIQ6	0.15148	0.09634	0.08291	0.13775	0.26846	0.21811	0.27932	0.32516
	0.0559	0.2256	0.2973	0.0824	0.0006	0.0056	0.0003	<.0001
SSIQ7	0.23302	0.16961	0.16360	0.09272	0.28027	0.19759	0.34135	0.20159
	0.0030	0.0320	0.0387	0.2436	0.0003	0.0123	<.0001	0.0106
SSIQ8	0.13008	0.03120	0.11215	0.15126	0.13161	0.20182	0.14804	0.17712
	0.1011	0.6953	0.1580	0.0562	0.0971	0.0105	0.0617	0.0250
SCS1	-0.06628	-0.11240	0.03088	-0.05793	-0.05349	-0.19605	-0.13926	-0.21650
	0.4050	0.1570	0.6983	0.4669	0.5017	0.0130	0.0790	0.0060
SCS2	0.08222	0.00405	0.01590	-0.03376	-0.06295	-0.02421	-0.08770	0.00728
	0.3013	0.9595	0.8418	0.6717	0.4291	0.7612	0.2701	0.9272
SCS3	-0.05060	0.03637	0.09659	-0.06175	0.08404	0.11810	-0.03665	-0.03767
	0.5252	0.6479	0.2244	0.4379	0.2907	0.1369	0.6454	0.6362
SCS4	-0.05555	-0.01886	0.06383	-0.12318	-0.15186	-0.14567	-0.10013	-0.13205
	0.4854	0.8128	0.4226	0.1207	0.0552	0.0661	0.2078	0.0960
SCS5	-0.18221	-0.08377	-0.08025	-0.04057	-0.00994	-0.12902	-0.02252	-0.12063
	0.0211	0.2923	0.3131	0.6105	0.9007	0.1039	0.7774	0.1287

	SVF10	SVF11	SVF17	SWPT	SWPE	SDET	SDEE	SWBT
SVF2	0.09028	0.17676	0.11601	-0.03938	0.09159	-0.03937	-0.04142	0.02699
	0.2563	0.0254	0.1441	0.6210	0.2494	0.6211	0.6031	0.7347
SVF3	0.15886	0.17622	0.18796	0.04982	0.19144	0.04653	0.02242	-0.03147
	0.0448	0.0258	0.0173	0.5315	0.0153	0.5591	0.7784	0.6928
SVF4	0.10585	0.08748	0.11086	0.21110	0.12421	0.10439	0.06155	0.01756
	0.1828	0.2714	0.1628	0.0074	0.1176	0.1890	0.4394	0.8256
SVF5	0.29993	0.25846	0.33388	-0.00416	0.05741	-0.05865	0.05488	-0.01557
	0.0001	0.0010	<.0001	0.9583	0.4709	0.4613	0.4907	0.8451
SVF6	0.22690	0.36616	0.36618	0.06490	0.14855	-0.03397	0.02301	0.09758
	0.0039	<.0001	<.0001	0.4149	0.0608	0.6698	0.7727	0.2196
SVF7	0.24122	0.52178	0.11072	0.08463	0.10105	0.07972	-0.04736	0.04285
	0.0021	<.0001	0.1634	0.2873	0.2036	0.3163	0.5520	0.5906
SVF8	0.16485	0.30225	0.16392	0.09236	-0.00550	-0.05229	-0.08533	0.05942
	0.0372	0.0001	0.0383	0.2454	0.9450	0.5114	0.2833	0.4554
SVF9	0.30939	0.59176	0.21594	0.12016	0.09975	0.16147	0.00305	0.10384
	<.0001	<.0001	0.0061	0.1301	0.2095	0.0414	0.9694	0.1913

SVF10	1.00000	0.27961	0.21651	-0.06695	0.05655	-0.11270	-0.12576	0.07819
		0.0003	0.0060	0.4003	0.4775	0.1559	0.1131	0.3257
SVF11	0.27961	1.00000	0.22463	0.10343	0.11958	0.15812	0.07066	0.02196
	0.0003		0.0043	0.1931	0.1320	0.0458	0.3746	0.7829
SVF17	0.21651	0.22463	1.00000	0.15197	0.07924	0.10462	0.10950	0.04522
	0.0060	0.0043		0.0551	0.3192	0.1880	0.1681	0.5702
SWPT	-0.06695	0.10343	0.15197	1.00000	0.23356	0.44779	0.39960	0.14417
	0.4003	0.1931	0.0551		0.0030	<.0001	<.0001	0.0689
SWPE	0.05655	0.11958	0.07924	0.23356	1.00000	0.28465	0.32994	0.08886
	0.4775	0.1320	0.3192	0.0030		0.0003	<.0001	0.2639
SDET	-0.11270	0.15812	0.10462	0.44779	0.28465	1.00000	0.51961	0.17075
	0.1559	0.0458	0.1880	<.0001	0.0003		<.0001	0.0309
SDEE	-0.12576	0.07066	0.10950	0.39960	0.32994	0.51961	1.00000	0.09571
	0.1131	0.3746	0.1681	<.0001	<.0001	<.0001		0.2286
SWBT	0.07819	0.02196	0.04522	0.14417	0.08886	0.17075	0.09571	1.00000
	0.3257	0.7829	0.5702	0.0689	0.2639	0.0309	0.2286	
SWBE	0.01349	-0.07607	-0.00532	-0.00277	-0.01658	-0.06910	-0.00606	-0.00558
	0.8656	0.3391	0.9468	0.9723	0.8351	0.3853	0.9394	0.9442
SSIQ1	-0.13705	-0.36756	-0.10878	-0.23538	-0.07701	-0.13707	-0.00842	0.05706
	0.0840	<.0001	0.1709	0.0027	0.3331	0.0839	0.9158	0.4736
SSIQ2	0.08747	0.26852	0.11976	0.30315	0.18172	0.18401	0.07006	0.04393
	0.2714	0.0006	0.1314	<.0001	0.0215	0.0198	0.3787	0.5813
SSIQ3	0.16918	0.22431	0.15036	0.24435	0.11568	0.02708	0.04086	0.03578
	0.0325	0.0044	0.0577	0.0018	0.1452	0.7339	0.6080	0.6533
SSIQ4	0.10859	0.24165	0.05849	0.13461	0.05876	0.12015	-0.03305	-0.05553
	0.1717	0.0021	0.4625	0.0897	0.4605	0.1302	0.6782	0.4855
SSIQ5	0.18618	0.24420	0.22815	0.07951	-0.02612	0.03639	-0.07007	0.07762
	0.0184	0.0019	0.0037	0.3176	0.7430	0.6478	0.3786	0.3292
SSIQ6	0.18408	0.36451	0.14428	0.07458	0.08977	-0.05075	-0.07388	-0.02729
	0.0198	<.0001	0.0687	0.3486	0.2589	0.5239	0.3532	0.7319
SSIQ7	0.08330	0.16339	0.05955	0.09099	0.08587	-0.03869	-0.07265	-0.02539
	0.2950	0.0390	0.4544	0.2525	0.2803	0.6271	0.3613	0.7499
SSIQ8	0.29427	0.05344	0.06006	-0.08766	-0.15882	-0.20649	-0.25825	-0.00676
	0.0002	0.5021	0.4506	0.2703	0.0449	0.0088	0.0010	0.9324
SCS1	-0.25453	-0.09090	-0.05495	0.11697	0.03657	0.16165	0.26602	0.03353
	0.0012	0.2530	0.4901	0.1408	0.6462	0.0411	0.0007	0.6738
SCS2	-0.02776	-0.07448	-0.01946	0.08306	0.05711	0.01323	0.14137	0.00016
	0.7275	0.3493	0.8071	0.2964	0.4732	0.8682	0.0746	0.9984
SCS3	-0.09245	0.10479	-0.04787	-0.00190	-0.03907	-0.05943	0.02302	-0.04944
	0.2450	0.1872	0.5478	0.9809	0.6238	0.4553	0.7726	0.5347
SCS4	-0.12670	-0.23386	-0.09309	0.04746	-0.09600	-0.07199	-0.05802	0.07887
	0.1104	0.0029	0.2417	0.5512	0.2272	0.3656	0.4661	0.3215
SCS5	0.10295	-0.08486	-0.07349	-0.09505	-0.06303	-0.15545	-0.04664	-0.14685

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            0.1952     0.2860     0.3557     0.2319     0.4284     0.0497     0.5581     0.0639

              SWBE      SSIQ1      SSIQ2      SSIQ3      SSIQ4      SSIQ5      SSIQ6      SSIQ7

SVF2      -0.21913   -0.10536    0.05484    0.17407    0.18657    0.18676    0.15148    0.23302
            0.0054     0.1849     0.4910     0.0277     0.0182     0.0180     0.0559     0.0030

SVF3      -0.18066   -0.22373    0.14262    0.15362    0.19430    0.11213    0.09634    0.16961
            0.0222     0.0045     0.0720     0.0524     0.0138     0.1580     0.2256     0.0320

SVF4      -0.08470   -0.28243    0.25040    0.30111    0.23896    0.16103    0.08291    0.16360
            0.2869     0.0003     0.0014     0.0001     0.0023     0.0419     0.2973     0.0387

SVF5      -0.13133   -0.19016    0.15510    0.23144    0.18913    0.19254    0.13775    0.09272
            0.0978     0.0160     0.0502     0.0032     0.0166     0.0147     0.0824     0.2436

SVF6       0.04191   -0.30826    0.34045    0.39995    0.24788    0.32173    0.26846    0.28027
            0.5988     <.0001     <.0001     <.0001     0.0016     <.0001     0.0006     0.0003

SVF7       0.00463   -0.47424    0.36996    0.36745    0.38903    0.34784    0.21811    0.19759
            0.9536     <.0001     <.0001     <.0001     <.0001     <.0001     0.0056     0.0123

SVF8       0.17461   -0.16639    0.16978    0.18558    0.12072    0.20821    0.27932    0.34135
            0.0272     0.0355     0.0318     0.0188     0.1284     0.0082     0.0003     <.0001

SVF9      -0.02718   -0.55505    0.38660    0.37781    0.37321    0.45534    0.32516    0.20159
            0.7330     <.0001     <.0001     <.0001     <.0001     <.0001     <.0001     0.0106

SVF10      0.01349   -0.13705    0.08747    0.16918    0.10859    0.18618    0.18408    0.08330
            0.8656     0.0840     0.2714     0.0325     0.1717     0.0184     0.0198     0.2950

SVF11     -0.07607   -0.36756    0.26852    0.22431    0.24165    0.24420    0.36451    0.16339
            0.3391     <.0001     0.0006     0.0044     0.0021     0.0019     <.0001     0.0390

SVF17     -0.00532   -0.10878    0.11976    0.15036    0.05849    0.22815    0.14428    0.05955
            0.9468     0.1709     0.1314     0.0577     0.4625     0.0037     0.0687     0.4544

SWPT      -0.00277   -0.23538    0.30315    0.24435    0.13461    0.07951    0.07458    0.09099
            0.9723     0.0027     <.0001     0.0018     0.0897     0.3176     0.3486     0.2525

SWPE      -0.01658   -0.07701    0.18172    0.11568    0.05876   -0.02612    0.08977    0.08587
            0.8351     0.3331     0.0215     0.1452     0.4605     0.7430     0.2589     0.2803

SDET      -0.06910   -0.13707    0.18401    0.02708    0.12015    0.03639   -0.05075   -0.03869
            0.3853     0.0839     0.0198     0.7339     0.1302     0.6478     0.5239     0.6271

SDEE      -0.00606   -0.00842    0.07006    0.04086   -0.03305   -0.07007   -0.07388   -0.07265
            0.9394     0.9158     0.3787     0.6080     0.6782     0.3786     0.3532     0.3613

SWBT      -0.00558    0.05706    0.04393    0.03578   -0.05553    0.07762   -0.02729   -0.02539
            0.9442     0.4736     0.5813     0.6533     0.4855     0.3292     0.7319     0.7499

SWBE       1.00000   -0.07910    0.08790    0.08297    0.10879    0.10046    0.09551    0.12733
                       0.3201     0.2690     0.2969     0.1709     0.2063     0.2296     0.1086

SSIQ1     -0.07910    1.00000   -0.68022   -0.67427   -0.66278   -0.66900   -0.55830   -0.45154
            0.3201                <.0001     <.0001     <.0001     <.0001     <.0001     <.0001

SSIQ2      0.08790   -0.68022    1.00000    0.63962    0.40139    0.53720    0.49485    0.46700
            0.2690     <.0001                <.0001     <.0001     <.0001     <.0001     <.0001

SSIQ3      0.08297   -0.67427    0.63962    1.00000    0.47452    0.66219    0.49930    0.45652
            0.2969     <.0001     <.0001                <.0001     <.0001     <.0001     <.0001

SSIQ4      0.10879   -0.66278    0.40139    0.47452    1.00000    0.63437    0.37795    0.49161
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           0.1709    <.0001    <.0001    <.0001              <.0001    <.0001    <.0001


SSIQ5     0.10046  -0.66900   0.53720   0.66219   0.63437   1.00000   0.53917   0.45740
           0.2063    <.0001    <.0001    <.0001    <.0001              <.0001    <.0001

SSIQ6     0.09551  -0.55830   0.49485   0.49930   0.37795   0.53917   1.00000   0.37148
           0.2296    <.0001    <.0001    <.0001    <.0001    <.0001              <.0001

SSIQ7     0.12733  -0.45154   0.46700   0.45652   0.49161   0.45740   0.37148   1.00000
           0.1086    <.0001    <.0001    <.0001    <.0001    <.0001    <.0001

SSIQ8     0.11448  -0.34575   0.21552   0.29880   0.31086   0.40384   0.34307   0.25989
           0.1494    <.0001    0.0062    0.0001    <.0001    <.0001    <.0001    0.0009

SCS1      0.04064   0.16681  -0.14707  -0.07777  -0.14413  -0.13576  -0.12675  -0.16160
           0.6099    0.0350    0.0635    0.3283    0.0690    0.0869    0.1102    0.0412

SCS2     -0.10889   0.10010  -0.06039   0.10130   0.02252   0.02225  -0.13939   0.02281
           0.1705    0.2079    0.4481    0.2024    0.7775    0.7800    0.0788    0.7746

SCS3     -0.03859  -0.01123  -0.01613   0.01333   0.07144  -0.07133  -0.02712   0.04387
           0.6280    0.8879    0.8396    0.8671    0.3693    0.3700    0.7336    0.5817

SCS4     -0.00376  -0.03634  -0.03527   0.06041   0.03725  -0.05423  -0.10255  -0.01794
           0.9624    0.6483    0.6579    0.4479    0.6400    0.4958    0.1969    0.8218

SCS5      0.16265   0.03370   0.05583   0.02701  -0.15728  -0.03663  -0.00881  -0.02375
           0.0399    0.6722    0.4832    0.7345    0.0470    0.6457    0.9120    0.7656

            SSIQ8          SCS1          SCS2          SCS3          SCS4          SCS5

SVF2      0.13008      -0.06628       0.08222      -0.05060      -0.05555      -0.18221
           0.1011        0.4050        0.3013        0.5252        0.4854        0.0211

SVF3      0.03120      -0.11240       0.00405       0.03637      -0.01886      -0.08377
           0.6953        0.1570        0.9595        0.6479        0.8128        0.2923

SVF4      0.11215       0.03088       0.01590       0.09659       0.06383      -0.08025
           0.1580        0.6983        0.8418        0.2244        0.4226        0.3131

SVF5      0.15126      -0.05793      -0.03376      -0.06175      -0.12318      -0.04057
           0.0562        0.4669        0.6717        0.4379        0.1207        0.6105

SVF6      0.13161      -0.05349      -0.06295       0.08404      -0.15186      -0.00994
           0.0971        0.5017        0.4291        0.2907        0.0552        0.9007

SVF7      0.20182      -0.19605      -0.02421       0.11810      -0.14567      -0.12902
           0.0105        0.0130        0.7612        0.1369        0.0661        0.1039

SVF8      0.14804      -0.13926      -0.08770      -0.03665      -0.10013      -0.02252
           0.0617        0.0790        0.2701        0.6454        0.2078        0.7774

SVF9      0.17712      -0.21650       0.00728      -0.03767      -0.13205      -0.12063
           0.0250        0.0060        0.9272        0.6362        0.0960        0.1287

SVF10     0.29427      -0.25453      -0.02776      -0.09245      -0.12670       0.10295
           0.0002        0.0012        0.7275        0.2450        0.1104        0.1952

SVF11     0.05344      -0.09090      -0.07448       0.10479      -0.23386      -0.08486
           0.5021        0.2530        0.3493        0.1872        0.0029        0.2860

SVF17     0.06006      -0.05495      -0.01946      -0.04787      -0.09309      -0.07349
           0.4506        0.4901        0.8071        0.5478        0.2417        0.3557
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SWPT	-0.08766 0.2703	0.11697 0.1408	0.08306 0.2964	-0.00190 0.9809	0.04746 0.5512	-0.09505 0.2319
SWPE	-0.15882 0.0449	0.03657 0.6462	0.05711 0.4732	-0.03907 0.6238	-0.09600 0.2272	-0.06303 0.4284
SDET	-0.20649 0.0088	0.16165 0.0411	0.01323 0.8682	-0.05943 0.4553	-0.07199 0.3656	-0.15545 0.0497
SDEE	-0.25825 0.0010	0.26602 0.0007	0.14137 0.0746	0.02302 0.7726	-0.05802 0.4661	-0.04664 0.5581
SWBT	-0.00676 0.9324	0.03353 0.6738	0.00016 0.9984	-0.04944 0.5347	0.07887 0.3215	-0.14685 0.0639
SWBE	0.11448 0.1494	0.04064 0.6099	-0.10889 0.1705	-0.03859 0.6280	-0.00376 0.9624	0.16265 0.0399
SSIQ1	-0.34575 <.0001	0.16681 0.0350	0.10010 0.2079	-0.01123 0.8879	-0.03634 0.6483	0.03370 0.6722
SSIQ2	0.21552 0.0062	-0.14707 0.0635	-0.06039 0.4481	-0.01613 0.8396	-0.03527 0.6579	0.05583 0.4832
SSIQ3	0.29880 0.0001	-0.07777 0.3283	0.10130 0.2024	0.01333 0.8671	0.06041 0.4479	0.02701 0.7345
SSIQ4	0.31086 <.0001	-0.14413 0.0690	0.02252 0.7775	0.07144 0.3693	0.03725 0.6400	-0.15728 0.0470
SSIQ5	0.40384 <.0001	-0.13576 0.0869	0.02225 0.7800	-0.07133 0.3700	-0.05423 0.4958	-0.03663 0.6457
SSIQ6	0.34307 <.0001	-0.12675 0.1102	-0.13939 0.0788	-0.02712 0.7336	-0.10255 0.1969	-0.00881 0.9120
SSIQ7	0.25989 0.0009	-0.16160 0.0412	0.02281 0.7746	0.04387 0.5817	-0.01794 0.8218	-0.02375 0.7656
SSIQ8	1.00000	-0.16026 0.0429	-0.01066 0.8935	0.01769 0.8243	-0.00076 0.9924	-0.12588 0.1127
SCS1	-0.16026 0.0429	1.00000	0.05115 0.5206	0.11940 0.1326	-0.01372 0.8633	0.04563 0.5667
SCS2	-0.01066 0.8935	0.05115 0.5206	1.00000	-0.01867 0.8147	0.14863 0.0607	-0.00797 0.9204
SCS3	0.01769 0.8243	0.11940 0.1326	-0.01867 0.8147	1.00000	0.05488 0.4906	0.03740 0.6387
SCS4	-0.00076 0.9924	-0.01372 0.8633	0.14863 0.0607	0.05488 0.4906	1.00000	0.06873 0.3878
SCS5	-0.12588 0.1127	0.04563 0.5667	-0.00797 0.9204	0.03740 0.6387	0.06873 0.3878	1.00000

Vita

Aaron Bangor

Aaron Bangor was born in August of 1973 in Maryland, the second of twins, to James and Donna Bangor. He attended public schools near Damascus, MD, until he was graduated salutatorian of his high school class in June of 1992.

In the Fall of 1992 Aaron enrolled at Virginia Tech and pursued studies in the field of Industrial and Systems Engineering and Economics, receiving a Bachelor’s of Science and Bachelor of Arts, respectively, in May of 1996. During this time, Aaron joined Alpha Pi Mu (the industrial engineering honor society) in December of 1993 and became an undergraduate research assistant in May of 1995 in the Displays and Controls Laboratory. In the spring of 1996 Aaron had a paper from an economics history course published as a “model research paper” in an English workbook.

Aaron continued at Virginia Tech in the Fall of 1996 in pursuit of a Master’s of Science degree, specializing in Human Factors, in the Industrial and Systems Engineering Department, where he continued as a graduate research assistant in the DCL. In 1997 he became a Student Affiliate member of the Human Factors and Ergonomics Society. Aaron finished his M.S. degree in the summer of 1998, completing his thesis research titled: “Improving Accessibility to CRT Displays: Readability for the Visually Impaired.”

In the fall of 1998 Aaron continued at Virginia Tech, deciding to complete his human factors engineering education in Blacksburg by pursuing a Doctor of Philosophy degree. During this time he attended the HFES conferences in Chicago (1998) and Houston (1999). At the Houston conference Aaron presented a paper based on his thesis research. In the spring of 2000 Aaron earned his Associate Human Factors Professional designation. As he finished his degree work in the Fall of 2000, he moved to Austin, TX to join SBC Technology Resources, Inc. in their Human Factors Engineering group.