Improving Access to Computer Displays: Readability for Visually Impaired Users

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(ABSTRACT)

In the field of human factors engineering the issue of how to present electronic text to people has been studied intensely for over 35 years. However, one major consideration that has largely been overlooked in these studies is how visual impairments affect reading of computer text. Specifically, the issue of how text can be modified to improve readability of CRTs for individuals with low vision. A 2x5x2x3 (visual capability, font size, polarity, and contrast) mixed-factor, repeated-measures experimental design was used to determine if changes in font size, contrast polarity, and/or contrast can improve reading speeds and reduce error rate for people with low vision.

The results of this experiment show that alterations in text can be made that do not affect unimpaired vision readers while dramatically improving the reading capabilities of the impaired vision population. For character size, 12 and 14 point font sizes were found to be too small for the visually impaired population examined. In general, 18 and 30 point font sizes were equal to each other and to the 24 point font size, but for some interactions these two were found to produce longer response times and higher error rates. Thus, a 24 point font size is recommended.

Unlike previous research with visually impaired participants, this experiment found that negative (white-on-black) polarity worsened reading performance. It is thought that this discrepancy is a result of polarity's interaction with small font sizes. For this reason, it is recommended that for font sizes of 18 points and below, positive polarity should be used. For 24 and 30 point sizes either polarity is satisfactory, though previous research (Legge, Pelli, Rubin, and Schleske,

1

1985b; NRC, 1995; Rubin and Legge, 1989) suggests negative polarity might be better for some visually impaired readers..

Contrasts of 3:1, 7:1, and 18:1 were used in this experiment and had no significant effect for either vision group. However, contrast did significantly interact with both font size and polarity. For font sizes of 18 points or below, it is recommended that contrasts of 18:1 be used for either polarity, but this is very important if negative polarity is used.

The above recommendations are based on a small group of impaired vision readers. Visual impairments vary widely and the sample used in this experiment represented only a portion of them, with respect to both cause and severity. Wherever possible, computer text should be tailored to the unique needs of its users.

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Dr. Patrick Koelling is one of the most personable professors I have ever met. Always willing to take the extra time needed to teach; by the myriad conversations I have had with him, he realizes that education is not just the facts and methods taught in the classroom, but that education is a process of molding an educated person – not a developing walking, talking book.

While these have been two outstanding teachers in my career at Virginia Tech, the two most outstanding teachers I have ever had are my parents. Perhaps their training as teachers made them excellent parents; perhaps it was because of their own experiences; perhaps it was luck. Regardless of the reason, the outcome can not be quarreled with – I am where I am today because of who they have made me and the unwavering support and love they have provided me. Although they appear to be disparate individually, they are the finest parental team a person could hope for.

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It’s no *Naval War of 1812*, but hopefully it has been done just as well.

1

TABLE OF CONTENTS

1

LIST OF TABLES

1

LIST OF FIGURES

1

1.0 INTRODUCTION

Because of the ever increasing power of microcomputers, people now use them for a variety of work and personal uses. People use computers to write documents, maintain databases, manage finances, draw diagrams and graphics, make presentations, compile mailing lists, search computer databases, write programs, and use the Internet (Lazzaro, 1993). In 1990, there were as many as 40 million VDTs in the United States (Konz, 1995) and this number has increased rapidly ever since.

There are an estimated 3.7 million people in the United States who are visually disabled; that is, who have corrected visual acuity no better than 20/70 in the better eye or who have a maximum visual field of no more than 30 degrees (NRC, 1995). About 200,000 of these people are blind (have no useful pattern vision) and 3.5 million have low vision. The leading causes of low vision are diseases that are common in old age: age-related maculopathy, cataract, glaucoma, diabetic retinopathy, and optic nerve atrophy (NRC, 1995). An additional nine million Americans live with other, milder forms of visual impairment that interfere with daily living tasks, especially in adverse lighting conditions. McNulty and Suvino (1993) report that there are approximately 14 million Americans whose vision disallows independent access to regular print. The National Research Council (1995) also reports that for the age group of 20 to 44 years old, there are almost 400,000 persons with low vision and another 29,000 who are totally blind. Lastly, because the majority of visually impaired people are elderly, the number of Americans with low vision is growing as the Baby Boom generation reaches retirement age and as Americans' lifespan increases (Legge, Pelli, Rubin, and Schleske, 1985b).

The salient problem this study addressed is the inability of visually impaired individuals to interact with computer terminals they come into contact during their everyday lives. Terminals these people use frequently can be altered to the specific needs and preferences of these disabled individuals. However, there are many computers today that are used publicly which can not be adjusted to the user's capabilities. The following is an excerpt from the *Americans with Disabilities Act* (ADA):

> *Section 30.303 Auxiliary aids and services.*
> *Section 30.303 of the final rule requires a public accommodation to take such steps as may be necessary to ensure that no individual with a disability is excluded, denied services, segregated or otherwise treated differently than other individuals because of the absence of auxiliary aids and services, unless the public accommodation can demonstrate that taking such steps would fundamentally alter the nature of the goods, services, facilities, advantages, or accommodations being offered or would result in an undue burden. This requirement is based on section 302(b)(2)(A)(iii) of the ADA.*

Thus, federal law mandates that steps shall be taken to make accommodations for public accessibility by the visually impaired. This statutory requirement needs to be met for legal reasons. It is this problem of auxiliary aid accommodations for the visually disabled that this study has attempted to partially remedy.

The objective of this thesis research was to define the problems that people with visual impairments experience with *cathode ray tube* (CRT) computer displays. To begin this thesis, the issues related to the readability of "soft copy" text have been investigated for computer users with normal, unimpaired vision and then this investigation was extended to display characteristics that may help and hinder the visually impaired when reading CRT screens. Once these issues have been defined, the work has attempted to uncover some of the display characteristics that could be adjusted to equate the readability between the unimpaired and impaired computer users.

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2.0 BACKGROUND

Before the details of the thesis research are discussed, a brief background of visual impairment, what the term "readability" implies, and CRT display characteristics that affect readability for people with unimpaired and impaired vision will be presented.

2.1 Visual Impairment

People with low vision may have any one of a number of problems with their vision, from poor acuity (blurred or fogged vision) to loss of all central vision (only see with edges of their eyes) to tunnel vision (like looking through a tube or soda straw) to loss of vision in different parts of their visual field, as well as other problems (glare, night blindness, etc.) (Vanderheiden 1994). For purposes of measuring reading performance, Legge et al. (1985b) found that most visual impairments fall into two categories: intact central fields vs. central fields loss and cloudy vs. clear ocular media. These categorizations accounted for 64% of the variance in peak reading rates for impaired vision observers (Legge et al., 1985b).

There are many terms to define the cause and severity of vision loss a person has. However, most of these are objective, quantitative measures and only give partial insight into what the actual visual capability of the person is. Terms such as "low vision," "visually impaired," "legally blind," "print impaired," or "blind," all have definitive meanings, most of which have general acceptance in the United States. However, for the purposes of this study, these terms are used interchangeably since most of these categories were represented by the participants in this study. Persons with significant vision loss of any type are referred to as having "impaired vision" in this study; persons with normal eyesight have been classified as having "unimpaired vision.” These terms were chosen

1

since the major criterion for this study is to differentiate the needs of people who can access visual display terminal (VDT) workstations without functional limitations from those whose vision loss limits their ability to use these computers. Since people with low vision (best correctable visual acuity of 20/70 to 20/200) or those who are legally blind (best correctable visual acuity of 20/200 or worse) all may be unable to access VDT workstations. For this study, any term reflecting some degree of vision loss will be treated as a person who can use CRT displays *if and only if* special display parameters are changed to allow them to read the text comfortably or at all.

2.2 Known Readability Characteristics for Readers with Unimpaired Vision

The human visual system's ability to read is integral to many of life's major activities. Reading has been studied for quite some time and several characteristics have been found to enhance or degrade it (Legge, Pelli, Rubin, and Schleske, 1985a). With the advent of computer displays, some of these presentation characteristics have the same effect whether presented in hard copy (on paper) or soft copy (on the computer screen). However, there are many new variables particular to CRT displays that affect readability in addition to these traditional characteristics.

Readability is the ability to recognize the form of a word or group of words for contextual purposes (ANSI/HFS, 1988). It is defined as the 75% correct identification level (i.e., three out of four chance level) of target words in the Tinker Reading Passages test.

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2.2.1 Text Size

The size of a character can be specified in two different ways. First, is to define it by point size. In traditional printing, one point is equal to 1/72 of an inch. Thus, 12 point font is a character which measures 1/6 of an inch in height. For computer displays, however, this definition is somewhat altered. A point on a VDT generally is equal to one pixel, thus the addressibility (the distance between each pixel) and the resolution (the size of each pixel) will determine how large the letter is. Thus, most standards for visual displays use minutes of visual arc to define character size. This has the added bonus of being an independent measure with respect to viewing distance.

Gould and Grischkowsky (1984) found a 20 to 30 percent slower proofreading speed for a VDT over hard copy, though Dillon (1994) cites studies that have achieved near equal speed between the two media. This reduction appears to be mostly related to image quality due to low screen resolution (Jorna, 1989). Font sizes of 10 to 12 minutes of arc are the minimum that should be used for legibility (ANSI/HFS, 1988; Shurtleff, 1980), but most international ergonomic standards stipulate anywhere from 16 to 22 minutes of arc as the minimum character size for good readability (Smith, 1996). According to the ANSI/HFS-100 (1988) standard, font size is required to be a minimum of 16 minutes of arc and a maximum of 24 minutes of arc with a preferred range of 20 to 22 minutes of arc. For maximum reading rate, Legge et al. (1985a) found that a font size of at least 0.3 degrees (18 minutes) was necessary (below which a fairly rapid drop-off in reading rate was noticed); this reading rate held fairly constant up until 2.0 degrees of visual arc where it began to drop off slowly.

2.2.2 Contrast Polarity

Contrast polarity specifies whether the letters are light and the background dark, or vice versa. Positive polarity is the traditional hard copy presentation of dark characters on a light background, whereas negative polarity is the opposite, with light characters on a dark background. (Confusion on this topic is common; “negative contrast” is often used in place of positive polarity and “positive contrast” is often used in the place of negative polarity.) The contrast polarity of alphanumeric symbols usually has little effect on recognition for people with normal vision (NRC, 1995). The ANSI/HFS-100 (1988) standard specifies that either is acceptable for VDT users with normal vision. Legge et al. (1985a) also reports that there is no systematic difference between contrast polarity for persons with unimpaired vision. Sanders and McCormick (1993) report that the research is mixed on the topic, some research showing that there is no significant difference and other research pointing to a preference for positive polarity displays. Dillon (1994) also reports that there may be some degree of increased reading speed attributable to positive polarity displays.

There are benefits and drawbacks to both polarities that have been identified for people with unimpaired vision. Positive polarity displays can reduce the effects of reflected glare, but may be more prone to display flicker (ANSI/HFS, 1988). However, it has also been theorized that positive polarity displays with greater amount of light emission, force the pupil to constrict more and that this better focuses the image on the retina, increasing readability (NRC, 1983). Conversely, this increased constriction causes greater eye fatigue (Dillon, 1994) and visual discomfort. However, in a study of pupil accommodation with both positive and negative polarity displays, no significant different was found for short durations (less than one minute) (Collins, Davis, and Goode, 1994). With the greater space-averaged display luminance of positive polarity displays, this would seem to indicate that the white background with black text would be the preferred alternative. Additionally, positive polarity displays seem to have greater

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subjective preference (NRC, 1983), perhaps due to their likeness to traditional paper text. Finally, Snyder, Decker, Lloyd, and Dye (1990) found that positive polarity yielded a 4% greater reading speed when compared with negative polarity.

2.2.3 Contrast

Generally, increases in display luminance will lead to greater visual performance (Legge et al., 1985a; NRC, 1983). For standard visual tasks, as the contrast between a visual target and its background decreases, its size must increase to make it equally discriminable (Sanders and McCormick, 1993). ISO 9241 specifies that a minimum luminance modulation ($M = [(L_{max} - L_{min})/(L_{max} + L_{min})]$) of M = 0.40 be used for monochrome displays and that a minimum value of 0.70 is required for color displays (Smith, 1996). ANSI/HFS-100 (1988) recommends that at a minimum, a luminance modulation of M = 0.50 be used, but that a value of M = 0.75 is recommended. Shurtleff (1980) recommends that at least a contrast ratio of 18:1 (M = 0.89) should be used for general display conditions. Legge, Rubin, and Luebker (1987) found that reading rates for people with normal vision are largely unaffected by luminance modulations above M = 0.10. However, Wells (1994) determined that a contrast ratio of 7:1 (M = 0.75) was preferred to minimize error rates for the Tinker Reading Test and to achieve high subjective image quality ratings.

2.2.4 Other Characteristics

Within-line spacing seems to be another characteristic that affects readability. Single spacing increased the number of eye fixations and decreased the reading speed in one study almost 11% when compared to double-spaced text (Dillon,

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1994). Sanders and McCormick (1993) also suggest that increasing between-line spacing may increase the clarity of text.

Dillon (1994) reports that proportional width fonts seem to have a slight beneficial effect on reading speed over fixed-width fonts, though this conclusion is not universal in the literature. ANSI/HFS (1988) and Arditi, Knoblauch, and Grunwald (1990) also report this finding, suggesting that the proportional width fonts allow more letters in foveal vision and this allows faster reading speeds. Finally, Legge and Rubin (1986) report that there are no reading differences due to the color of the text.

2.3 Possible Readability Gaps for the Visually Impaired

Because many people with visual impairments still have some visual capability, many can read with the assistance of magnifiers, bright lighting, and glare reducers. Many people with low vision are helped immensely by use of larger lettering, sans-serif typefaces, and high contrast coloring (Vanderheiden, 1994). Studies conducted by Lin and Williges (1995) and Lampert and Lapolice (1995) deem magnification and contrast to be two major functional considerations for the visually impaired. However, while modifications such as large type, Braille, and synthesized speech have been used to help the visually impaired bridge the readability gap, such drawbacks as limited perceptibility and increased memory load have arisen as new human factors problems for VDT workstations (Griffith, 1990). Thus, most factors might initially help low vision computer users, but then eventually hurt their performance. Some of the following text traits and presentation formats have been identified as capable of helping the low vision population.

2.3.1 Text Size

Perhaps the most essential trait of text and its suitability for people with low vision is the size of the characters (Legge et al., 1985b; McNulty and Suvino, 1993). In fact, text enlargement is one of the most widespread technologies to help the visually impaired read computer screens (Lazzaro, 1993). Although many users employ screen magnification hardware or software to enlarge their view, performance and image quality are improved if larger font sizes are available prior to magnification (Bergman and Johnson, 1995). Many users with low vision can use an application without a screen enlargement program, provided the application allows users to adjust the font size (Vanderheiden, 1994). In fact, it is recommended that a large size default font be provided to the disabled user to achieve compliance with Section 508 of the 1973 Rehabilitation Act (Smith, 1996).

Although the degree of magnification that a visually impaired person needs is quite specific to the individual's visual impairment, a font size of six degrees of visual arc was found to be highly correlated with peak reading rates (Legge et al., 1985b). However, in Legge et al.'s (1985b) study, text was scrolled horizontally across a monitor – most of the time only 10 characters appearing in a 7 cm high, 25 cm wide window. While this peak reading value is an important piece of psychophysical information, it does not deal directly with the trade-off between character size and the amount of text that can be presented on the screen at one time nor does it include the additional time required due to line breaks.

2.3.2 Contrast Polarity

For some people with low vision (especially those with ocular light scatter due to cataracts) acuity and reading performance is better for the light-on-dark, negative polarity condition (NRC, 1995). This finding is likely due to the abnormal light

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scatter in eyes with cloudy ocular media that results in a veiling luminance and consequently reduced retinal-image contrast (Rubin and Legge, 1989). Legge et al. (1985b) found that negative polarity increased peak reading rates 10-50% when compared to positive polarity presentations. However, this finding was exclusively for those visually impaired participants who had cloudy ocular media; those with clear ocular media demonstrated no significant difference due to contrast polarity (Legge et al., 1985b). This has also been noted with the use of closed-circuit television systems and microforms where many users have found negative polarity to be beneficial (McNulty and Suvino, 1993). Smith (1996) also stipulates that compliance with Section 508 requires the display offer a negative polarity option for the visually impaired user.

2.3.3 Contrast

Most people with low vision have reduced contrast sensitivity (Rubin and Legge, 1989). McNulty and Suvino (1993) report that to aid in the readability of hard copy materials by the visually impaired, ensuring strong contrast between the ink and the (nonglare) paper is an effective treatment. It also has been reported that people with poorer eyesight benefit more from increased retinal illumination than people with normal sight (NRC, 1983). Vanderheiden (1994) suggests that computer users with low vision can benefit by the display using a high contrast between text and background. In fact, using highly saturated and high contrast colored lights for displays is a good design guideline to follow to aid the disabled in accessing the screen (Smith, 1996). Rubin and Legge (1989) found that most subjects with low vision had higher critical contrasts (the luminance modulation that produces half the maximum reading rate) than those with normal vision, indicating a lower tolerance for contrast reduction. It was also discovered that critical contrast values were linked closely to contrast sensitivity for letters, but did not vary systemically with type of vision loss (Rubin and Legge, 1989).

2.3.4 Other Possible Gaps

For people with low vision, Vanderheiden (1994) has identified other readability characteristics that should be addressed in display design. He recommends several other modifications to aid the visually impaired:

- enlarging or otherwise enhancing the current area of focus
- allowing the user to adjust the fonts, colors and cursors used in the software to make them more visible
- eliminating patterned backgrounds where they might interfere with text

These suggestions can be used for generic display design involving text that people with visual impairment may reasonably be expected to read.

It also is known that people with visual impairments have more difficulty with display clutter (Lampert and Lapolice, 1995). Increasing the number of irrelevant objects on the display has more of an adverse effect for people with low vision than those with unimpaired vision. Additionally, Lampert and Lapolice (1995) mention time considerations as a factor in a visually impaired person's reading performance. Not only is it common for the visually impaired person to take longer for the task, but they also may experience a fading effect or "wash out" after sustained close work.

Legge and Rubin (1986) found that there were little to no wavelength effects for people with impaired vision due to cloudy ocular media and/or central field loss. Only subjects with degenerative diseases of the photoreceptors showed any sensitivity to wavelength, tending to read better in the blue than in the red (Legge and Rubin, 1986). Legge et al. (1990) found that low vision subjects read text faster with luminance contrast than color contrast. Consequently, relative to normal vision, low vision reading is hampered, not enhanced by color contrast.

Finally, Mansfield, Legge, and Bane (1996) found that different fonts can affect reading rates for the visually impaired. They found as much as a 10% performance improvement for Times Roman (proportional width font) over Courier (fixed width font). These readability differences were stronger near the acuity limit (Arditi et al., 1990; Mansfield et al, 1996).

These display characteristics have been identified by previous research and shown to affect reading performance for electronic text. This review of the literature has endeavored to take these known parameters and determine a suitable range for each that might cause a range of performance for both persons with unimpaired and impaired vision. The objective of this thesis is to take the data gathered from the experiment and develop display guidelines that will equate readability between the two vision groups.

3.0 METHODS

The following describes the participants for this study, the equipment used to carry out the experiment, and the procedures that were followed during the data collection phase of this experiment.

3.1 Participants

Participants with unimpaired and impaired vision were used to conduct this study. There were an equal number of females and males in the unimpaired vision group, an unequal number in the impaired vision group (see Section 3.1.2 for why an unequal number was used). They were drawn from the population of Southwest Virginia, between the ages of 18 and 45, skilled in using a computer, had English as their native language, and had at least a high school education.

3.1.1 Unimpaired Vision Group

Eight participants were sought (four female and four male) from the population of Southwest Virginia to participate in this study as the unimpaired vision group. Each of the participants met the following criteria:

- participants did not have ocular disease;
- participants had at least 20/30 corrected or uncorrected vision in both eyes.
- participants had to pass all administered vision tests before the experiment began

All had visual acuity of greater than 20/30 for near, binocular vision and all passed the contrast sensitivity test. The specific vision tests can be found in section 3.3.2

For the purposes of data analysis, two of these data sets were dropped to more easily analyze the data in conjunction with those from the impaired vision participants. The data from participant #2 (female) was dropped because she was the only unimpaired vision participant who did not measure at least 20/20 for the visual acuity exam, measuring 20/22. Participant #5 (male) was dropped since his data set had one missing value.

3.1.2 Impaired Vision Group

Although it had been intended to collect data from eight impaired vision participants with an equal number of females and males, data collection was terminated after obtaining data from only six participants -- four male and two female. Collection of data began on March 13, 1998 and was stopped on May 15, 1998; it was closed lacking data from two female impaired vision participants because there was little expectation of finding additional participants in a timely manner.

All of the participants were in fact legally blind (see Section 2.1 for definition), with corrected or uncorrected vision or had some other form of visual disability that requires special accommodations be made to the display to allow them to read it. The vision tests were administered to this vision group for evaluation purposes only.

The following is a table listing the visual capabilities of the six impaired vision participants in this study as evaluated by the Ortho-Rater near, binocular visual acuity test and the Vistech contrast sensitivity test. The actual contrast sensitivity curves can be found in Appendix E.

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TABLE 3.1 -- Results of Vision Exams for Impaired Vision Participants

		Contrast Sensitivity	
Part. #	Acuity[1]	Normal Range[2]	Seen[3]
9	20/400	0	0
10	20/200	0	2
13	20/400	0	2
14	20/50	2	4
15	20/100	0	2
16	20/100	2	5

[1] The Ortho-Rater exam only measured 20/200 vision and better; any values above 20/200 are those reported by the participant if the Ortho-Rater could not give a value.

[2] The value reported in the "Normal Range" field is the number of spatial frequencies (out of a total of 5) the participant did not achieve a normal score.

[3] The value reported in the "Seen" Field is the number of spatial frequencies that were visible to the participant.

Additionally, the age restriction was lifted for the second female impaired vision participant (Participant #10; 49 years 10 months) because of the difficulty in obtaining female impaired vision participants. The age restriction was intended principally for the unimpaired vision group to eliminate any age-related vision degradation. Since any age-related vision degradation would be superseded by preexisting visual impairment for the impaired vision group, the age restriction for this vision group was imposed to eliminate possible confounding effects for any between-subject comparisons. Dr. Robert Beaton, Committee Chair gave permission for the lifting of the age restriction for Participant #10, agreeing with the experimenter that the data which could be obtained was far more valuable than any confounding effects that might arise.

For Participant #15 trial #94 was missed by the participant. This was for 30 point font size, positive polarity, and 7:1 (M = 0.75) contrast. For purposes of data analysis, the other 47 values from the Time and Word Error cells were averaged and entered into the missing fields. This method was chosen so as not to bias

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any statistical tests and to allow the use of a balanced Analysis of Variance to analyze the data set.

3.2 Equipment

Room 530B of Whittemore Hall in the Displays and Controls Laboratory was used to setup and conduct this experiment. This room was chosen because of its adjustable lighting (only fluorescent lighting was used), its size, and its restricted access. It also has 18% grey walls that minimized reflected glare. An Apple Color Plus 14” monitor with an addressibility of 640 x 480 pixels, a 0.28 mm resolution, 11.9” viewable area, and refreshed at a rate of 67 Hz was used to present the Tinker passages to the participant during the experiment. No anti-reflectance coating was present on the display screen.

The participants used only a standard Macintosh one-button mouse to control the experimental program. The program was run on an Apple Power Macintosh 8500 personal computer, running MacOS 8.0 at 120 MHz with 32 MB of RAM.

The software used to administer the Tinker Reading Passages Test was developed with SuperCard 3.0 for Macintosh. The program was an original design and developed solely by the experimenter. The program administered the 18 practice passages and a different set of Tinker passages for each of the 14 participants used in this study. Finally, the program outputted to a text file the times for each trial.

A 29 inch tall desk was used for the participants. The monitor rested an additional 10 inches above the desk, sitting on a monitor stand that allowed the monitor to be swiveled and tilted to each participants liking. An armed, swivel chair with height adjustment was provided to the participants.

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3.3 Procedures

The following are the procedures that the experimenter followed to carry out the study. It details how the experimenter recruited the participants, how the participants were screened for the study, and what these participants were asked to perform to complete the study.

3.3.1 Demographic Data

After each participant signed the informed consent form, they were given a short survey to complete. The age, gender, computer experience, and education level of each participant was gathered. A copy of this survey can be found in Appendix B.

The participants in this study ranged in age from 19 years 2 months to 49 years and 10 months. The average age was 28 years 1 month with a standard deviation of 9.73 years. For the unimpaired vision group, average age was 25 years 4 months with a standard deviation of 3.17 years. For the impaired vision group, average age was 30 years 10 months with a standard deviation of 13.43 years. All participants reported using a computer at least one hour a day. Each participant had at least a high school education and those that did not have a college degree were currently enrolled in college.

3.3.2 Vision Tests

Participants were required to perform two vision tests. Near, binocular visual acuity was assessed using an Ortho-Rater device. Contrast sensitivity was measured using the Vistech Contrast Sensitivity Test. For the unimpaired vision group, both tests needed to be passed. Passing for the unimpaired vision group was determined to be 20/30 for near visual acuity and at least 20/30 equivalent visual acuity for the Vistech test. For the impaired vision group, visual acuity and contrast sensitivity tests were used to make sure that the impaired vision participants had sufficient vision loss. The results of these tests were recorded for later analysis. Once these tests were completed, the primary portion of the experiment was begun.

3.3.3 The Tinker Reading Test

The participants in the Tinker Reading Test were seated in the testing room lit at approximately 300 lux (+/- 2% error); this value was chosen because it falls approximately in the middle of recommended ambient illumination ranges (ANSI/HFS-100, 1988; Konz, 1995). Participants sat at an office desk that supported the monitor and the keyboard, which was located directly in front of them. The participants were encouraged to view the display screen from their preferred viewing distance, height, and angle.

Before beginning the test, the participant listened to a set of instructions read to them by the experimenter to familiarize them with the testing procedures. A copy of these instructions can be found in Appendix C.

The experimental procedure required the participant to read a two to four sentence paragraph presented on the screen and then to make a verbal report identifying the target word. The target word for the Tinker Test is a word that appears out of context in the sentence and/or paragraph. On each trial in the readability test, a randomly selected passage from the modified Tinker Reading Test was displayed on the screen.

The passages were not presented directly in the center of the screen. Each passage was presented toward the upper left-hand corner of the screen. The first letter began at the 72x72 pixel position. (This position was chosen to approximate a one inch top and left margin.) This specific position was chosen because of the commonality of using one inch margins for documents. The reason that centering was not used was because this would cause the passages to begin at differing locations on the screen. To minimize search times for the beginning of each paragraph and, consequently, possible bias against the impaired vision group, a uniform position was decided upon.

When the Start button was initially pressed and then released, the computer displayed the paragraph and began a timer. This timer measured the length of time between when the paragraph was first displayed and when the mouse button was depressed. This gauged the reaction time (RT) for each readability test trial.

The participant initiated the presentation of each passage by depressing and releasing a "Start" button (the mouse button for this experiment). When the participant identified the word that was out of context, he was instructed to press the Start button again and verbally report the word he believed to be out of context. The investigator then recorded the verbal response as "correct" or "incorrect." If the participant was unable to read the passage, a response of "incorrect" was recorded. If the participant accidentally pressed the Start button before being able to identify the target word, that trial was deemed to have missing data and the participant was instructed to begin the next trial at his discretion.

To prevent a "double hit" of the Start button (pressing the Start button twice in quick succession) which would accidentally begin the next trial, a delay of three seconds was programmed into the software between the completion of one trial and the earliest possible beginning of the next trial. This delay also was included to ensure any short term visual store was expunged (Wickens, 1992).

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Upon button release -- whether intentional or by accident -- the display screen was blanked of all letters and replaced with a pattern of vertical black lines on a light grey background (Hunter, 1988). This pattern was set to the average luminance of the positive and negative polarity backgrounds. This was used to ensure that the passage was not readable either due to phosphor persistence or retinal afterimage (Hunter, 1988).

After viewing the inter-trial screen for at least three seconds, the participant used the Start button to begin the next passage. This procedure was used for the 18 practice trials and continued through all 120 trials used in data collection.

3.3.4 Experimental Design

The following are the three factors and their corresponding levels that were used in the experiment to determine possible readability differences between the unimpaired and impaired vision groups.

Font Size. An equal number of five different font sizes was presented to the participants. These sizes were 12, 14, 18, 24, and 30 point font, in the proportional width, sans-serif font of Helvetica. These sizes are equivalent to 0.1667, 0.1944, 0.2500, 0.3333, and 0.4167 inches respectively.

It should be noted here that in SuperCard a font size of 36 point was specified. However, in the Adobe Type Manager “Preserve Line Spacing” was set. Since 36 point font is not predefined for Helvetica (all four other font sizes are), the intended font size was different from what was actually displayed on the screen. The actual font size was measured as 30 point font by a two-dimensional CCD microphotometer (Photometrics, Model: AF 200; Questar Lens) and this value is used in the rest of this report.

1

Contrast Polarity. Two contrast polarities were presented to the participants during the experimental session. The first is termed "positive polarity" and had a white background with black text. The other is termed "negative polarity" and had a black background with white text. An equal number of each of these polarities were presented to the participants.

Luminance Modulation. Luminance modulation, defined by the ANSI/HFS-100 (1988) standard is equal to:

$$M = \frac{(L_{max} - L_{min})}{(L_{max} + L_{min})} \qquad \text{(Eq. 3.1)}$$

This measure of contrast was used as the third factor in this study and contained three levels. This factor was used in place of strict screen luminance since only black on white and white on black color schemes were used for this study and thus came closest to approximating screen luminance effects on readability. However, the luminance modulation data were thought to be more generalizable.

The study used three luminance modulation values. These were M = 0.50 which is defined as the minimum value that displays at VDT workstations are required to have (ANSI/HFS, 1988); a value of M = 0.75 which is the preferred luminance modulation for VDT workstations (ANSI/HFS, 1988); and a third value of M = 0.89 (contrast of 18:1) which Shurtleff (1980) believes to be an optimum value. Table 3.1 lists the luminance values that produced these three luminance modulation values for each polarity.

TABLE 3.2 -- Screen Luminance of Foreground and Background Used for Determination of Luminance Modulation Values (cd/m^2)

	Polarity			
	Positive		Negative	
Luminance Modulation	Foreground	Background	Foreground	Background
M = 0.50	32.7	96.6	16.0	5.13
M = 0.75	13.9	96.6	30.1	5.13
M = 0.89	5.13	96.6	96.6	5.13

These values were collected using a Minolta CS-100 luminance meter, a 0 degree angle of declination, at a distance of 16 inches, in the same lighting conditions that the experiment took place (300 lux ambient luminance). An equal number of trials at each luminance modulation value was presented to the participants.

Presentation Order. Before the presentation of trials used for data collection, participants were exposed to 18 practice passages. The 18 practice passages were derived from the use of three font sizes (12, 18, and 30), two contrast polarities, and three luminance modulation values; the presentation of these passages was randomized. The 14 and 24 point font sizes were not used during the practice session because they were deemed to be insignificant for practice purposes.

For the data collection trials, a total of 30 factor combinations was derived from five font sizes, two display polarities, and three luminance modulation values. The participant was presented with four trials at each factor combination for a total of 120 individual Tinker Test passages. These combinations were randomized in accordance with the psychophysical method of constant stimuli (Gescheider, 1985).

3.3.5 Data Gathered

Two response variables were collected. The first of these was Response Time. Response Time was measured as the time from the initial presentation of the Tinker passage on the screen to the depression of the mouse button. The SuperCard 3.0 software measures time to an accuracy of 1/60 (0.016667) of a second. The second response variable was the error rate for identifying the out-of-context word. If the word was identified correctly a value of “0” was recorded; if the word was identified incorrectly, a “1” was recorded.

For any trial in which the participant could not read the Tinker passage, the experimenter recorded no time value and an incorrect word error value. However, for purposes of data analysis, a value of 120 seconds was entered for all trials for which the participant could not read the passage. This was done to bias any results for which a participant could not read the passage in such a direction so as to render it an implausible solution for the experiment. The actual value of 120 was chosen because this was considerably above the highest recorded time (75.96667 seconds for Participant #13 (impaired vision)) and was a satisfactory time limit which could have been imposed for each experimental trial.

Finally, the repeated measures design collected a time and word error value for four passages for each combination of independent variables for each participant. These four times and four error values were averaged for each participant before data analysis began, reducing the data set to thirty response time and word error values for each of the twelve participants. This was done to minimize random error effects while still maintaining the integrity of the collected data.

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3.3.6 Pretesting

Two participants who did not take part in actual recorded data trials underwent the exact testing procedures that were used in the data collection trials. This pretesting was conducted to make sure that the software functioned properly, that the participants understood and carried out the instructions, and to familiarize the investigator with testing and data recording procedures.

1

4.0 RESULTS AND DISCUSSION

The following section reports the data gathered in this study, the analyses that were performed via statistical methods, and a discussion of the conclusions drawn from those analyses.

The data generated during the experimental sessions were analyzed by a series of statistical tests to determine if the variables manipulated during testing had any effect on the participants' reading ability. The principal test used was the balanced Analysis of Variance (ANOVA). For any significant factors with more than two levels, the Newman-Keuls sequential range test was used to determine if levels of the same factor were significantly different.

4.1 ANOVA for Response Time

Table 4.1 shows the ANOVA table for Response Time:

TABLE 4.1 -- ANOVA for Response Time

Source	df	SS	MS	F	p
Between-Subjects Factors					
Vision	1	29712.5	29712.5	6.59	0.028
Subject(Vision)	10	45089.3	4508.9		
Within-Subjects Factors					
Size	4	16121.3	4030.3	4.25	0.006
Vision*Size	4	15280.6	3820.2	4.03	0.008
Size*Subject(Vision)	40	37910.0	947.8		
Polarity	1	3410.7	3410.7	6.22	0.032
Vision*Polarity	1	3334.5	3334.5	6.08	0.033
Polarity*Subject(Vision)	10	5487.8	548.8		
Contrast	2	980.7	490.3	2.51	0.106
Vision*Contrast	2	987.1	493.5	2.53	0.105
Contrast*Subject(Vision)	20	3904.3	195.2		
Size*Polarity	4	3462.6	865.7	4.83	0.003
Vision*Size*Polarity	4	3290.7	822.7	4.59	0.004
Size*Polarity*Subject(Vision)	40	7174.0	179.4		
Size*Contrast	8	719.0	89.9	1.85	0.079
Vision*Size*Contrast	8	745.0	93.1	1.92	0.068
Size*Contrast*Subject(Vision)	80	3876.9	48.5		
Polarity*Contrast	2	1074.0	537.0	3.44	0.052

Vision*Polarity*Contrast	2	1152.5	576.3	3.70	0.043
Polarity*Contrast*Subject(Vision)	20	3118.9	155.9		
Size*Polarity*Contrast	8	926.9	115.9	2.41	0.022
Vision*Size*Polarity*Contrast	8	1022.0	127.7	2.66	0.012
Size*Polarity*Contrast*Subject(Vision)	80	3839.0	48.0		
Total	359	192620.3			

After examining the four main factors (vision, size, polarity, and contrast), the order in which they appear in the ANOVA table corresponds exactly with a ranking of their respective mean squares from largest to smallest. This would seem to indicate that the vision variable in this experiment had the largest influence on response time, followed by font size, polarity, and lastly by contrast. This order is how the significant results of this experiment are analyzed and discussed below.

4.1.1 Vision

Vision

Based on evaluation of the mean square, the main effect of vision had the most impact on response time and was significant (p = 0.028). As shown in Figure 4.1, the average response time for the impaired vision group was higher than that for the unimpaired vision group.

1

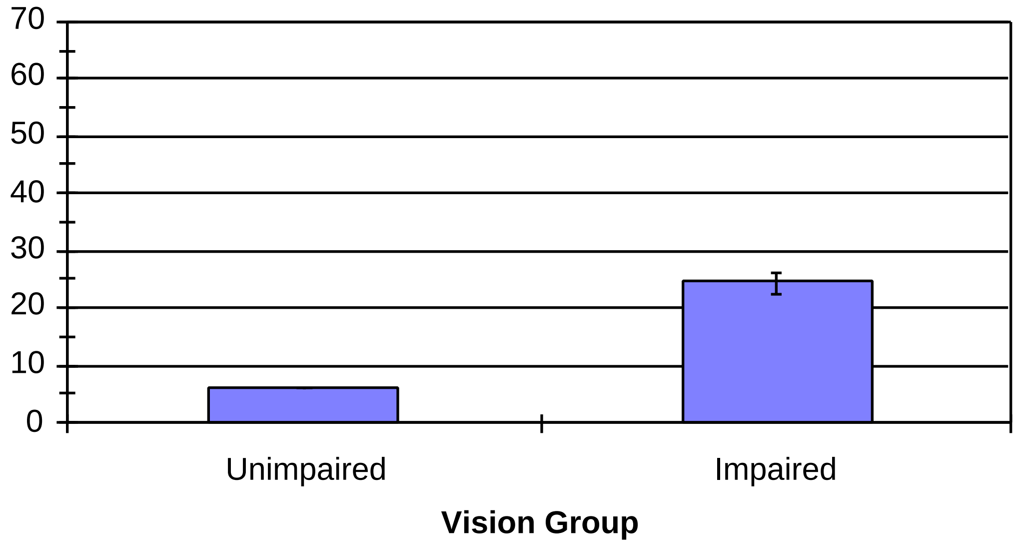

Figure 4.1. Main effect of vision group on reading time.

The mean for the unimpaired vision group at 6.155 s and for the impaired vision group it was 24.325 s -- almost a 400% increase in response time due to visual impairments was found. This one comparison illustrates the need for designing accessibility accommodations for people with low vision. What some of these accommodations might be can be discovered by showing how the two vision groups reacted to the three other main effects.

Vision x Font Size

The interaction of vision and font size was found to be significant (p = 0.008). Figure 4.2 shows how varying font size in this experiment caused response times to change for both vision groups.

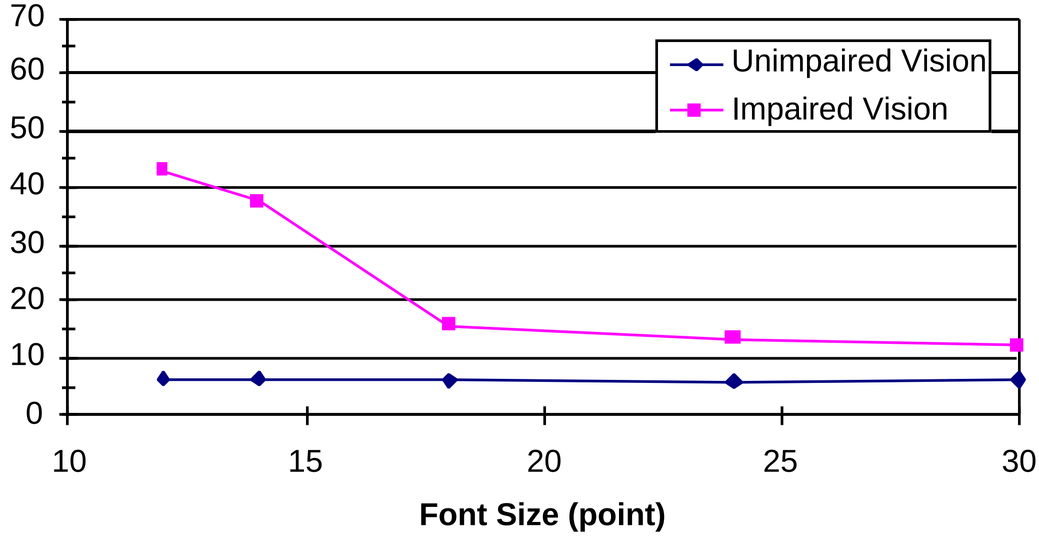

Figure 4.2. Interaction between vision and font size on response time.

This is a remarkable relationship. It is clear from a Newman-Keuls analysis that altering the font size had little to no significant effect for the unimpaired vision group ($p > 0.05$). Legge et al. (1985a) found that peak reading rates were maintained over a range of 0.3 to 2.0 degrees of visual arc. To drop below the minimum value of 0.3 degrees would have required participants to sit at least 31.8" from the screen. To rise about the 2.0 upper limit, participants would have been required to sit within 11.9" from the screen. Although exact measurements were not taken during the experiment, all unimpaired vision participants sat well within this range, thus the insensitivity to font size for the unimpaired vision group shown is expected.

This can not be said for the impaired vision group, however. The Newman-Keuls range test applied to the impaired vision data shows that there is a significant break between the means for the 12 and 14 point font levels and the means for the 18, 24, and 30 point font levels. A comparison of the means by vision group for each font level shows that only the 30 point font size can be considered as not being significantly different between the two vision groups. This seems to suggest that for all five font sizes the unimpaired observer makes no distinction based on character size, but that for those with a visual impairment, characters must be 18, 24, or 30 points in height for them to make no distinctions. This finding that a break was found between 14 and 18 point font sizes agrees with some previous engineering research. In a study of remote control design, Lin and Williges (1995) determined that a 15 point bold font was necessary for equal readability for the elderly with some degree of vision loss. Furthermore, if reading time is to be statistically equated for the two vision groups, only the 30 point font size should be used.

Vision x Polarity

Figure 4.3 shows that the interaction between vision and polarity was significant (p = 0.033).

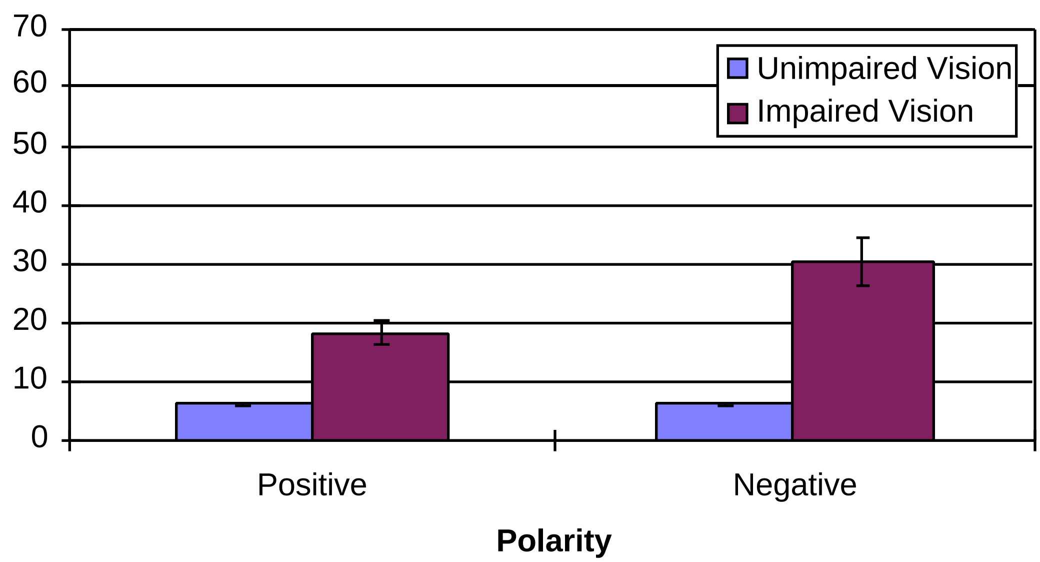

Figure 4.3. Interaction between vision and polarity on response time.

Again, we see that the impaired vision group had higher reading times when compared to the unimpaired vision group. Performing a Newman-Keuls range test showed that the unimpaired vision group is not significantly affected by polarity, but that there are significant differences between polarities for the impaired vision group and between each vision group for the same polarity.

The interesting conclusion drawn from these data, however, is that negative polarity is the *worse* condition for the impaired vision readers. Legge et al (1985b) and Rubin and Legge (1989) found that if impaired vision readers had a significant advantage by polarity it was positive polarity that caused longer reading times. This affinity was reported across the contrast ranges used in the present experiment, but used letters of six degrees of visual angle (Rubin and Legge, 1989) – far above the character sizes used in this study, being equivalent to approximately a 151 point font size from a viewing distance of 20".

One possible explanation that can be offered is that, in this experiment contrasts were altered by adjusting the foreground luminance while maintaining a constant background luminance. In Rubin and Legge (1989), they adjusted background luminance while maintaining a constant foreground luminance. It is possible that the different methodologies induce different perceived contrasts for the two polarities. It also could be that this group of six impaired vision readers happen to read better in positive polarity. Since the preference for positive polarity is contradicted by Rubin and Legge (1989), McNulty and Suvino (1993), and NRC (1995) it would stand to reason that there is an unidentified factor at work or the small impaired vision sample used was not representative of the larger impaired vision population with respect to polarity.

Vision x Contrast

The interactive effect of vision and contrast was not significant ($p = 0.105$) for this study. The contrasts of 3:1, 7:1, and 18:1 (luminance modulations of $M = 0.50$, $M = 0.75$, and $M = 0.89$, respectively) used in this study were well within the range that Legge et al. (1987) found to cause very little reading rate changes.

Additionally, these contrasts are above critical contrasts found for most impaired vision readers in Rubin and Legge (1989).

Vision x Font Size x Polarity

The three-way interaction of size, polarity, and vision group was significant at (p = 0.004). Figures 4.4a and 4.4b illustrate how size was affected by polarity first for the unimpaired vision readers and then the second graph show how they interacted for the impaired vision group.

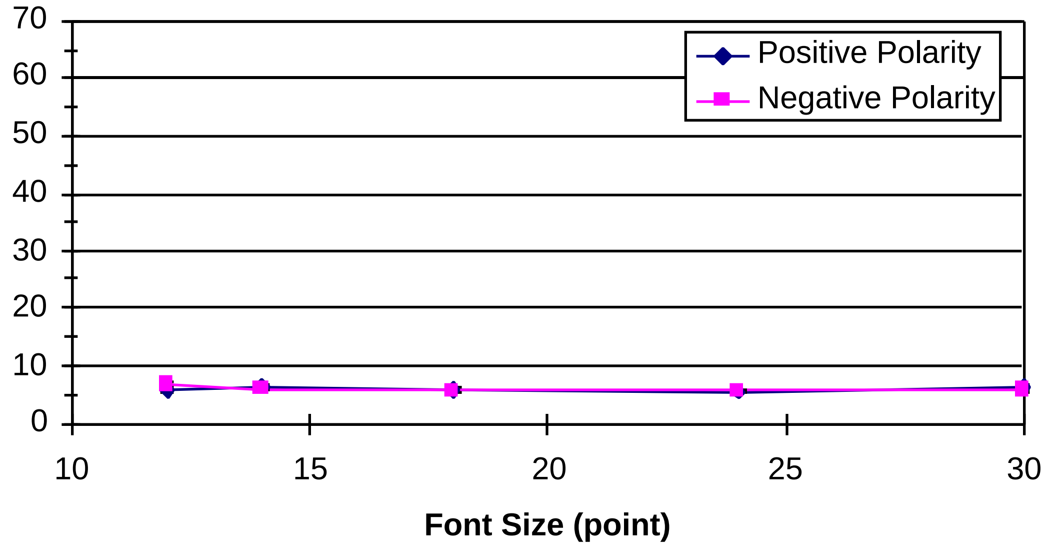

Figure 4.4a. Interaction between font size and polarity on response time for unimpaired vision.

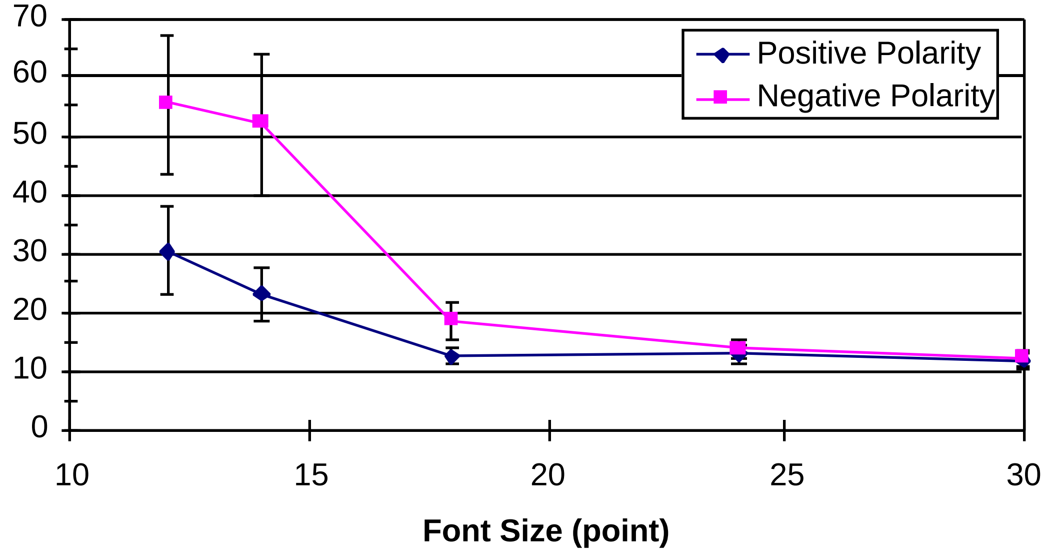

Figure 4.4b. Interaction between font size and polarity on response time for impaired vision.

Since it was shown previously in this section that the unimpaired vision group was not significantly affected by polarity, it is not surprising that the two lines in Figure 4.4a nearly overlap. The significance of this interaction comes from the impaired vision group. Two major conclusions can be drawn from Figure 4.4b. First, again we see that the 12 and 14 point font sizes caused reading times to be much higher than the other three. Performing the Newman-Keuls range test, however, shows that this is again true, but only for positive polarity. For negative polarity, the 18 point font size is significantly different than all other levels of font size. Comparing polarities with the Newman-Keuls test shows that for 12, 14, and 18 point fonts there is a significant difference in polarities. However, for 24 and 30 point sizes, there are no significant differences between polarities and no differences between these two font sizes.

The equality of polarities at the higher font sizes is not a surprising result. Unimpaired readers make little to no distinction for their reading speed between polarities (Legge et al., 1985a) and as font sizes increase and begin equating reading speed between the vision groups, it would seem to follow that any differences caused by polarity would be mitigated. The favoring of positive polarity at the smaller font sizes gives rise to another possible explanation as to why the impaired vision readers prefer positive polarity when the research suggest otherwise. In Rubin and Legge's study of contrast (1989) they held font size constant at 6 degrees of visual angle – a value they found to be generally optimal for impaired vision readers. Thus, while negative polarity was favored by some impaired vision readers across a range of contrasts, their polarity preference was not considered at character sizes that approached their threshold for small font sizes. The above interaction for font size and polarity for impaired vision readers might suggest that for character sizes below optimum for an impaired vision reader, positive polarity might offer a better reading condition.

Vision x Font Size x Contrast

The interaction between vision, size, and contrast for reading time was not significant ($p = 0.068$). However, it is shown in Figures 4.5a and 4.5b because it is close to significance and compares readily with the corresponding three-way interaction for word error.

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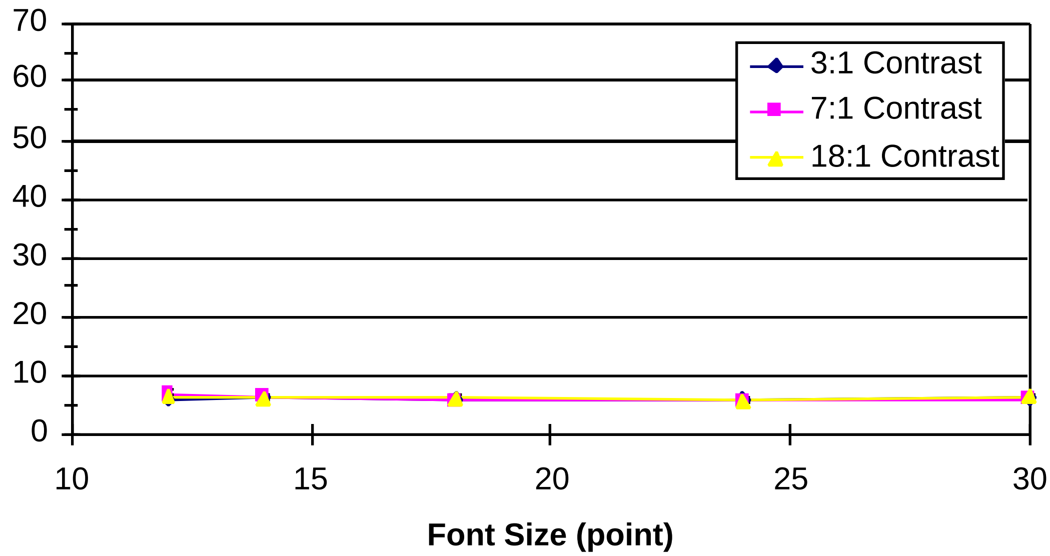

Figure 4.5a. Interaction between font size and contrast on response time for unimpaired vision.

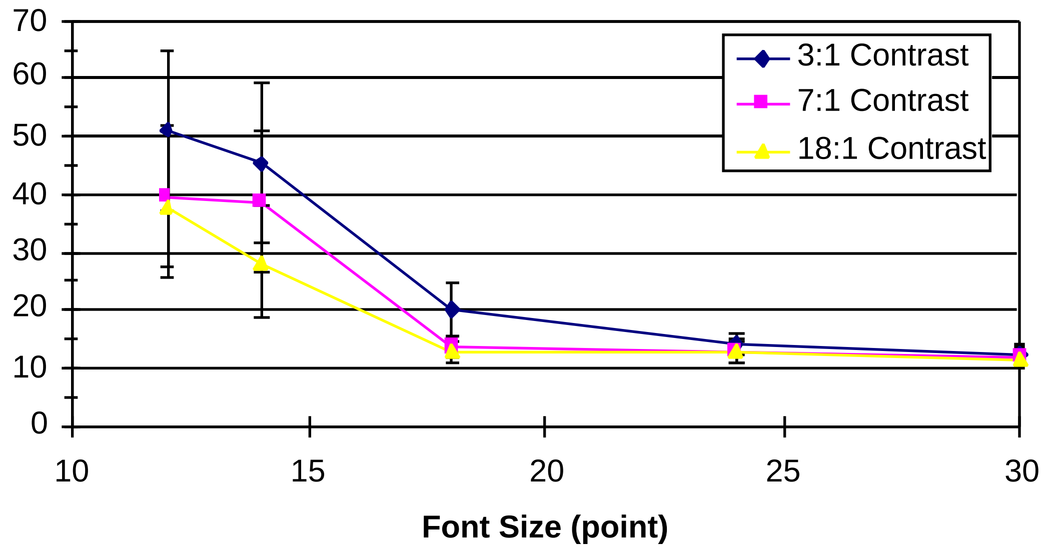

Figure 4.5b. Interaction between font size and contrast on response time for impaired vision.

Since this effect is not significant it is inappropriate to perform a Newman-Keuls test. However, there are several aspects of the preceding two plots that should be noted so they can be compared to the corresponding interaction for word error. First, it should be noted that neither font size or contrast affects the unimpaired vision group. For the impaired vision group, the 12 and 14 point font sizes again show higher reading times and the 18 point size seems to be almost as good as the apparently optimum sizes of 24 and 30 point. Additionally, even though the standard errors overlap for the three contrasts at each font size, the 12 and 14 point font sizes would seem to show that the higher contrast conditions improved reading time. While Rubin and Legge (1989) used only one character size for evaluating contrast effects for impaired vision readers, Legge et al. (1987) found that contrast played an ever increasing role in maintaining readability near critically small character sizes for unimpaired vision. Since all the font sizes used in this experiment are well below the 6 degree characters used in Rubin and Legge (1989), it would seem appropriate that the smaller font sizes would be more affected by lower contrasts.

Vision x Polarity x Contrast

The interaction between vision, polarity, and contrast is significant at ($p = 0.043$). Figures 4.6a and 4.6b have separated the interaction between polarity and contrast by the two vision groups.

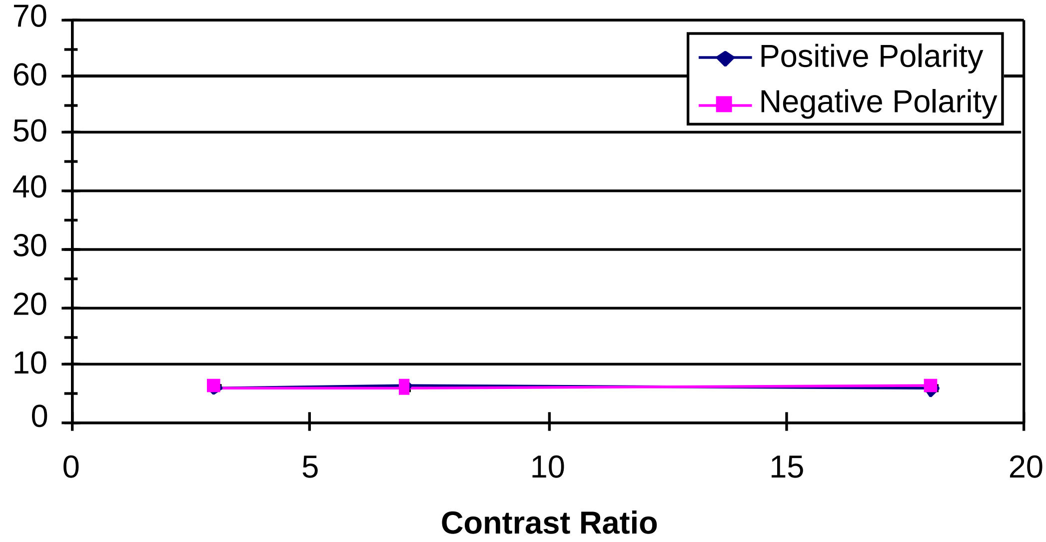

Figure 4.6a. Interaction between polarity and contrast on response time for unimpaired vision.

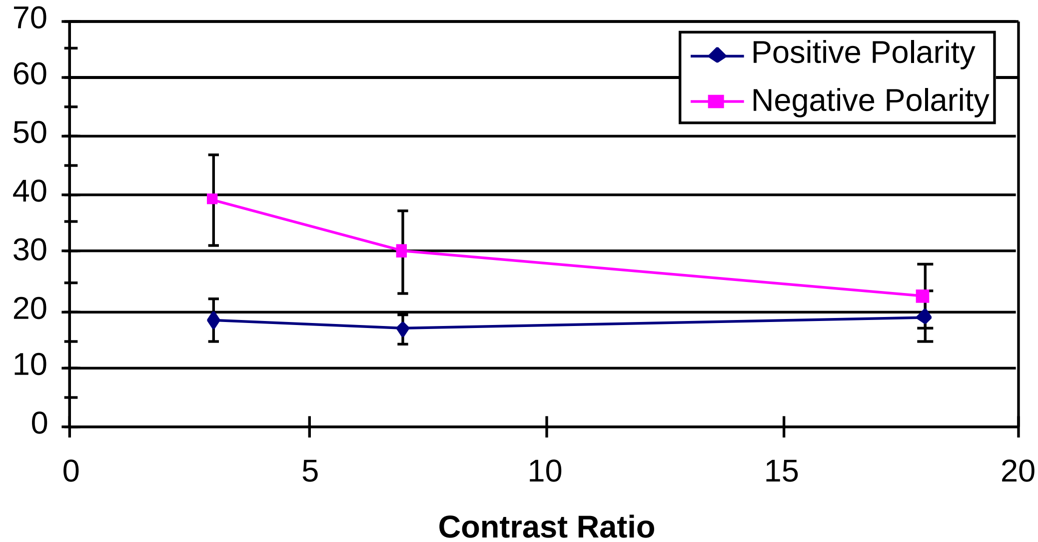

Figure 4.6b. Interaction between polarity and contrast on response time for impaired vision.

For this interaction it is apparent that unimpaired vision readers were affected very little or not at all by either polarity or contrast. Performing the Newman-Keuls range test shows that there are no significant differences for either the level of contrast or polarity. This agrees with Legge et al. (1985a) and Legge et al. (1987). The significance again comes from the variance found in the impaired vision data. Performing the Newman-Keuls range test shows that there are no significant differences at $\alpha = 0.05$ between the three levels of contrast for positive polarity. However, the three levels of contrast for negative polarity are all significantly different; response time falls with increasing contrast for negative polarity. For all three levels of contrast negative polarity is significantly worse than positive polarity with respect to response time, although the difference shrinks with increasing contrast. Rubin and Legge (1989) showed that increasing contrast can lead to better reading rates and that critical contrasts (the contrast were a participant read at half his peak rate) could be as high as 9:1 (luminance modulation of $M = 0.80$), thus the improvement for negative polarity is not unexpected. Furthermore, if the three contrast levels used in this experiment were well above the critical contrast for the reader, it is not unexpected that there would be no significant difference between them (Rubin and Legge, 1989).

The interesting result that the above plot shows is that apparently the impaired vision group was well above its critical contrast for positive polarity, but was still on an improving interval for their contrast sensitivity function. This might suggest that the impaired vision group perceived contrast for negative polarity far below that for positive polarity, even though the physical contrasts were the same. As was mentioned earlier in this section, Rubin and Legge (1989) found that if any polarity differences were present for impaired vision readers, they would favor negative polarity. Methodology differences or the impaired vision sample used for this study could account for this discrepancy, but the better performance of positive polarity for the impaired vision group has no corroborating research and is, in fact, contradicted by Rubin and Legge (1989), McNulty and Suvino (1993), and NRC (1995).

Vision x Font Size x Polarity x Contrast

The four-way interaction of vision, size, polarity, and contrast is significant (p = 0.012). Figures 4.7a, 4.7b, 4.7c, and 4.7d illustrate the interactions between font size and contrast first for unimpaired vision and positive polarity, then by unimpaired vision and negative polarity, next by impaired vision and positive polarity, and finally by impaired vision and negative polarity.

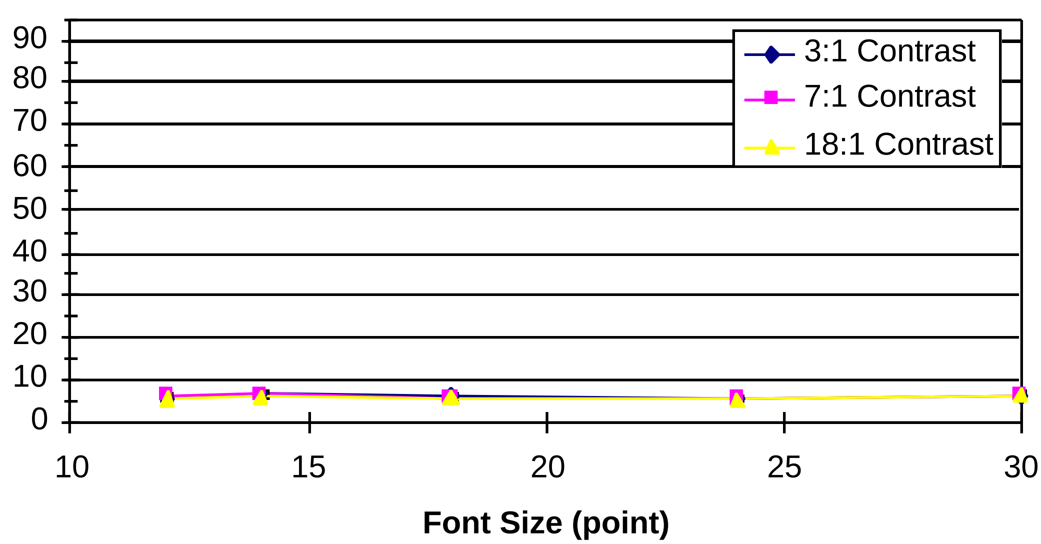

Figure 4.7a. Interaction between font size and contrast on response time for unimpaired vision and positive polarity.

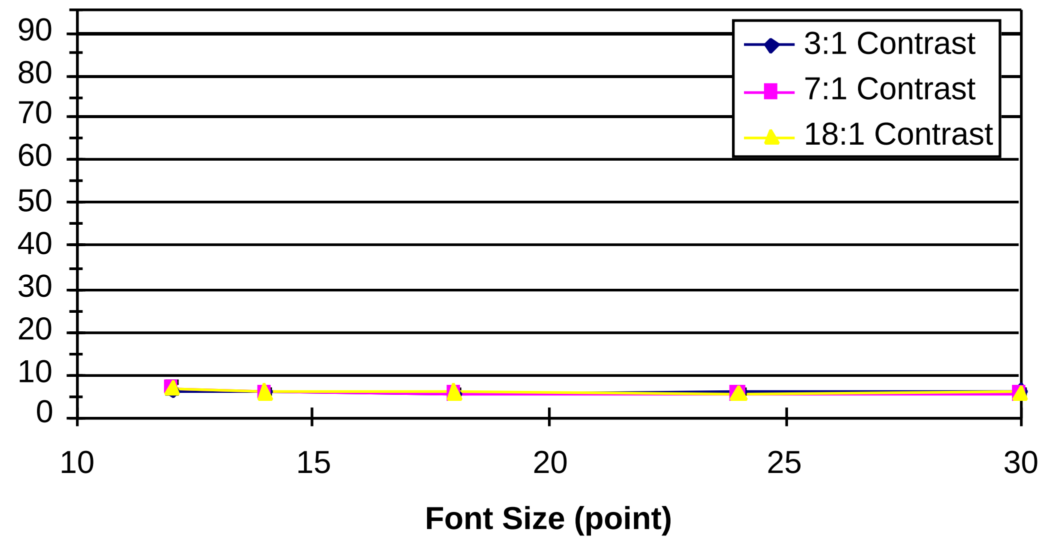

Figure 4.7b. Interaction between font size and contrast on response time for unimpaired vision and negative polarity.

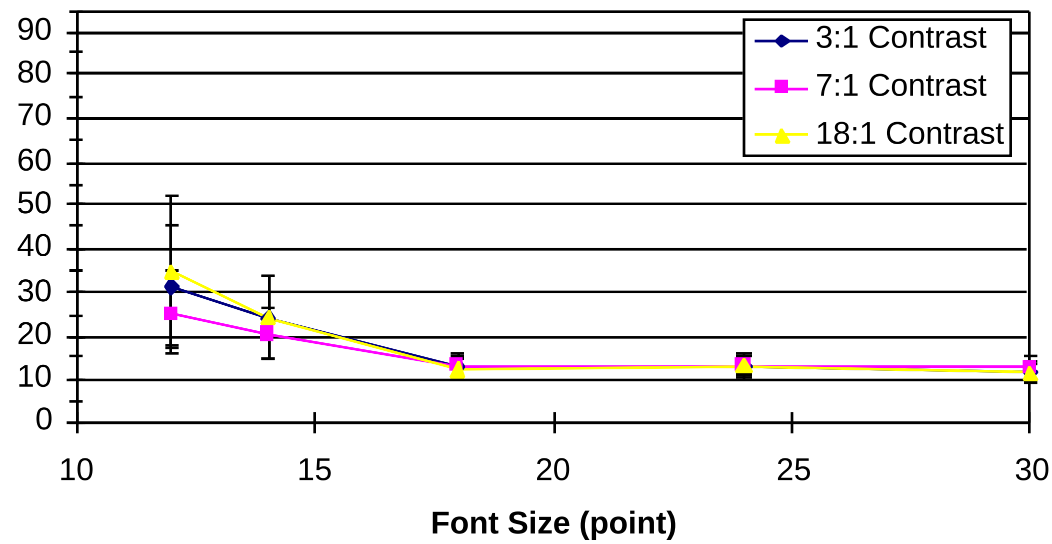

Figure 4.7c. Interaction between font size and contrast on response time for impaired vision and positive polarity.

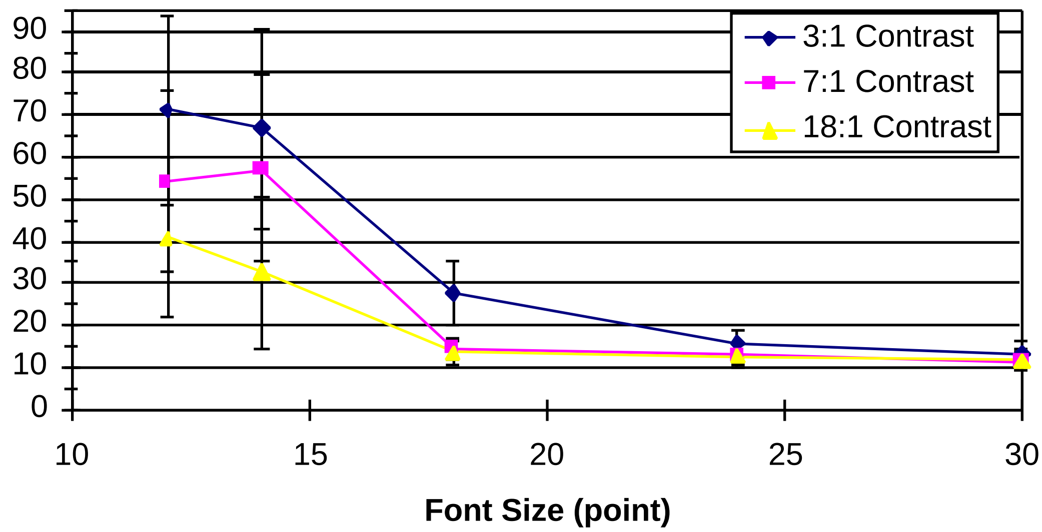

Figure 4.7d. Interaction between font size and contrast on response time for impaired vision and negative polarity.

Once more, we see that the unimpaired vision participants were unaffected by changes in font size, polarity, or contrast. We see again that the 12 and 14 point font sizes were particularly deficient for the impaired vision group, with 18 point being almost as good as 24 and 30 point. However, the one important conclusion that can be drawn from this interaction that is not readily apparent in the other plots is that the 3:1 contrast for negative polarity seems to be a very poor condition for reading. This is most readily illustrated for the 18 point font size condition. Of the six combinations of contrast and polarity for the impaired vision group and 18 point font size, the only combination that yields a significantly higher reading time at $\alpha = 0.05$ for the Newman-Keuls range test is that for negative polarity and 3:1 (lowest) contrast. Newman-Keuls tests on differences amongst 24 and 30 point font sizes between contrasts and polarities show no significant differences. Once more, Legge et al (1985a) and Legge et al. (1987) explain the indifference on the part of the unimpaired vision group. Legge et al

(1985b) and Rubin and Legge (1989) explain the higher response times for 12, 14, and 18 point font conditions and why higher contrast seem to improve reading for the same font size. However, as mentioned before, the lower performance with negative polarity is not corroborated by other research for impaired vision readers. However, the indifference of the impaired vision group to contrast and polarity at the 24 and 30 point font conditions would seem to indicate that these two sizes bring performance of the impaired vision group onto a more equal footing with the unimpaired vision group.

4.1.2 Font Size

The main factor that had the next largest mean square for response time behind vision was font size. Although most conclusions about font size have already been addressed in the discussion about vision, the following section addresses how font size and its interactions with polarity and contrast -- without respect to vision group -- affected response time.

Font Size

The main effect for font size was significant (p = 0.006). Figure 4.8 shows this main effect.

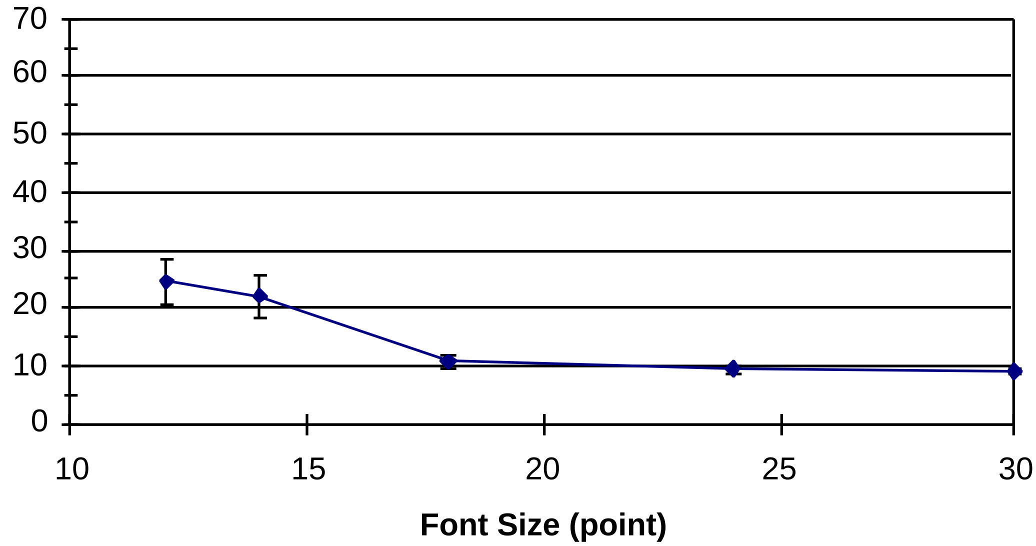

Figure 4.8. The main effect on font size for reading time.

This plot looks remarkably like that for the impaired vision group interacting with font size, though it is tempered somewhat. Because the unimpaired vision group was not affected by changes in font size, this is not surprising. It illustrates a common theme for the main effects and interactions that do not separate the data by vision group, namely that any variability -- and consequently significance -- is caused by the responses of the impaired vision group. Thus, the plots that do not separate the data by vision group should look very much like the plots for the impaired vision group, moderated by the resilience of the unimpaired vision group. Newman-Keuls analysis shows that again the break occurs between 14 and 18 point font size. This is expected in the context of the research by Lin and Williges (1995) and Legge et al. (1985b).

Font Size x Polarity

The interaction between size and polarity was significant ($p = 0.003$). Figure 4.9 shows the interactive relationship.

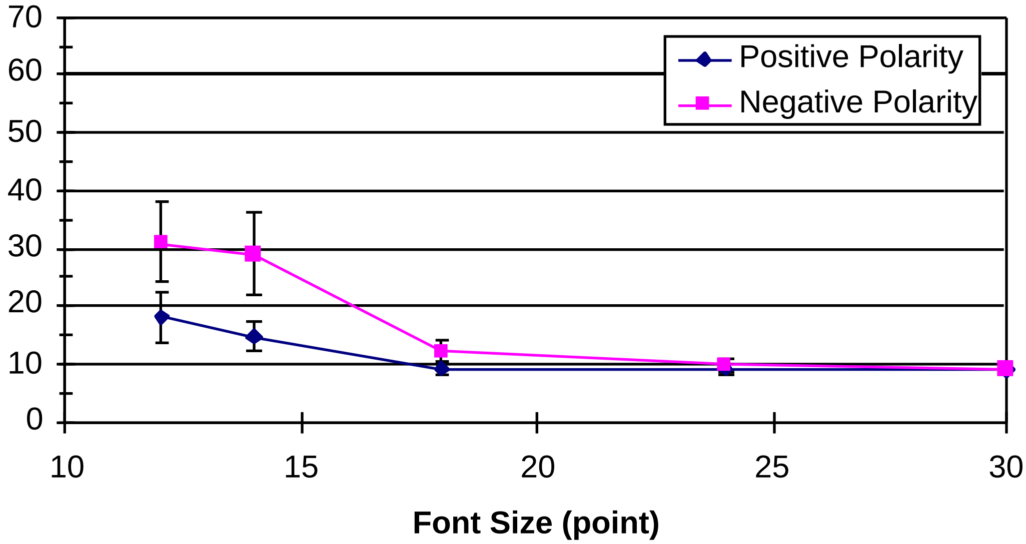

Figure 4.9. Interaction between font size and polarity on response time.

This graph shows two characteristics that were noticed while evaluating the data for the impaired vision participants. First, the 12 and 14 point font sizes are significantly higher than the other three font sizes at $\alpha = 0.05$ according to the Newman-Keuls test -- as expected in the context of the research by Lin and Williges (1995) and Legge et al. (1985b). The other noteworthy conclusion that can be drawn from this plot and which was previously seen for the impaired vision data viewed by themselves, is that negative polarity is significantly worse than positive polarity. More specifically, however, negative polarity is significantly worse for only the smaller font sizes in this case 12 and 14 point sizes. Again it must be stated that this polarity difference is not seen in previous literature, but it is enlightening that the higher font sizes seem to show an indifference to polarity for the combination of the vision groups.

Font Size x Contrast

The interaction between size and contrast for response time is not significant (p = 0.079). The interaction is reported in Figure 4.10 because it is close to significance and compares well with the corresponding interaction for word error.

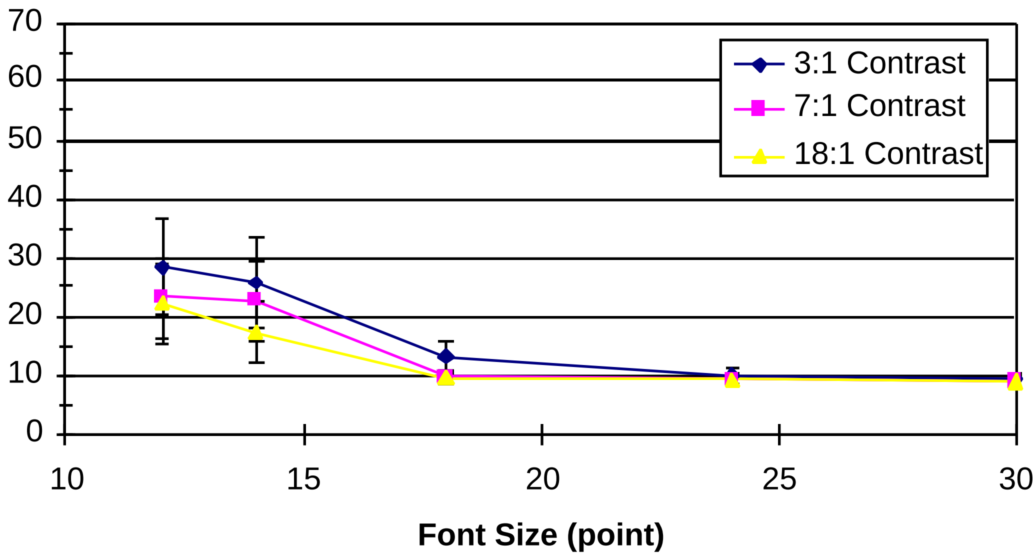

Figure 4.10. Interaction between font size and contrast on response time.

Performing a Newman-Keuls analysis for this interaction is not appropriate since it was not significant, but again a break is readily apparent between the 14 and 18 point font sizes. Also, it appears that as contrast increases response time decreases.

Font Size x Polarity x Contrast

The interaction between size, polarity, and contrast was significant (p = 0.022). Figures 4.11a and 4.11b show this interaction, first by presenting the relationship between size and contrast for positive polarity and then the interaction between size and contrast for negative polarity..

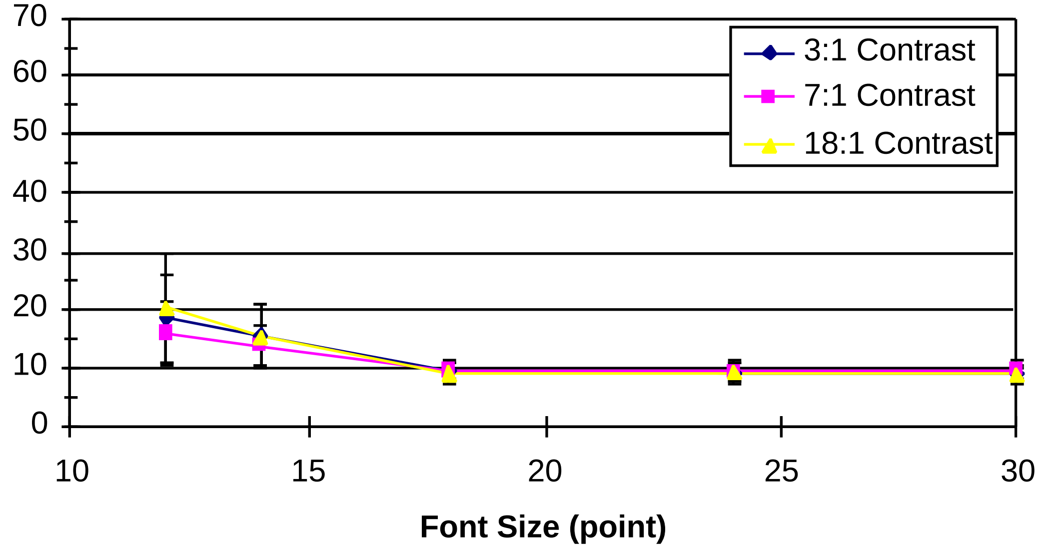

Figure 4.11a. Interaction between font size and contrast on response time for positive polarity.

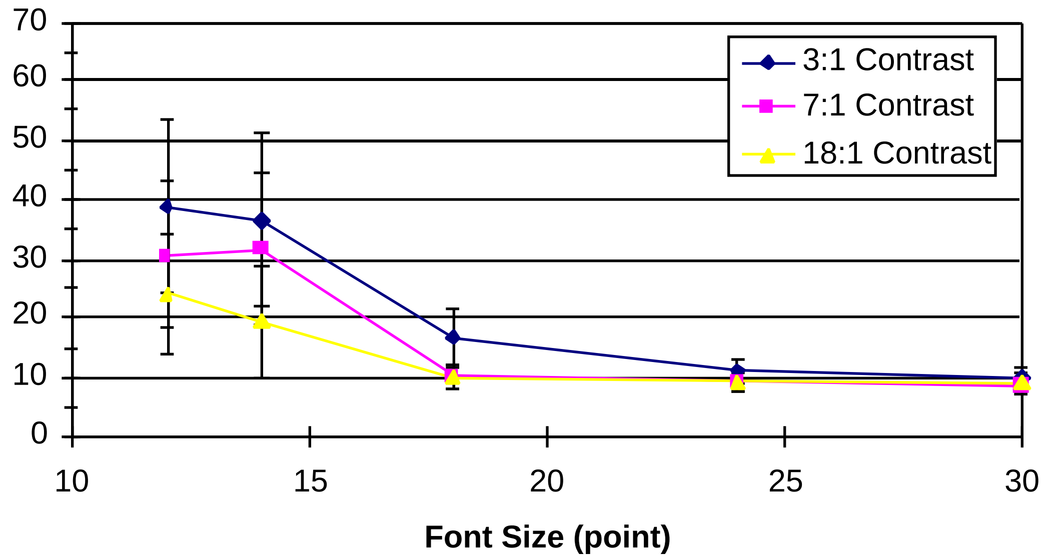

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Figure 4.11b. Interaction between font size and contrast on response time for negative polarity.

Again, Newman-Keuls analysis found a break for all contrasts between 14 and 18 point font sizes. Additionally, means for negative polarity are significantly higher for 12 and 14 point font sizes that for those of positive polarity. For 24 and 30 point font sizes, there are no significant differences between contrast and polarity. However, as is seen in the four-way interaction, the 3:1 contrast, negative polarity condition has a significantly higher response time than for the five other combinations of contrast and polarity for 18 point font.

4.1.3 Polarity

Polarity

The main effect for polarity has the third highest mean square value for the four main effects for this experiment. The main effect was significant (p= 0.032). Figure 4.12 depicts the effect polarity had on response time.

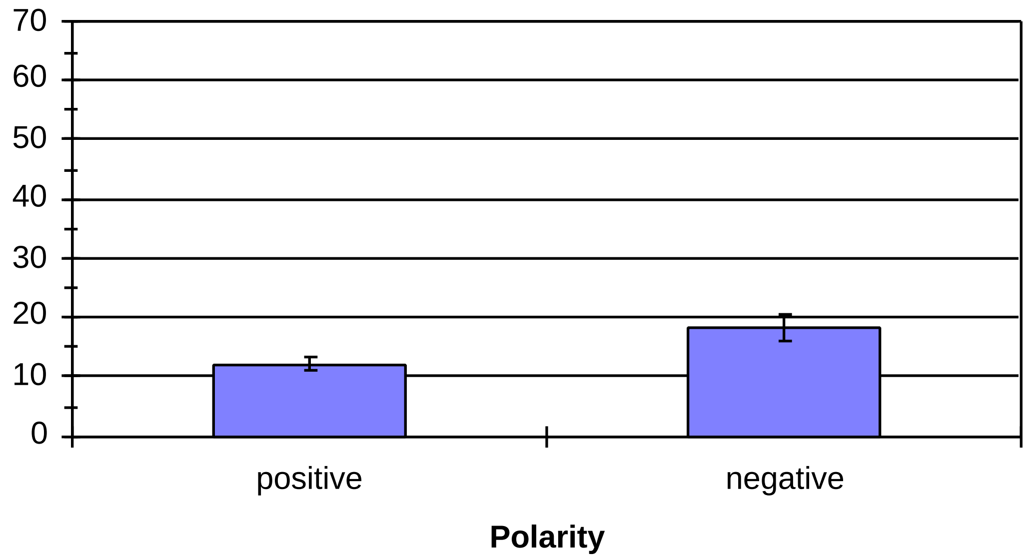

Figure 4.12. Main effect on polarity for reading time.

Response time for negative polarity is significantly higher than that for positive polarity, causing approximately a 50% increase in reading times. But again, it is noteworthy that the unimpaired vision group was not significantly affected by polarity, but the impaired vision group was. Consequently, the significant difference has carried over strictly from the impaired vision data and this plot provides little valuable information.

Polarity x Contrast

The interaction between polarity and contrast was significant (p = 0.052). Figure 4.13 depicts this relationship.

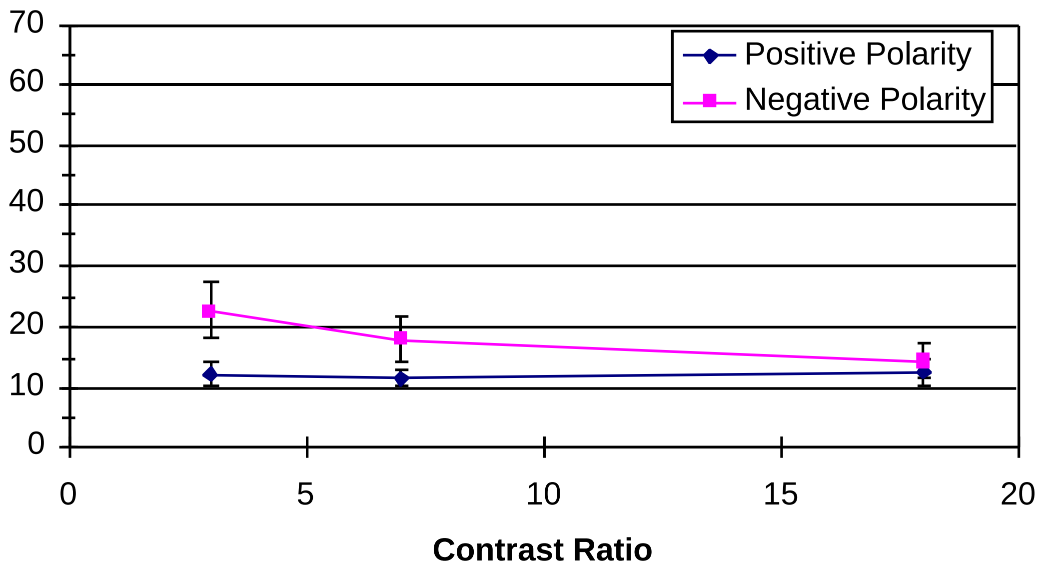

Figure 4.13. Interaction between polarity and contrast on response time.

Newman-Keuls analysis has been performed. Again, as with the impaired vision data for polarity by contrast, the three levels of contrast for positive polarity are not significantly different. However, all three levels of contrast for negative polarity are different; response time decreasing with increasing contrast. Unlike the impaired vision taken by itself, the highest contrast condition for this interaction is not significantly different between polarities. This is probably due to the moderating effect of the unimpaired vision data. Like the interactions seen when polarity and contrast interactions were broken down for the impaired vision group, we see the higher response times for negative polarity that can not be corroborated by previous research. Additionally, while Legge et al. (1987) and Rubin and Legge (1989) might support the staticness of response time across the three levels of contrast for positive polarity *or* the improvements for negative polarity for increasing contrast, it seems odd that both occur for the same physical contrast levels unless there is an underlying difference in how the two polarities are read.

4.1.4 Contrast

Contrast

Of the four main factors, contrast had the smallest mean square value and is being addressed last. All interactions for response time have been addressed already. The only main effect that has not been considered so far is that for contrast. However, contrast did not significantly affect response time ($p = 0.106$). Legge et al. (1987) and Rubin and Legge (1989) both suggest that these three contrast levels are far enough above critical contrasts for both unimpaired and many impaired vision readers to support the fact that there was no significant effect on response time for contrast.

4.2 ANOVA for Word Error

Table 4.2 is the ANOVA table for Word Error:

TABLE 4.2 -- ANOVA for Word Error

Source	df	SS	MS	F	p
Between-Subjects Factors					
vision	1	1.16730	1.16730	5.39	0.043
subject(vision)	10	2.16528	0.21653		
Within-Subjects Factors					
Size	4	1.29063	0.32266	3.50	0.015
Vision*Size	4	1.12951	0.28238	3.06	0.027
Size*Subject(Vision)	40	3.69230	0.09231		
Polarity	1	0.27778	0.27778	5.62	0.039
Vision*Polarity	1	0.33011	0.33011	6.80	0.026
Polarity*Subject(Vision)	10	0.49444	0.04944		
Contrast	2	0.10972	0.05486	3.20	0.062
Vision*Contrast	2	0.09306	0.04653	2.71	0.091
Contrast*Subject(Vision)	20	0.34306	0.01715		
Size*Polarity	4	0.44965	0.11241	6.87	0.000
Vision*Size*Polarity	4	0.51632	0.12908	7.88	0.000
Size*Polarity*Subject(Vision)	40	0.65486	0.01637		
Size*Contrast	8	0.15937	0.01992	2.96	0.006

Vision*Size*Contrast	8	0.15174	0.01897	2.82	0.008
Size*Contrast*Subject(Vision)	80	0.53889	0.00674		
Polarity*Contrast	2	0.10972	0.05486	5.23	0.015
Vision*Polarity*Contrast	2	0.13472	0.06730	6.42	0.007
Polarity*Contrast*Subject(Vision)	20	0.20972	0.01049		
Size*Polarity*Contrast	8	0.15243	0.01905	1.77	0.095
Vision*Size*Polarity*Contrast	8	0.17951	0.02244	2.09	0.046
Size*Polarity*Contrast*Subject(Vision)	80	0.85972	0.01075		
Total	359	15.21597			

The order of the factors listed in Table 4.3 match how the factors are listed in the previous sections. However, after examining the four main factors (vision, size, polarity, and contrast), the order in which they appear in the ANOVA table corresponds exactly with a ranking of their respective mean squares from largest to smallest. This would seem to indicate that the vision variable in this experiment had the largest influence on word error rate, followed by font size, polarity, and lastly by contrast. This order is how the significant results of this experiment are analyzed and discussed below.

4.2.1 Vision

Vision

The main effect of vision had the most impact on word error rate and was significant (p = 0.043). As shown in Figure 4.14, the average word error rate for the impaired vision group was higher than that for the unimpaired vision group.

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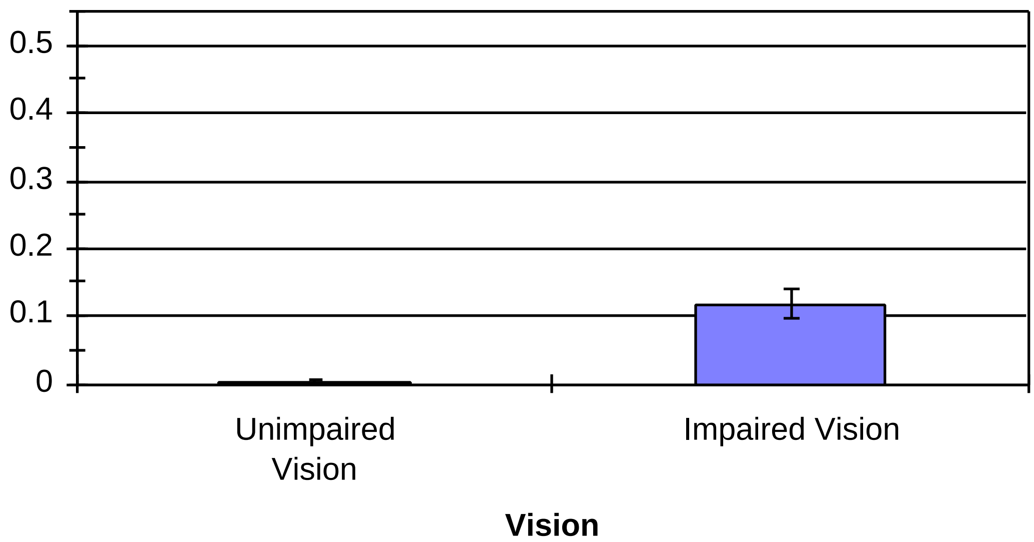

Figure 4.14. Main effect of vision group for word error.

The mean for the unimpaired vision group was 0.00278 and for the impaired vision group it was 0.11667 -- almost a 4200% increase in error rate due to visual impairments was found. This one comparison illustrates the need for designing accommodations that afford access to people with low vision. What some of these accommodations might be can be shown by how the two vision groups were affected by the other main effects.

Vision x Font Size

For the interactive effect of vision and font size, another significant effect ($p = 0.027$) was found. Figure 4.15 shows how varying font size in this experiment caused word error rates to change for both vision groups.

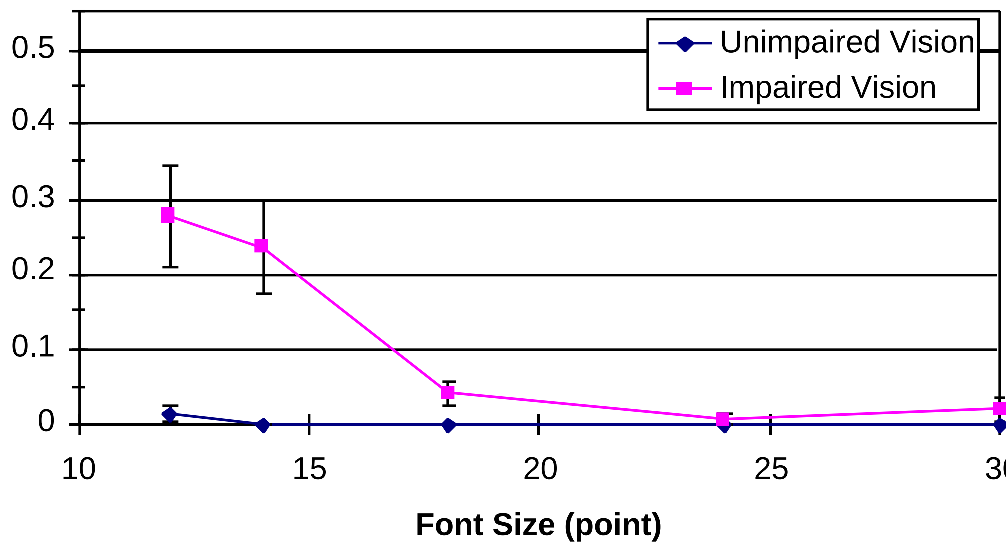

Figure 4.15. Interaction between vision and font size on word error.

It is clear that altering the font size had little to no significant effect for the unimpaired vision group ($p > 0.05$). Legge et al. (1985a) found that peak reading rates were maintained over a range of 0.3 to 2.0 degrees of visual arc. As presented in the discussion of this interaction for response time, unimpaired vision participants fell within this visual arc range during testing and consequently this insensitivity to font size is not surprising.

The Newman-Keuls range test was applied to the impaired vision group data and showed that there is a significant break between the means for the 12 and 14 point font levels and the means for the 18, 24, and 30 point font levels. A comparison of the means by vision group for each font level shows that the 18, 24, and 30 point font sizes can be considered as not being significantly different between the two vision groups ($p > 0.05$). An observer with unimpaired vision makes no distinctions based on character size, but that for those with a visual impairment, characters must be 18, 24, or 30 points in height for them to make no distinctions.

The significant break between 14 and 18 point font sizes has been found previously. In a study of remote control design, Lin and Williges (1995) determined that a 15 point bold font was necessary for equal readability for the elderly with some degree of vision loss. Furthermore, if reading error rate is to be statistically equated for the two vision groups, font sizes ranging from 18 to 30 points should be used.

Vision x Polarity

Figure 4.16 shows that the interaction between vision group and polarity was significant (p = 0.026).

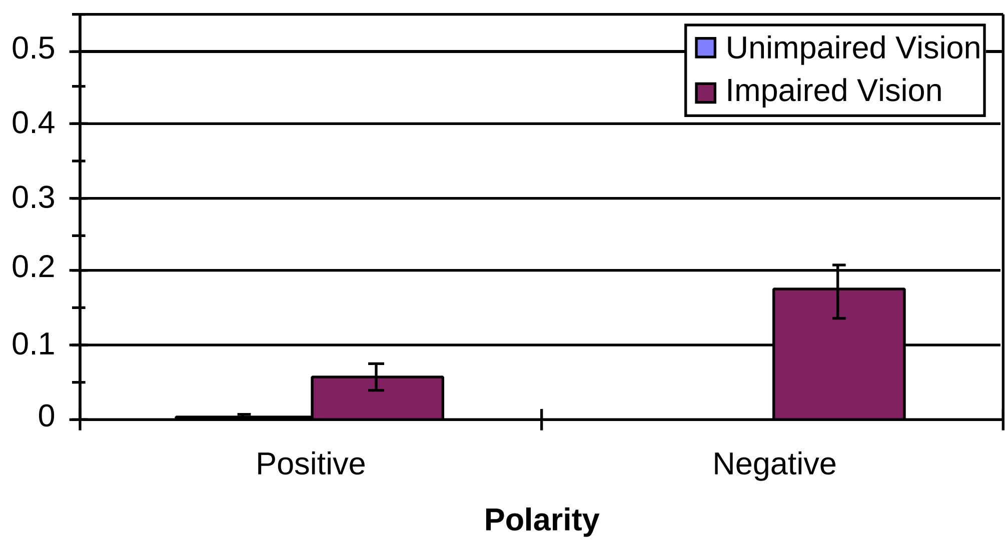

Figure 4.16. Interaction between vision and polarity on word error.

Once more, we see that the impaired vision group had higher reading times when compared to the unimpaired vision group. A Newman-Keuls range test showed that the unimpaired vision group is not significantly affected by polarity.

1

For the impaired vision group, negative polarity caused higher error rates than for positive polarity. Finally, the range test showed that the impaired vision group had higher error rates for both polarities when compared with the unimpaired vision group ($p < 0.05$).

The interesting observation drawn from the data, however, is that negative polarity is the *worse* condition for the impaired vision readers. Legge et al (1985b) and Rubin and Legge (1989) found that if impaired vision readers had a significant advantage by polarity it was negative polarity that caused better reading performance. However, a major difference between the current experiment and these studies is that they used letters of six degrees of visual angle (determined to be a generalized optimum for impaired vision readers) while this study used a range of font sizes that have been show to be, in part, sub-optimum (Rubin and Legge, 1989).

A possible explanation for this disparity is that in this experiment, contrasts were altered by adjusting the foreground luminance while maintaining a constant background luminance. In Rubin and Legge (1989) they adjusted background luminance while maintaining a constant foreground luminance. It is possible that the different methodologies induce different perceived contrasts for the two polarities. It also could be that the group of six impaired vision readers used in this experiment happen to read better in positive polarity. Since the preference for positive polarity is contradicted by McNulty and Suvino (1993), NRC (1995), and Rubin and Legge (1989), it would stand to reason that there is an unidentified factor at work or the small impaired vision sample used was not representative of the larger impaired vision population with respect to polarity.

Vision x Contrast

The interaction between vision and contrast was not significant ($p = 0.091$) for this study. The contrasts of 3:1, 7:1, and 18:1 (luminance modulations of M =

1

0.50, M = 0.75, and M = 0.89, respectively) used in this study were well within the range that Legge et al. (1987) found to cause very little reading rate reductions. Additionally, these contrasts are above critical contrasts found for most impaired vision readers in Rubin and Legge (1989).

Vision x Font Size x Polarity

The three-way interaction of size, polarity, and vision group was significant (p = 0.000). Figures 4.17a and 4.17b illustrate how size was affected by polarity first for the unimpaired vision readers and then the second graph show how they interacted for the impaired vision group.

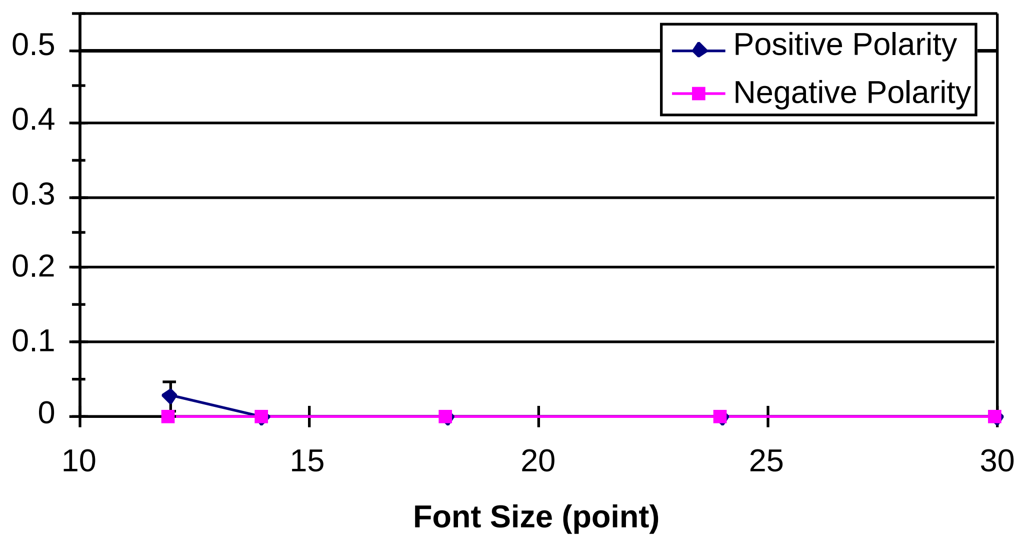

Figure 4.17a. Interaction between font size and polarity on word error for unimpaired vision.

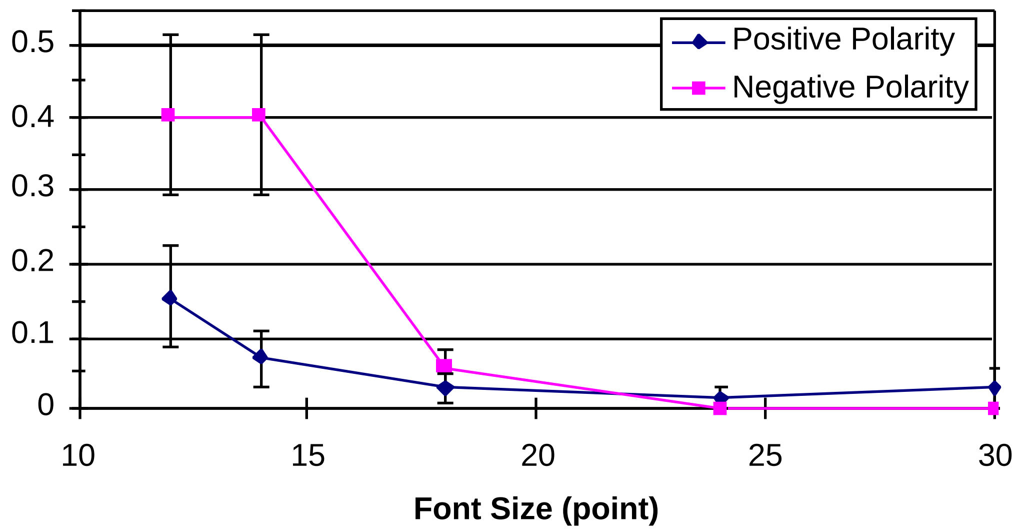

Figure 4.17b. Interaction between font size and polarity on word error for impaired vision.

Since it was shown previously in this section that the unimpaired vision group was not significantly affected by polarity, it is not surprising that the two lines in Figure 4.17a nearly overlap. The significance of this interaction comes from the impaired vision group. Figure 4.17b leads to two conclusions. First, we see again that the 12 and 14 point font sizes caused word error rates to be much higher than the rates for 18, 24, and 30 points. Performing a Newman-Keuls range test shows that this is again true, but only for negative polarity. For positive polarity, only the 12 point font size is significantly different than all other levels of font sizes. Comparing polarities with the Newman-Keuls test shows that for 12 and 14 point font sizes there is a significant difference in polarities – positive polarity yielding lower word error rates. However, for 18, 24, and 30 point sizes there are no significant differences between polarities and no differences between these three font sizes for the same polarity. The equality of polarities at the higher font sizes is not a surprising result. Unimpaired readers make little to no distinction for their reading speed (and consequently for error rates) between polarities (Legge et al., 1985a) and as font size increases and begins equating word error rates between the two vision groups, it would follow that any differences caused by polarity would be mitigated.

The favoring of positive polarity at the smaller font sizes leads to another possible explanation for why this study's conclusion concerning polarity differ from previous research. While negative polarity was favored by some impaired vision readers across a range of contrasts, their polarity preference was not considered at character sizes that approached their font size threshold. The above interaction for font size and polarity might suggest that for character sizes below optimum for an impaired vision reader, positive polarity might offer a better reading condition.

Vision x Font Size x Contrast

The interaction between vision, font size, and contrast for reading time was significant (p = 0.008). The corresponding interaction for reading time was not significant, but comparing the two interactions should reveal that their trends are comparable. Figures 4.18a and 4.18b depict the interaction of font size by contrast first for the unimpaired vision group and then for the impaired vision group.

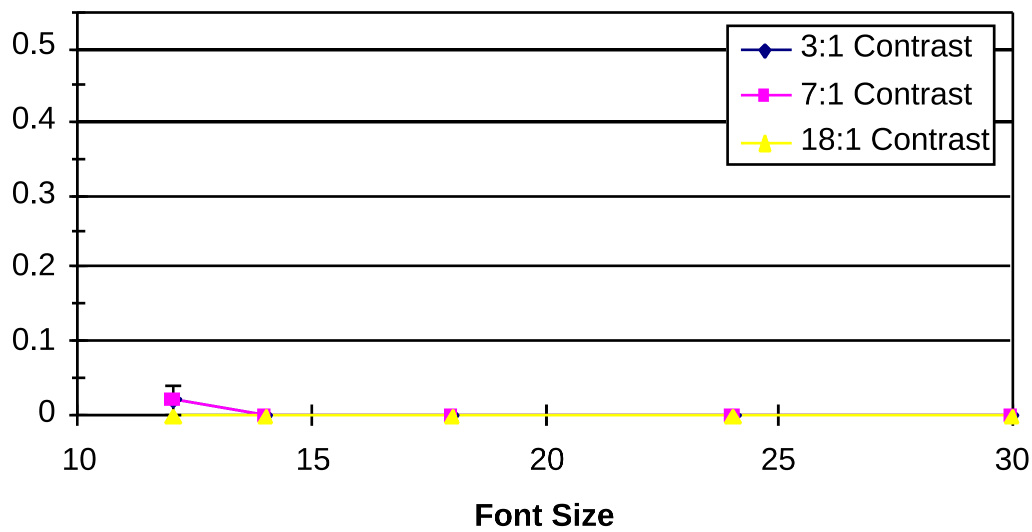

Figure 4.18a. Interaction between font size and contrast on word error for unimpaired vision.

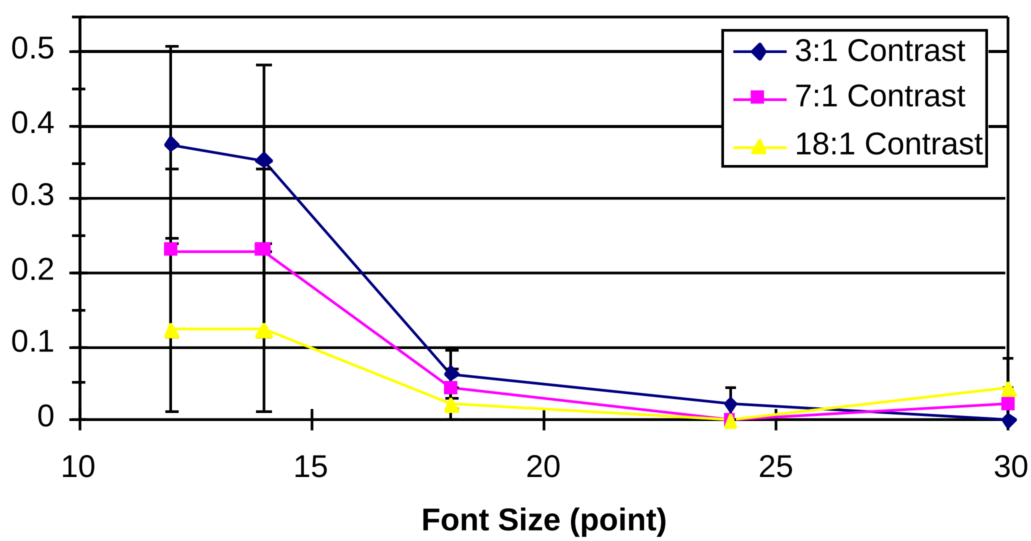

Figure 4.18b. Word error as a function of the interaction between font size and contrast for impaired vision.

A Newman-Keuls test at $\alpha = 0.05$ showed that font size and contrast had no significant effect for the unimpaired vision group. For impaired vision readers the data show that they had more trouble with the 12 and 14 point font sizes than for the other three sizes. For increasing contrast, both the 12 and 14 font sizes had improving error rates, but 18, 24, and 30 point sizes were not significantly different by contrast ($\alpha = 0.05$). Additionally, one other significant result from the range test is noteworthy. For the 18:1 contrast condition, the 30 point font size condition has a significantly higher error rate than the 24 point size for the same contrast. Legge et al. (1987) found that contrast played an ever increasing role in maintaining readability near critically small character sizes for unimpaired vision. Since Rubin and Legge (1989) did not vary font size in their experiment, it is not known what role contrast plays in reading critically small characters for the impaired vision reading population, but it seems reasonable that contrast would play an ever increasing role in readability for that population as well and this interaction seems to indicate that this hypothesis is true.

Vision x Polarity x Contrast

The interaction between vision, polarity, and contrast is significant ($p = 0.007$). Figures 4.19a and 4.19b have separated the interaction between polarity and contrast by the two vision groups.

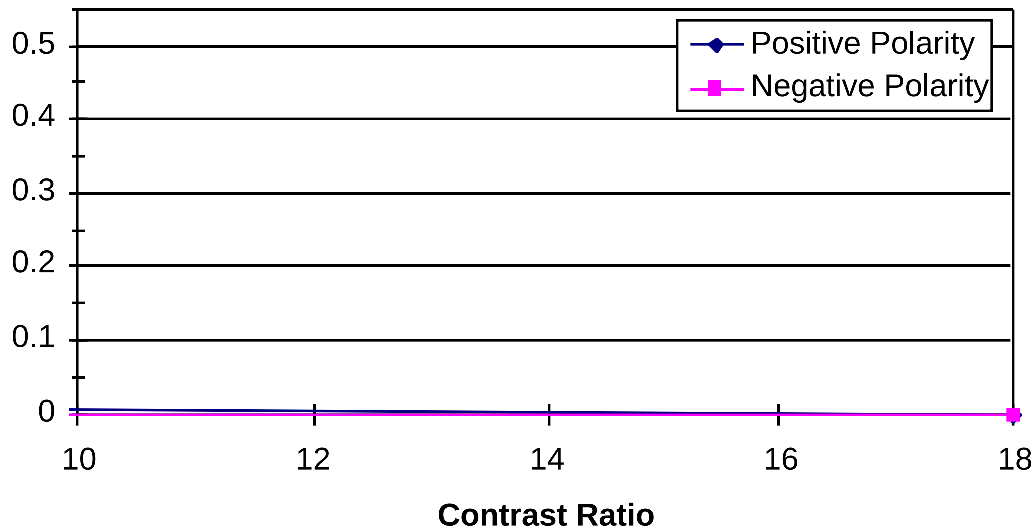

Figure 4.19a. Interaction between polarity and contrast on word error for unimpaired vision.

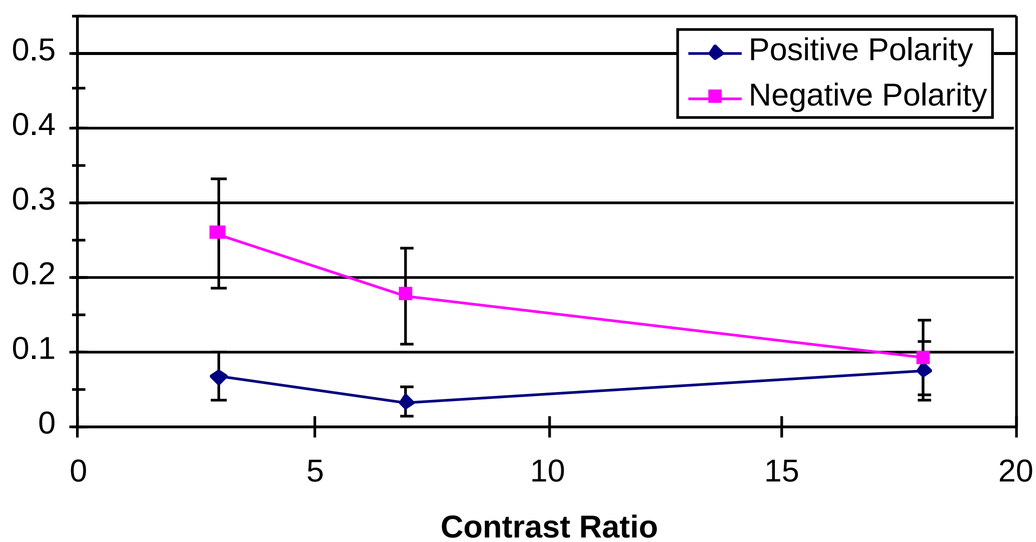

Figure 4.19b. Interaction between polarity and contrast on word error for impaired vision.

Once again, unimpaired vision readers were affected very little or not at all by either polarity or contrast. Performing the Newman-Keuls range test showed that there are no significant differences for either the level of contrast or polarity ($p < 0.05$). This agrees with Legge et al. (1985a) and Legge et al. (1987). The significance again comes from the variance found in the impaired vision data. Performing the Newman-Keuls range test shows that there are significant differences at $\alpha = 0.05$ between the three levels of contrast for positive polarity. The 7:1 condition has a significantly lower error rate than that for 3:1 and 18:1 contrast levels, but 3:1 and 18:1 are not significantly different, indicating a preference for the intermediate level of contrast. For negative polarity all the three levels of contrast are significantly different; word error rates fall with increasing contrast for negative polarity. For the 3:1 and 7:1 contrast levels negative polarity is significantly worse than positive polarity, though the difference is smaller for the 7:1 contrast than for 3:1. Comparing the two polarities for the 18:1 contrast condition, showed that there is no significant difference at ($p < 0.05$). Rubin and Legge (1989) showed that increasing contrast can lead to better reading rates (and consequently lower error rates) for readers with impaired vision and that critical contrasts (the contrast were a participant reads at half his peak rate) could be as high as 9:1 (luminance modulation of $M = 0.80$), thus the improvement for negative polarity is not unexpected.

Interestingly, the impaired vision group seems to have been well above its critical contrast for positive polarity, but was still on an improving interval for their contrast sensitivity function. In fact, for positive polarity, the impaired vision group seemed to be so far above critical contrast that they began to have more errors as contrast was increased from 7:1 to 18:1. This might be explained by the brighter background causing increased intraocular light scatter, thus reducing the retinal contrast of the letters (Legge et al., 1985b; Rubin and Legge 1989).

This suggests that the impaired vision group perceived the contrast for negative polarity far below that for positive polarity, even though the luminance contrasts were the same. One conclusion to draw from this interaction (and one that the response time interaction did not show) is that for the impaired vision group, 18:1 contrast was not significantly different between the two polarities. The implication here is that, like font size, as contrast increases, polarity differences disappear.

Vision x Font Size x Polarity x Contrast

The four-way interaction of vision, size, polarity, and contrast is significant ($p = 0.046$). Figures 4.20a, 4.20b, 4.20c, and 4.20d illustrate the interactions between font size and contrast first for unimpaired vision and positive polarity, then by unimpaired vision and negative polarity, next by impaired vision and positive polarity, and finally by impaired vision and negative polarity.

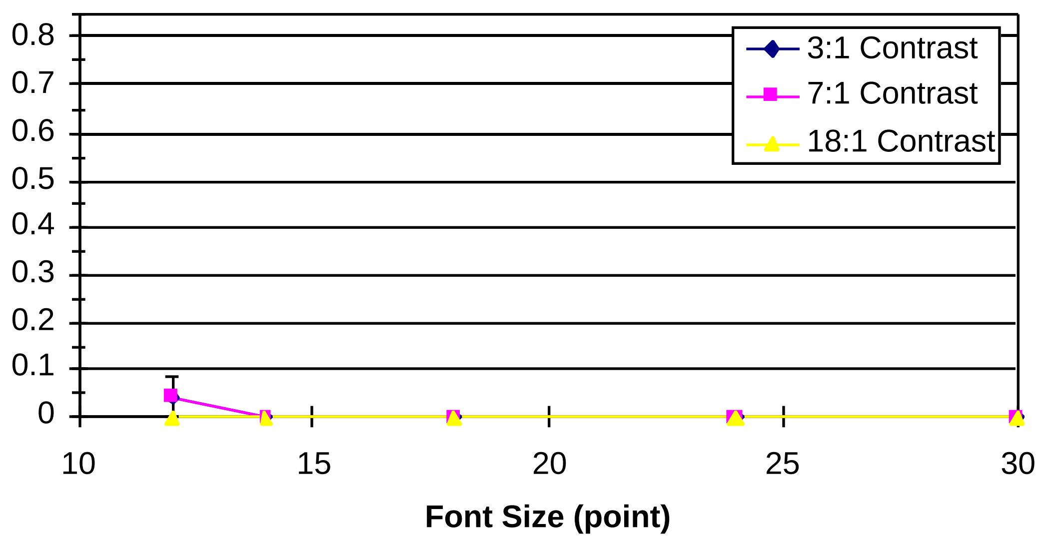

Figure 4.20a. Interaction between font size and contrast on word error for unimpaired vision and positive polarity.

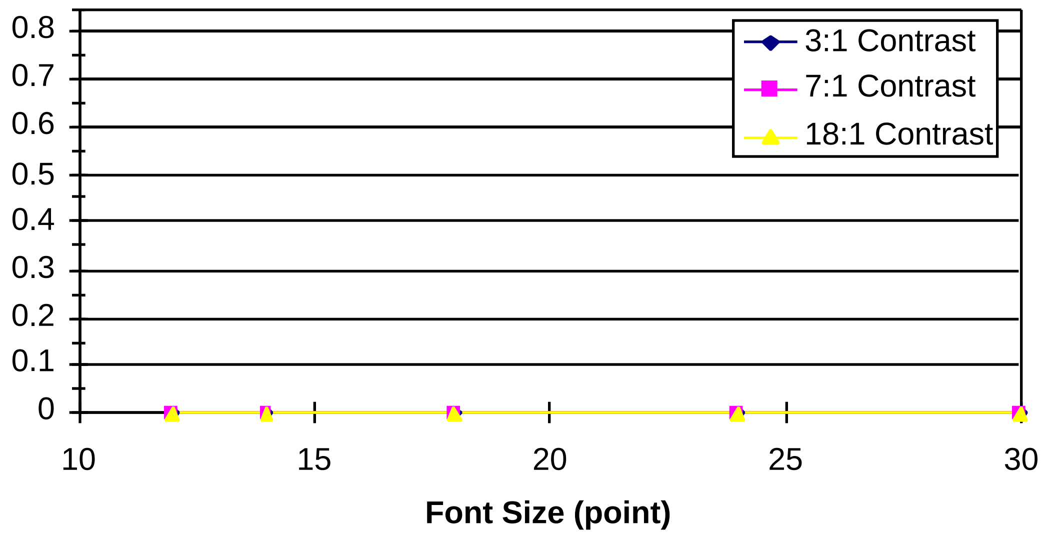

Figure 4.20b. Interaction between font size and contrast on word error for unimpaired vision and negative polarity.

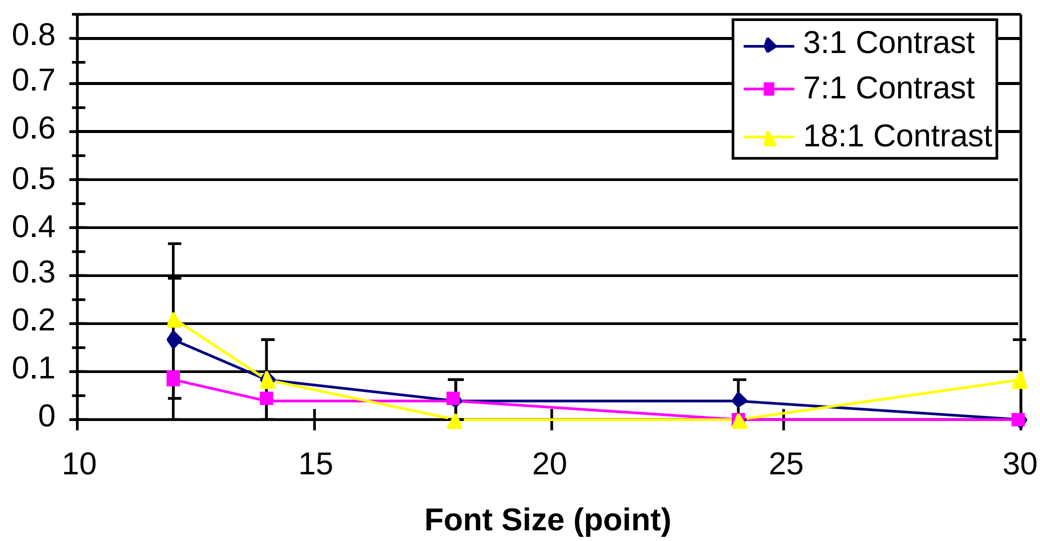

Figure 4.20c. Interaction between font size and contrast on word error for impaired vision and positive polarity.

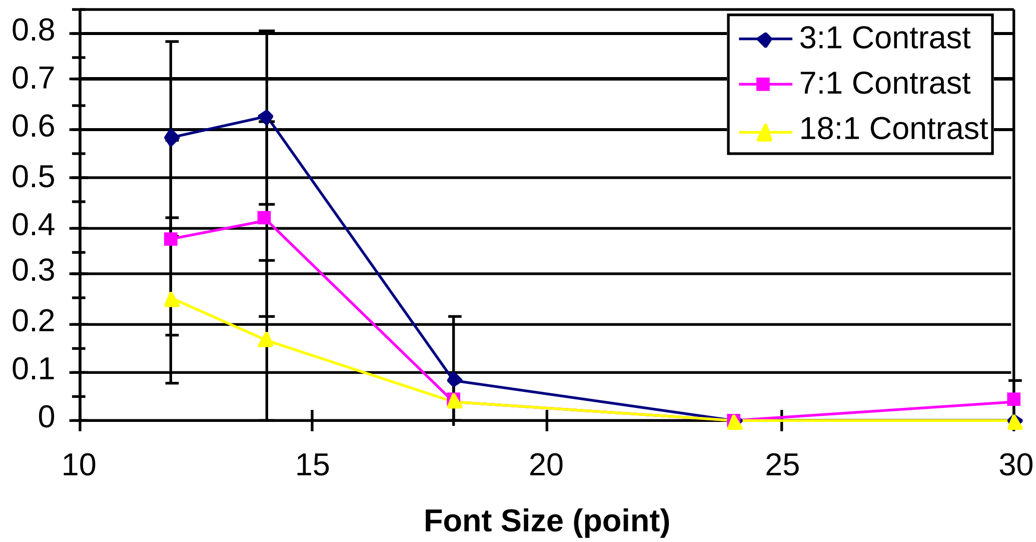

Figure 4.20d. Interaction between font size and contrast on word error for impaired vision and negative polarity.

A Newman-Keuls range test showed that the unimpaired vision participants were unaffected by changes in font size, polarity, or contrast. Once more, Legge et al (1985a) and Legge et al. (1987) have previously shown this indifference for unimpaired vision readers. Again the 12 and 14 point font sizes caused poorer performance for the impaired vision group, with 18 point being significantly different than both the 12 and 14 point sizes as well as the 24 and 30 point sizes.

One new, important conclusion that can be drawn from this interaction that is not readily apparent in the other plots. The 3:1 contrast for negative polarity seems to be a very poor reading condition. This is most readily illustrated for the 18 point font size condition. Of the six combinations of contrast and polarity for the impaired vision group at 18 points, the only combination that yields a significantly higher reading time at $\alpha = 0.05$ for the Newman-Keuls range test is that for negative polarity and 3:1 (lowest) contrast.

Another new finding showed significantly higher error rates caused by the 18:1 (highest) contrast condition for positive polarity. As was seen in the interaction for polarity and contrast for the impaired vision group, this highest contrast for positive polarity seems to have induced higher error rates. This might be explained by the brighter background inducing increased intraocular light scatter, thus reducing the retinal contrast of the letters (Legge et al., 1985b; Rubin and Legge, 1989). Legge et al (1985b) and Rubin and Legge (1989) why higher contrast seem to improve reading for the same font size. However, as mentioned before, the lower performance with negative polarity is not corroborated by other research for impaired vision readers.

4.2.2 Font Size

The main factor that had the next largest mean square for word error rate following vision was font size. Although most conclusions about font size have already been addressed in the discussion about vision, the following section addresses how font size interacted with polarity and contrast without respect to vision.

Font Size

The main effect for font size by itself was significant (p = 0.015). Figure 4.21 shows the main effect for size.

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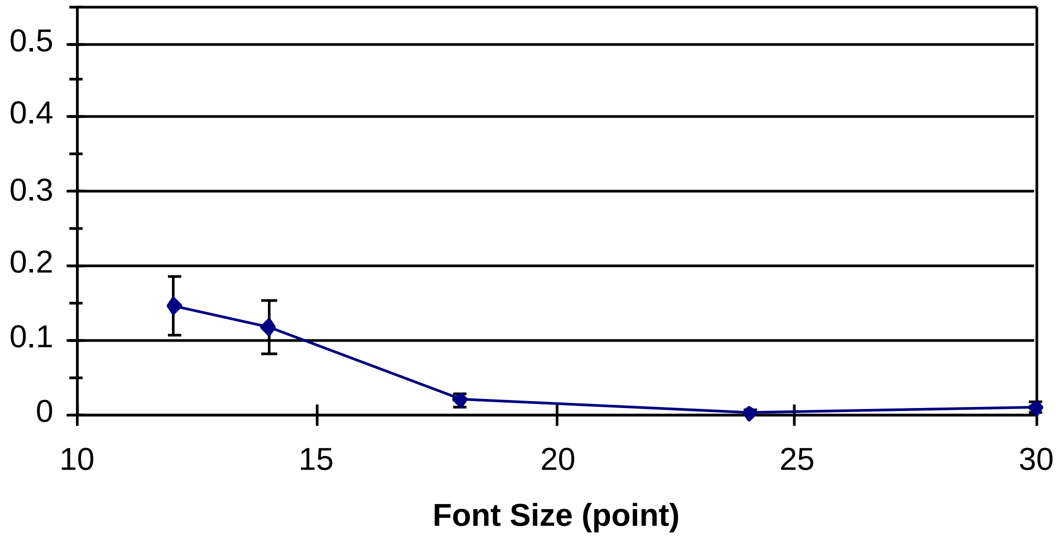

Figure 4.21. Main effect of font size for word error.

Again, it should be noted that plots which do not separate the data by vision group look like the corresponding interaction for impaired vision by itself with some moderating effects from the constancy of the unimpaired vision group. The above interaction shows this to be true, looking remarkably like the interaction between impaired vision and font size. Newman-Keuls analysis showed that a break occurs between 14 and 18 point font size. This is expected in the context of the research by Lin and Williges (1995) and Legge et al. (1985b).

Font Size x Polarity

The interaction between size and polarity is significant ($p = 0.000$). Figure 4.22 shows the interactive relationship.

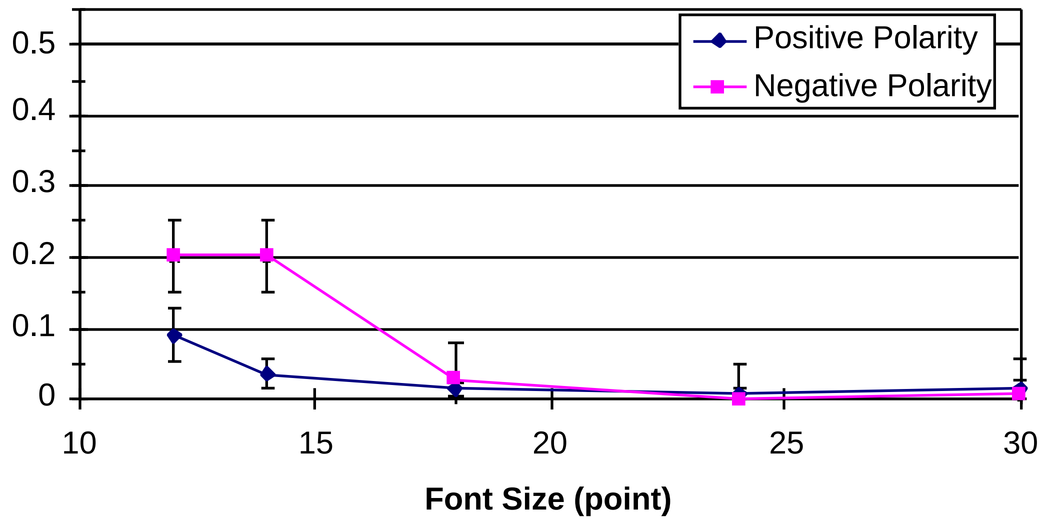

Figure 4.22. Interaction between font size and polarity on word error.

The 12 and 14 point font sizes are significantly higher than the other three font sizes for negative polarity at $\alpha = 0.05$ according to the Newman-Keuls test; this is expected in the context of the research by Legge et al. (1985b) and Lin and Williges (1995). However, unlike what is seen for the impaired vision data by itself, all levels of font size for positive polarity are significantly different from one another except for the 12 point condition. The other noteworthy conclusion that can be drawn from this plot and which was previously seen for the impaired vision data viewed by themselves, is that negative polarity is significantly worse than positive polarity. Specifically, negative polarity is significantly worse for only the smaller font sizes in this case 12 and 14 point sizes. Again it must be stated that this polarity difference is not seen in previous literature, but it is enlightening that the higher font sizes seem to show an indifference to polarity. This lends support to the conclusion that font size plays a role in polarity preference.

Font Size x Contrast

The interaction between size and contrast for word error rate is significant (p = 0.006). Figure 4.23 shows the relationship that was found.

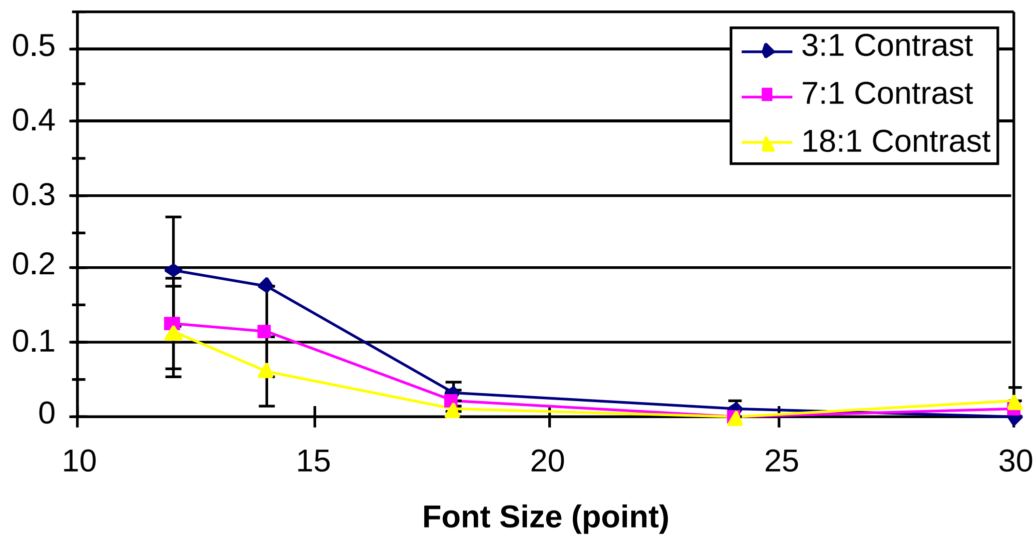

Figure 4.23. Interaction between font size and contrast on word error.

A Newman-Keuls analysis showed a break is readily apparent between the 14 and 18 point font sizes. Also, for the 18, 24, and 30 point font sizes for each of the three contrasts there are no significant differences found by Newman-Keuls testing ($p > 0.05$). An important discovery, however, is that for the 14 point font condition, increasing contrast significantly reduces error rate. This is partially true for the 12 point size condition where an increase in contrast from 3:1 to 7:1 lowers error rates, but an increase from 7:1 to 18:1 did not significantly improve word error rates ($p > 0.05$). These findings correspond with previous analyses for these experimental data. When font size is large enough, contrast has no significant effect on error rates, but for the critically small font sizes, contrast plays an ever increasing role in reading (Legge et al., 1987).

Font Size x Polarity x Contrast

The interaction between size, polarity, and contrast was not significant (p = 0.095). It is being presented here for comparison with the significant interaction for size, polarity, and contrast for response time. Figures 4.24a and 4.24b show this interaction, first by presenting the relationship between size and contrast for positive polarity and then the interaction between size and contrast for negative polarity.

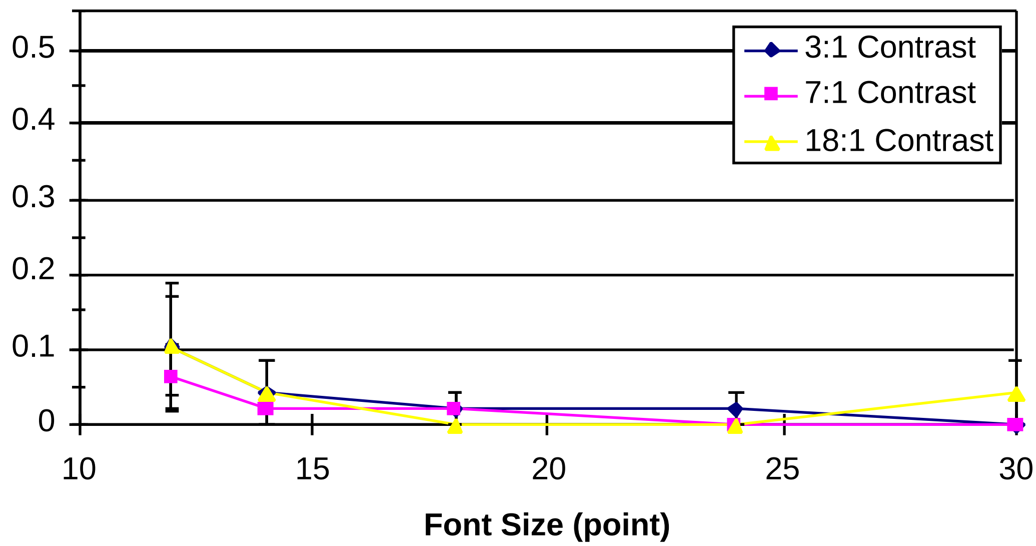

Figure 4.24a. Interaction between font size and contrast on word error for positive polarity.

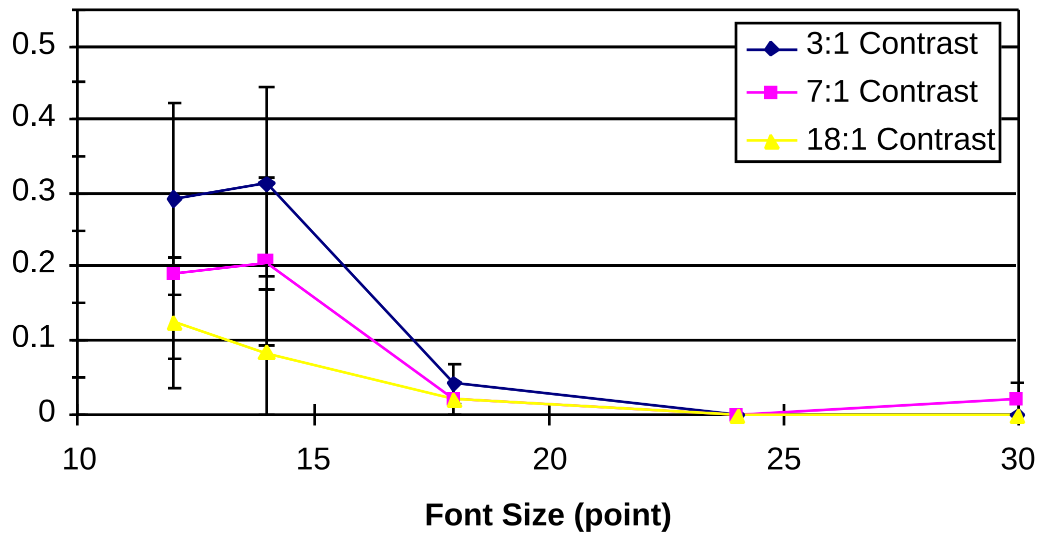

Figure 4.24b. Interaction between font size and contrast on word error for negative polarity.

Performing a range test for this interaction is not appropriate since this interaction is not significant at α = 0.05. However, it is worth noting for comparison with the same interaction for response time. In particular, for the smaller font sizes contrast plays an important role, but as font sizes increase, contrast becomes less important. Additionally, positive polarity seems to have better error rates than negative polarity. Both of these observations can be made for the significant interaction between size, polarity, and contrast for response time as well as be seen in other interactions for word error.

4.2.3 Polarity

Polarity

The main effect for polarity has the third highest mean square value for the four main effects for this experiment. The main effect was significant (p= 0.039). Figure 4.25 depicts the effect polarity had on response time.

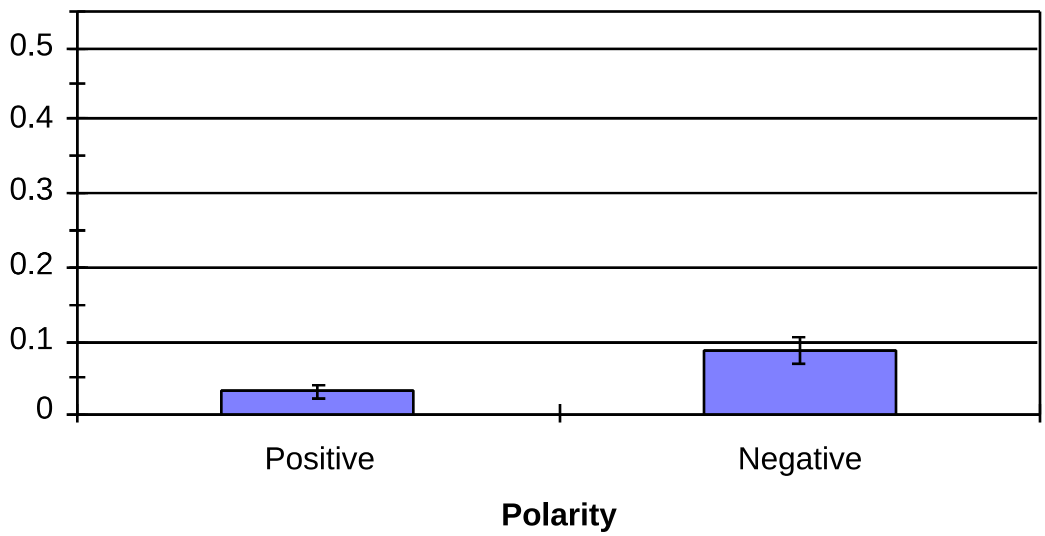

Figure 4.25. The main effect on polarity for word error.

Word error for negative polarity is significantly higher than that for positive polarity. Referring to the significant interaction between vision and polarity, the unimpaired vision group was not significantly affected by polarity, but the impaired vision group was. Consequently, the significant difference has carried over strictly from the impaired vision data and this plot does not provide any important conclusions. This higher error rate for negative polarity is contradicted by previous research (Legge et al 1985b; Rubin and Legge 1989). For this experiment it is thought that font size and, to a lesser extent, contrast has caused this discrepancy.

Polarity x Contrast

The interaction between polarity and contrast was significant (p = 0.015). The interactive effect for word error is shown in Figure 4.26.

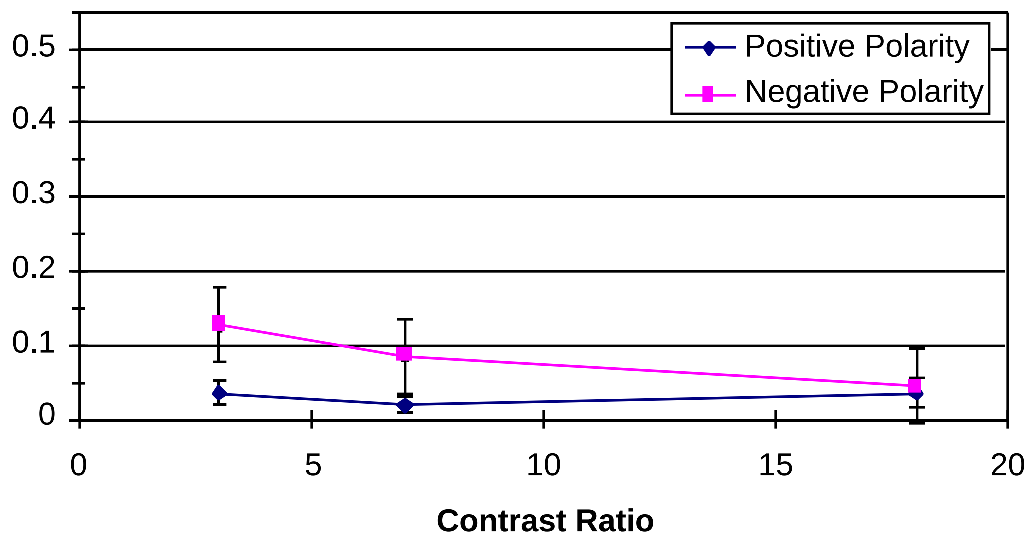

Figure 4.26. Interaction between polarity and contrast on word error.

For the impaired vision data for polarity by contrast, the three levels of contrast for positive polarity are not significantly different according to Newman-Keuls analysis at $\alpha = 0.05$. As is seen with response time, there is no difference between polarities at the 18:1 (highest) contrast condition. This is likely caused by the moderating effect of the unimpaired vision data. The higher error rates observed for negative polarity are not supported by previous research for either vision group. However, as suggested previously, this may not be directly attributable to polarity itself, but implies that contrast plays an interactive role in reading for polarity

4.2.4 Contrast

Contrast

Of the four main factors, contrast had the smallest mean square value and is being addressed last. All interactions for word error have been addressed already. The only main effect that has not been considered so far is that for contrast. However, contrast did not significantly affect response time at $\alpha = 0.05$ ($p = 0.062$). Legge et al. (1987) and Rubin and Legge (1989) both suggest that these three contrast levels are far enough above critical contrasts for both unimpaired and many impaired vision readers to support the fact that there was no significant effect on response time for contrast.

4.3 Observation of the Experimenter

One final result of the study should be noted. It was observed by the experimenter that the impaired vision participants leaned forward to bring their eyes closer to the screen. While this enlarged the apparent size of the letters to these participants, the preceding data analysis illustrates that this did not negate readability differences amongst the various levels of font size. What this observation does imply is that persons with visual impairments need to be allowed to adjust their reading distance in order for the above readability to be demonstrated in practice. Consequently, they should be afforded unrestricted access between their eyes and the monitor.

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5.0 SUMMARY AND IMPACT

Redundant or useless research benefits no one and since the direct application of scientific data to concrete problems of humankind is the major goal of engineering, this study has been designed to have a real impact on humankind's scientific knowledge. With the large growth in the use of computers in everyday life, this study is intended to contribute to the general knowledge base for future reference by researchers who may develop a national standard, configure computer interfaces, or design a software product intended to be used by the visually impaired population.

5.1 Summary of Findings

The conclusions of this thesis research are strictly for the Helvetica sans-serif, proportional-width font type. Additionally, the conclusions that are drawn from the data of the unimpaired vision group is somewhat more generalizable than the impaired vision group because of the greater homogeneity of the visual capabilities found in that group. But the conclusions drawn from the impaired vision group data must be considered more carefully. The finding in this study that negative polarity is worse for impaired vision readers contradicts most previous (though somewhat limited) research in this area and may cast some doubt on how generalizable the data from this sample of impaired vision participants is. Furthermore, as was discussed in Section 2, there is a high degree of variability in reading performance for people with impaired vision. In the *Psychophysics of Reading* series, Legge et al. have found it difficult to account for more than 60-70% of peak reading rate variance by objective measures. Thus, conclusions drawn from this experiment should be considered carefully and not as concrete, all-encompassing guidelines that will work for all readers with impaired vision, for all applications, in all conditions.

With these caveats in mind, several conclusions have been drawn from this experiment. The most important of which is that alterations to electronic text can be made to improve readability for persons with low vision, while at the same time leaving the reading performance of the unimpaired vision population unaffected. At least for the factors and the ranges used in this experiment, this means that a large range of font sizes, either contrast polarity, or a wide range of contrasts can be considered for which reading can be improved for the visually impaired without harming the reading of users with no vision loss.

For character size, 12 and 14 point font sizes were found to be inadequate sizes for the visually impaired population. In general, 18 and 30 point font sizes were equal to each other and to the 24 point font size, but for some interactions these two were found to produce longer response times and higher error rates. Specifically, the two four factor interactions and the three factor interactions for font size, polarity, and contrast show that the 18 point font condition was equal across all polarity and contrast conditions except for the negative polarity, 3:1 (lowest) contrast condition. For 30 point font size, positive polarity, and the 18:1 (highest) contrast condition, it was found that word error rates were significantly higher than other error rates for this combination of size, polarity, and contrast. Thus, a 24 point font size is recommended.

Unlike previous research, this experiment found that positive polarity was preferred by the visually impaired. It is not known exactly why this occurred, though methodology differences and impaired vision participant sampling could be possible explanations. It is probable that this discrepancy is a result of polarity's interaction with small font sizes. For this reason, it is recommended that for font sizes of 18 points and below positive polarity be used. For 24 and 30 point sizes either polarity is satisfactory, though negative polarity has been shown to be favored by some impaired vision readers in previous research (Legge et al., 1985b; Rubin and Legge, 1989).

Contrast by itself had no significance for either vision group. However, contrast did significantly interact with both font size and polarity. If font sizes of 18 points or below are used, it is recommended that contrasts of 18:1 be used for either polarity and that this is critically important if negative polarity is used.

Finally, resultant from the observation that low vision readers tend to sit closer to the screen than those without visual impairment, there should be no physical barrier placed in front of the monitor that would restrict the approach of the reader's eyes toward the screen. For example, barriers might include a transparent partition in front of the monitor or a deep desk that causes a wide separation of the eyes and the monitor.

5.2 Projected Data Use

It is desired that the data generated in this experiment will be used in the future to design and construct a software add-on for personal computers and computer terminals that are used in public locations. These data, in conjunction with data generated from future research, should be used to develop this software so that it can easily be installed on publicly accessed terminals in order to allow individuals with low vision easier, and hopefully, equal access to computers.

A secondary use could be to take the information obtained from this and future research and develop a supplemental ANSI/HFES standard for VDT workstations that would address the particular needs of the visually impaired computer user.

5.3 Future Research Possibilities

To make the vision of this software add-on and the supplemental national standard possible, further research into the display characteristics that influence readability and legibility for the visually impaired will need to be undertaken. Such characteristics as font type, screen luminance, ambient illumination, the use of color, leading (between line spacing), and anti-glare treatments, will need to be studied.

Another area for research is into what might have caused the different polarity effects in this study from previous research and anecdotal sources. As was suggested in Section 4, one possible reason for this may be methodological differences. In Rubin and Legge (1989) contrast was changed by altering background luminance, while in this thesis experiment foreground luminance was altered. Also, there is the issue of perceived versus physical contrast. Perhaps as a result of the different methodologies or due to other unidentified factors, perceived contrast may be different for the two polarities. Wickens, Gordon, and Liu (1998) report that contrast sensitivities are higher for positive polarity (“negative contrast”) than for negative polarity (“positive contrast”), attributing this difference to “certain asymmetries in the visual processing system,” but offer no further clue as to what these asymmetries might be or how they can be mitigated. However, it is thought that the polarity discrepancy may be the result of interactive effects, most noticeably with font size, but possibly also with contrast. Future research could better evaluate the possible existence and influence of such interrelationships.

Finally, the trade-off between increasing character size and the corresponding reduction in the amount of text that can be displayed on a monitor needs to be considered more fully. In this experiment the entire passage was shown on the screen. While this research has determined that a size of 24 points is needed for good reading performance for people with visual impairments, this value is offered without consideration for how it would impact the usability of software. Increased search and navigation times, disjointed and confusing appearances, and perhaps the necessity to place key information off the screen are some of the difficulties that increasing the font size may cause. Future research should be devised to address this issue so the needs of the visually impaired population can be served better.

5.4 Contributions

This study contributes to the library of scientific knowledge by focusing on a field that has been largely overlooked -- the needs of visually impaired users with respect to computer displays. This study intended to help the visually impaired access information via computer displays, especially computers located at public locations. Designing accessibility into engineered products and systems not only should be done for ethical reasons, but it will help to comply with accessibility requirements of the Americans with Disabilities Act.

As Griffith states in his 1990 article, "there is reason to hope that the benefits of research into human factors issues of people with visual impairments will also extend to the sighted user." It is hoped that this research will help both the blind members of the society as well as augment the knowledge base for those with unimpaired vision. However, Lin and Williges (1995) caution that any design which is considered to aid one group of users may hinder access to another population and consequently must be tested empirically by all user populations that will eventually use the product. This research thesis has shown that not only can alterations in design help the disabled, but that these changes can be made in such a way that the larger user population is not significantly affected.

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APPENDIX A:

Informed Consent Form

Title of Project: Access to CRT Displays by the Visually Impaired

Principle Investigator: Aaron Bangor

I. THE PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study about visual display quality. This study involves experimentation for the purpose of measuring display readability for Cathode Ray Tube (CRT) visual displays. The ultimate goal is to determine what display characteristics need to be modified to accommodate persons with low vision.

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 seated at a visual display terminal workstation and asked to view a CRT monitor. Paragraphs of text information will be presented on the monitor and you will be asked to read the information and identify the word that is out of context. You will see 120 of these paragraphs.

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

1) you have a visual acuity of 20/30 or better if you are in the unimpaired vision group
2) be visually impaired if you are in the impaired vision group (i.e. legally blind or have some other disability that limits your ability to read computer text)
2) you are free from ocular (eye) diseases if you are in the unimpaired vision group;
3) you are between 18 and 45 years of age.
4) you are a native speaker of English

III. RISKS OF THIS PROJECT

I understand that I am not exposing myself to any additional risk by participating in this study. I have used computers before and have experienced no unusual problems with them.

IV BENEFITS OF THIS PROJECT

Your participation in this experiment will provide information regarding what display parameters can be changed to better allow people with visual impairments to read the screen. No guarantee of benefits has been made to encourage you to participate. You may receive a hard copy summary of this research upon its completion by leaving a self-addressed envelope with the investigator or a soft copy summary if you leave your Email address and a preferred format (e.g. ASCII, .pdf, Word, etc.).

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 thesis without your written consent. The information you provide will have your name removed and only a subject number will identify you during analyses and any written reports of the research.

VI COMPENSATION

For participation in this project you will receive five dollars ($5) per hour. For any partial hour you contribute, you will be paid for the entire hour.

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 vision excludes you from both vision groups
2) you are not between the ages of 18 and 45 years.
3) you are not a native speaker of English

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 am between the ages of 18 and 45 years and am a native speaker of English. If I am part of the unimpaired vision group, I have never had any ocular disease to my knowledge.

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, Thesis Committee Chair - 231-8748; bobb@vt.edu
H. T. Hurd, IRB Chair Research Division - 231-9359

APPENDIX B:

Participant #:______

Demographic Data Survey

Supplemental Data Survey

What is your age? ______ years, ______ months

What is your gender? _____ Female _____ Male

What would you say your computer experience is?

___ Over four hours a day

___ At least one hour a day, but less than four hours

___ Once a day, but less than an hour a day

___ Every few (3 to 4) days for more than an hour on that day

___ Every few (3 to 4) days for under an hour on that day

___ At least once a week for more than an hour on that day

___ At least once a week for under an hour on that day

___ A few times a month

___ Don't regularly use computers but are skilled with them

What is your education level?

___ Completion of High School

___ Completion of 1 to 3 Years of College

___ Completion of College

___ Completion of Master's Degree

___ Completion of Doctorate Degree

APPENDIX C:

Instructions for the Participant

First, get comfortable at the computer terminal, adjust the seat, monitor, and keyboard to your liking. Don't worry about if you're sitting properly or not, just sit like you normally do at a computer.

The pattern that's on the screen now is what you will see when the screen doesn't have any words. It's sort of a test pattern like on your TV when the station goes out.

To begin a testing trial, simply press the mouse button ONCE. When you release the button, a few sentences will be shown on the screen. What you need to do is read the sentences in order and when you have completed reading the whole passage, figure out which word in them was out of context.

When you think you know which word is out of context, press the mouse's button again and tell the me what that word is. When you press the mouse button this second time, you should see the original test pattern come back on the screen.

When you feel comfortable enough to begin another trial, simply press the mouse button again. You will have to wait at least three seconds, however. At the end of these three seconds, the computer will beep to let you know that you can begin the next paragraph at any time.

When you begin the next paragraph, you might notice that the text has changed somewhat. The size, color, and brightness, of the letters might change for each new passage you will read. Regardless of the change, simply read the passage and identify the word that is out of context. If you are unable to read the particular combination of text size, brightness, or color, press the mouse button once and tell me that you could not read the words. Not being able to see the letters is a perfectly fine answer.

There will be 120 trials, but first there will be 18 practice paragraphs. The length of time the paragraph is on the screen is being measured, so be sure to take only the time you need and press the mouse button BEFORE you tell me the out of context word. If you have any questions you may ask them now, otherwise you may begin when you are ready.

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APPENDIX D:

Sample Reading Cards

NOTE: These cards are **NOT** actual size or contrast. They are presented here to help illustrate what the participants were shown and not for experimental use.

Oscar, a big white bear in the Lincoln Zoo, is photographed thousands of times each year. People like to look at him because he's such a beautiful and unusual bird.

12 point font
positive polarity
3: 1 contrast

Tommy got sick from the candy he ate yesterday and vowed he'd never eat another piece, but today he broke his vow by eating three pieces of cake after dinner.

12 point font
negative polarity
3:1 contrast

Our rugs went to the cleaners when we cleaned house for the holidays. Since they were so dirty, we were surprised to find such gayly colored hats with their return.

14 point font
negative polarity
7: 1 contrast

When we saw curtains at the windows and children playing in the yard of the house which had been vacant for years, we knew someone had finally burned the place.

18 point font
positive polarity
7:1 contrast

1

Betty was being married and her grandmother came many miles to attend the wedding. She was tired upon arriving, but said she didn't want to be absent from the funeral.

18 point font
negative polarity
3:1 contrast

Before he finished painting Mr. Collins' new country house, the painter quit working and left town, so Mr. Collins had to get a new cook to finish the job.

24 point
positive polarity
18:1 contrast

Martha needed a new dress, so Mother promised to take her downtown the next Saturday. They planned to attend the sale at the hat shop where they could buy it.

24 point font
negative polarity
18:1 contrast

Jack and Bill went after axes so they could help father chop down some small trees in the backyard. They each selected a sharp pencil to do their work.

30 point font
positive polarity
18:1 contrast

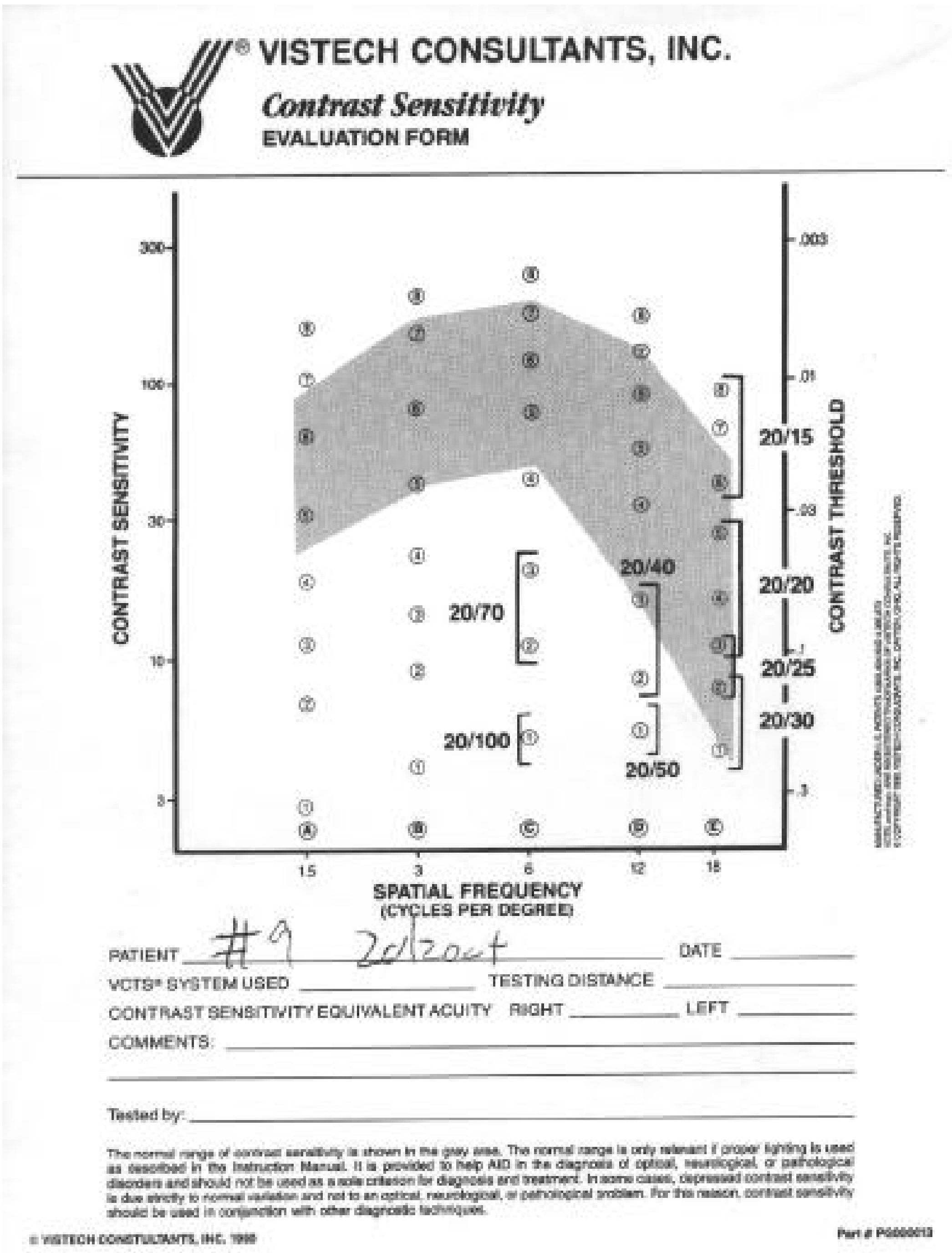
1

APPENDIX E:

Contrast Sensitivities of the Participants

NOTE: The shaded region represents the expected range for unimpaired vision.

Participant 9

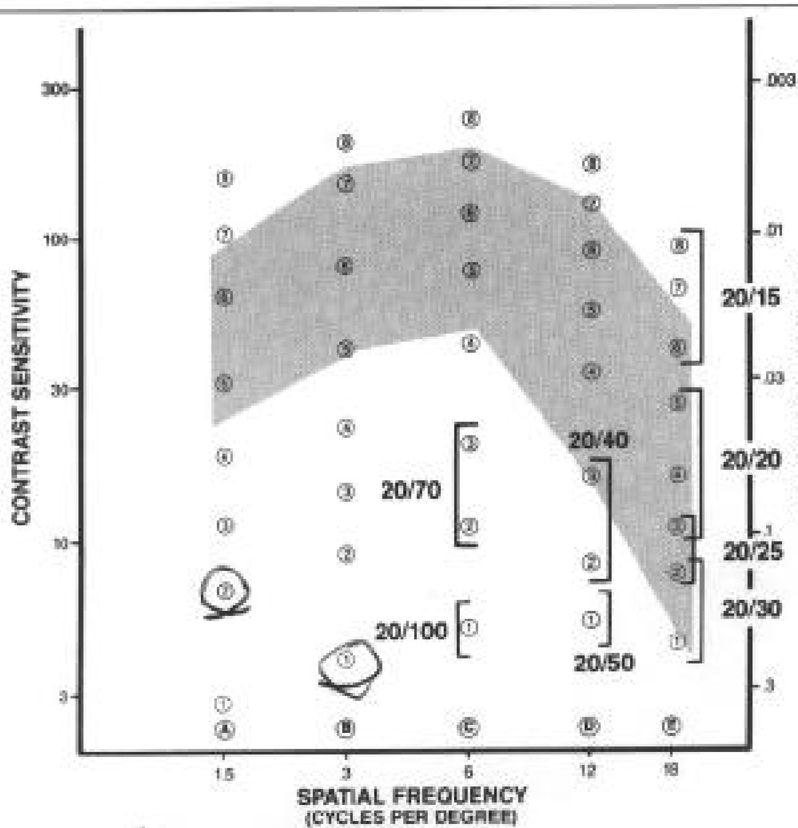


Participant 10

® VISTECH CONSULTANTS, INC.

Contrast Sensitivity

EVALUATION FORM



PATIENT #10 20/200 DATE ____________

VCTS® SYSTEM USED ____________ TESTING DISTANCE ____________

CONTRAST SENSITIVITY EQUIVALENT ACUITY RIGHT ____________ LEFT ____________

COMMENTS: ____________

Tested by: ____________

The normal range of contrast sensitivity is shown in the gray area. The normal range is only relevant if proper lighting is used as described in the Instruction Manual. It is provided to help AID in the diagnosis of optical, neurological, or pathological disorders and should not be used as a sole criterion for diagnosis and treatment. In some cases, depressed contrast sensitivity is due strictly to normal variation and not to an optical, neurological, or pathological problem. For this reason, contrast sensitivity should be used in conjunction with other diagnostic techniques.

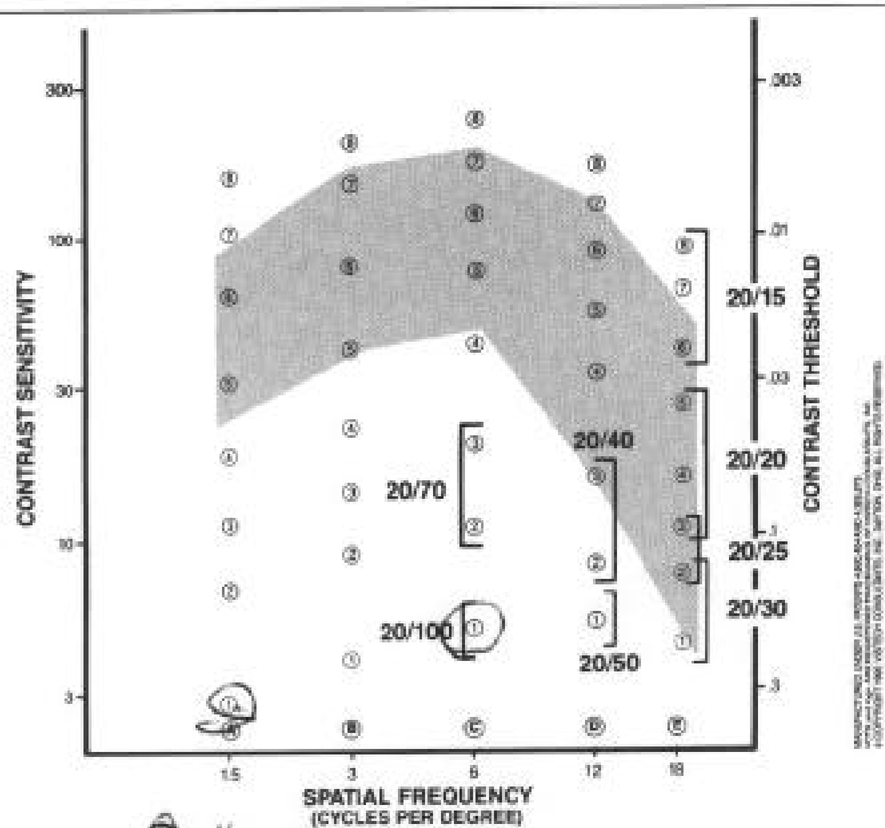
Part # FG900013

Participant 13

VISTECH CONSULTANTS, INC.

Contrast Sensitivity

EVALUATION FORM



PATIENT B #13 20/200+ DATE ________

VCTS® SYSTEM USED ________ TESTING DISTANCE ________

CONTRAST SENSITIVITY EQUIVALENT ACUITY RIGHT ________ LEFT ________

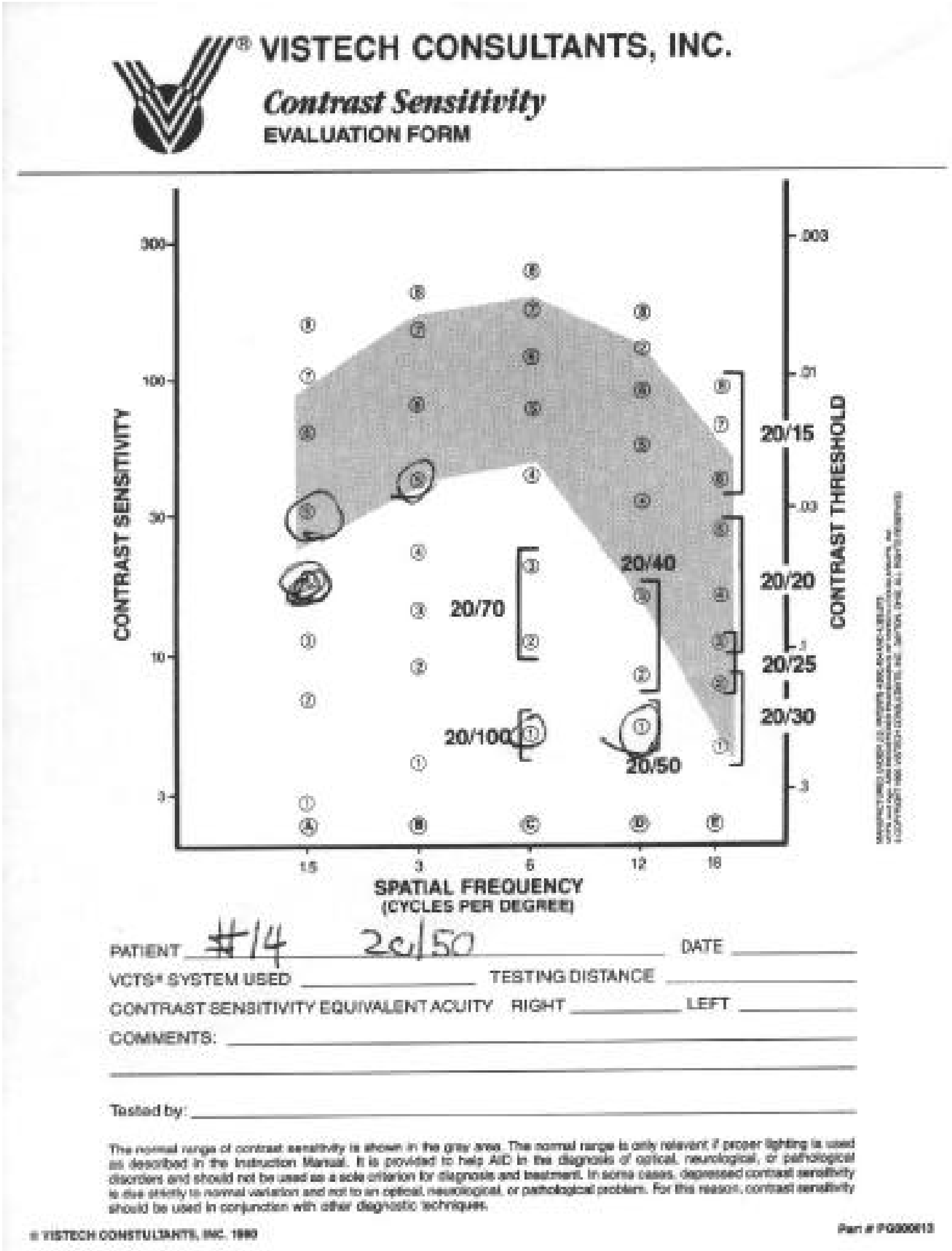
COMMENTS: ________

Tested by: ________

The normal range of contrast sensitivity is shown in the gray area. The normal range is only relevant if proper lighting is used as described in the Instruction Manual. It is provided to help AID in the diagnosis of optical, neurological, or pathological disorders and should not be used as a sole criterion for diagnosis and treatment. In some cases, depressed contrast sensitivity is due strictly to normal variation and not to an optical, neurological, or pathological problem. For this reason, contrast sensitivity should be used in conjunction with other diagnostic techniques.

Part # P [illegible]

Participant 14



VISTECH CONSULTANTS, INC.

Contrast Sensitivity

EVALUATION FORM

PATIENT #14 20/50 DATE ______

VCTS® SYSTEM USED ______ TESTING DISTANCE ______

CONTRAST SENSITIVITY EQUIVALENT ACUITY RIGHT ______ LEFT ______

COMMENTS: ______

Tested by: ______

The normal range of contrast sensitivity is shown in the gray area. The normal range is only relevant if proper lighting is used as described in the Instruction Manual. It is provided to help AID in the diagnosis of optical, neurological, or pathological disorders and should not be used as a sole criterion for diagnosis and treatment. In some cases, depressed contrast sensitivity is due strictly to normal variation and not to an optical, neurological, or pathological problem. For this reason, contrast sensitivity should be used in conjunction with other diagnostic techniques.

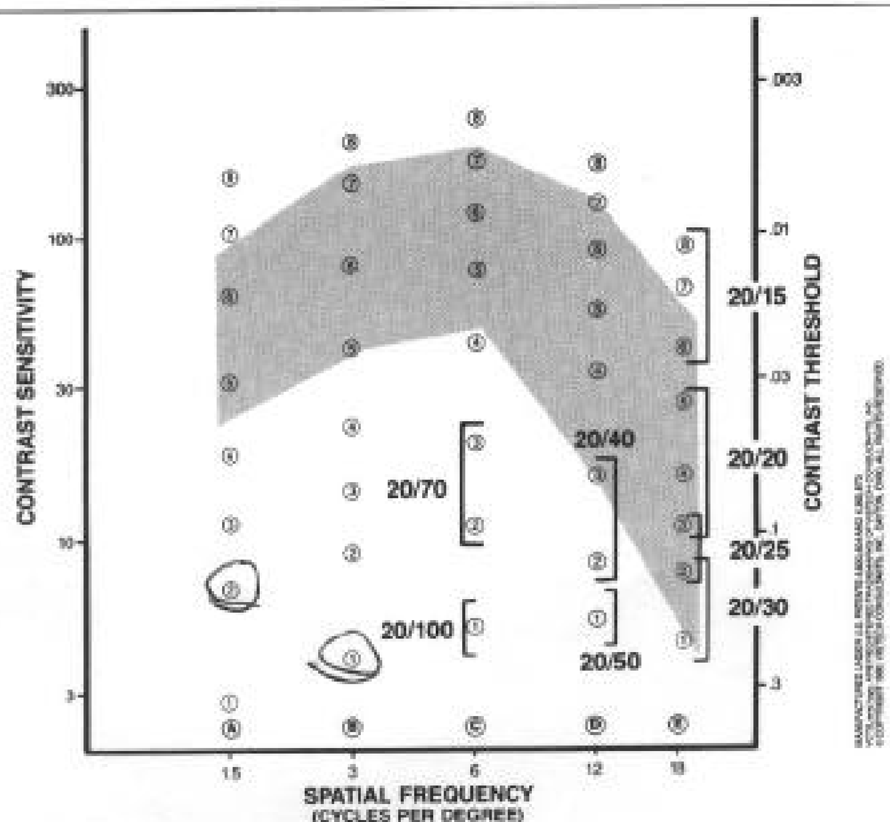
Part # PG000013

Participant 15

® VISTECH CONSULTANTS, INC.

Contrast Sensitivity

EVALUATION FORM



PATIENT #15 20/100 DATE ________

VCTS® SYSTEM USED ________ TESTING DISTANCE ________

CONTRAST SENSITIVITY EQUIVALENT ACUITY RIGHT ________ LEFT ________

COMMENTS: ________

Tested by: ________

The normal range of contrast sensitivity is shown in the gray area. The normal range is only relevant if proper lighting is used as described in the Instruction Manual. It is provided to help AID in the diagnosis of optical, neurological, or pathological disorders and should not be used as a sole criterion for diagnosis and treatment. In some cases, depressed contrast sensitivity is due strictly to normal variation and not to an optical, neurological, or pathological problem. For this reason, contrast sensitivity should be used in conjunction with other diagnostic techniques.

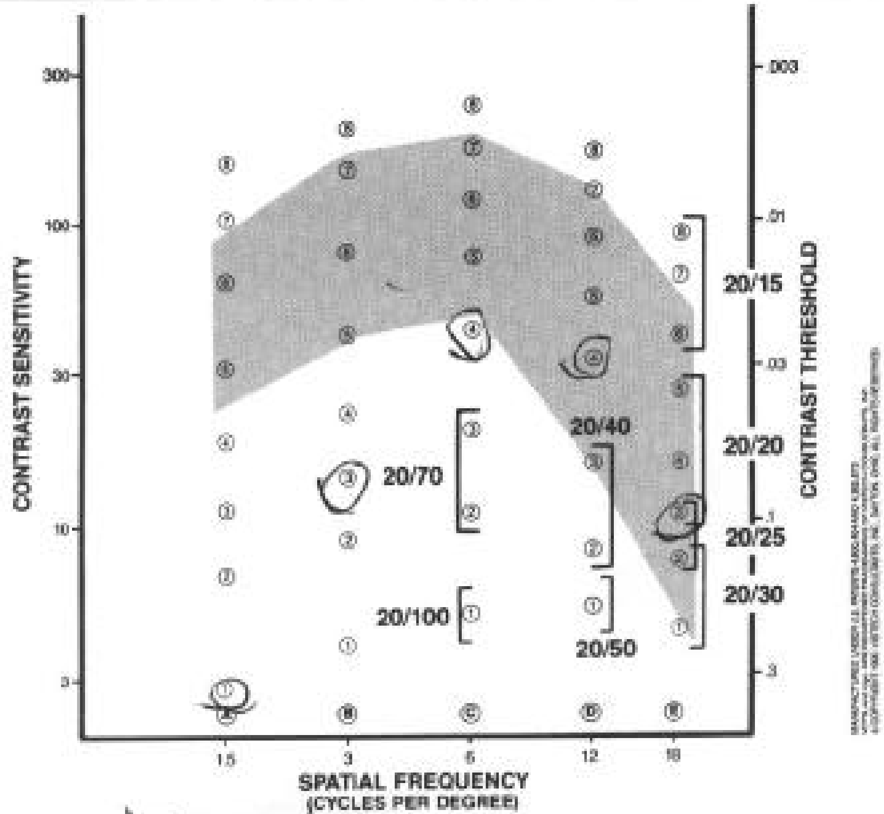
Part # P0000013

Participant 16

® VISTECH CONSULTANTS, INC.

Contrast Sensitivity

EVALUATION FORM



PATIENT #16 20/100 DATE ____________

VCTS® SYSTEM USED ____________ TESTING DISTANCE ____________

CONTRAST SENSITIVITY EQUIVALENT ACUITY RIGHT ____________ LEFT ____________

COMMENTS: ____________

Tested by: ____________

The normal range of contrast sensitivity is shown in the gray area. The normal range is only relevant if proper lighting is used as described in the Instruction Manual. It is provided to help AID in the diagnosis of optical, neurological, or pathological disorders and should not be used as a sole criterion for diagnosis and treatment. In some cases, depressed contrast sensitivity is due strictly to normal variation and not to an optical, neurological, or pathological problem. For this reason, contrast sensitivity should be used in conjunction with other diagnostic techniques.

Part # PG900813

Vita

Aaron Bangor was born on August 2, 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 fields of Industrial and Systems Engineering and Economics, receiving a Bachelor of Science and Bachelor of Arts degree, respectively, in May of 1996. During this time, Aaron joined Alpha Pi Mu (the industrial engineering honor society) in December of 1993, published a research paper concerning *The Road to Serfdom*, and joined the Displays and Controls Laboratory as an undergraduate research assistant in May of 1995.

Aaron continued at Virginia Tech in the Fall of 1996 in pursuit of a Master of Science degree, specializing in Human Factors in the Department of Industrial and Systems Engineering, where he has continued as a graduate research assistant in the Displays and Controls Laboratory.