

**THE EFFECTS OF LUMINANCE CONTRAST, RASTER MODULATION,  
AND AMBIENT ILLUMINATION ON TEXT READABILITY  
AND SUBJECTIVE IMAGE QUALITY**

by

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in

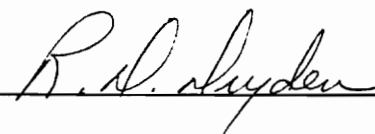
**Industrial and Systems Engineering**

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Committee Chairman: Robert J. Beaton  
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**(ABSTRACT)**

This thesis examined the effects of luminance contrast, raster modulation, and ambient illumination on readability and image quality of text presented on a CRT display. Participants read a Tinker Speed of Reading text passage on the monitor and then responded when they found the out-of-context word in the passage. Correct responses and response times were recorded. Participants also rated the image quality of the monitor by selecting a number between one (worst imaginable) and nine (best imaginable).

An ANOVA revealed that luminance contrast significantly affected errors. It is suggested that luminance contrasts of 7:1 be used to maintain low error rates. None of the independent variables affected the time required to read the Tinker passages. However, luminance contrast, raster modulation, and illumination significantly affected the subjective quality ratings. Participants rated the 3:1 luminance contrast,

the 1.2 RAR, and the 1000 lux ambient illumination conditions as possessing the lowest image quality.

From this research, it can be concluded that 7:1 is the preferred contrast ratio. This conclusion is based upon the findings that the 3:1 and 7:1 luminance contrast conditions produced the fewest errors and the 5:1 and 7:1 luminance contrast conditions produced the highest subjective image quality ratings. This recommendation holds over a RAR range of 0.8 to 1.2 and an ambient illumination range of 10 to 100 lux. High illumination levels would require special attention due to the low image quality ratings for the 7:1/1000 lux interaction.

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## TABLE OF CONTENTS

INTRODUCTION . . . . .	1
REVIEW OF LITERATURE . . . . .	3
Luminance Contrast . . . . .	3
Summary of Luminance Contrast . . . . .	11
Raster Modulation . . . . .	13
Resolution . . . . .	18
Addressability . . . . .	18
Resolution/Addressability Ratio . . . . .	18
Ambient Illumination . . . . .	20
Summary of Literature Review . . . . .	21
Research Goals . . . . .	23
METHOD . . . . .	24
Participants . . . . .	24
Equipment . . . . .	24
Experimental Conditions . . . . .	25
Task Description . . . . .	25
Experimental Design . . . . .	28
Dependent Variables . . . . .	30
Independent Variables . . . . .	30
Luminance Contrast . . . . .	31
Resolution/Addressability Ratio . . . . .	31
Ambient Illumination . . . . .	31
RESULTS . . . . .	32
Error Rate . . . . .	32
Reaction Time . . . . .	37

Subjective Ratings . . . . .	37
DISCUSSION . . . . .	51
CONCLUSIONS . . . . .	54
REFERENCES . . . . .	56
APPENDIX A . . . . .	61
VITA . . . . .	64

## LIST OF FIGURES

Figure 1. Obtained and Extrapolated Accuracy Values . . . . .	5
Figure 2. Obtained and Extrapolated Symbol Identification Rates . . . . .	6
Figure 3. Spot width profile . . . . .	14
Figure 4. Experimental Design . . . . .	29
Figure 5. Luminance contrast main effect on error rate . . . . .	34
Figure 6. Luminance Contrast and RAR error rate interaction. . . . .	36
Figure 7. Luminance Contrast and RAR interaction on subjective rating . . . . .	40
Figure 8. Luminance contrast main effect on subjective ratings . . . . .	41
Figure 9. Resolution/Addressability ratio main effect on subjective ratings . . . . .	43
Figure 10. Illumination main effect on subjective ratings . . . . .	46
Figure 11. Illumination and luminance contrast interaction on subjective ratings . . . . .	48

## LIST OF TABLES

TABLE 1. Luminance Contrast Standards . . . . .	8
TABLE 2. Summary of Luminance Contrast Literature . . . . .	12
TABLE 3. Ambient Illumination Standards . . . . .	22
TABLE 4. ANOVA Summary Table for Error Rate . . . . .	33
TABLE 5. Newman-Keuls Results for Luminance Contrast and Error Rate . . . . .	35
TABLE 6. ANOVA Summary Table for Reaction Time . . . . .	38
TABLE 7. ANOVA Summary Table for Subjective Rating . . . . .	39
TABLE 8. Newman-Keuls Results for Luminance Contrast and Subjective Rating . . . . .	42
TABLE 9. Newman-Keuls Results for Resolution/Addressability Ratio . . . . .	45
TABLE 10. Newman-Keuls Results for Illumination and Subjective Rating . . . . .	47
TABLE 11. Newman-Keuls results for illumination and luminance contrast interaction and subjective rating . . . . .	49

## INTRODUCTION

Visual Display Terminals (VDTs) have been in use for several decades, and their numbers are increasing rapidly. It is estimated that there will be more than 40 million VDTs in the workplace by the year 2000 (Giuliano, 1982; Mansfield, 1985). With this pervasive use of display technology, one can see the need for human factors research in visual display design. As computers become more involved in daily tasks, visual display research becomes ever more important (Nagy and Sanchez, 1992). Travis, Bowles, Seton, and Peppe (1990) add that the increasing availability of color graphics displays makes visual display design more complex.

The primary use of VDT's is the presentation of text. Today, VDTs are the primary medium through which humans and computers interact. Currently, people read books and newspapers from VDTs. In fact, *Electronic Villages*, which are making this new technology possible, are being developed in several cities around the United States. Because of this widespread use of display technology, it is important to optimize the legibility and readability of VDTs.

A reader is better able to devote his attention to understanding the information contained in a text when that text has high legibility (Van Nes, 1986). Unfortunately, little information exists on how to display information to optimize the user's performance and satisfaction.

The widespread use of VDTs has led to the development of ergonomic guidelines for VDT workstations (ANSI/HFS 100,1988; ISO 9241-3). However, there are those who do not believe that specific recommendations are necessary. Instead, they contend that display designers require only a set of general principles (Travis, et al., 1990). Interest in the human factors of VDT workstation design began in the United States and the United Kingdom almost 40 years ago, mainly concerning radar operator consoles (Zhu and Wu, 1990). But, the standardization of these workstations did not begin until 20 years later in West Germany (Zhu and Wu, 1990). Since then, numerous technical standards and guidelines on VDT ergonomics have been published (see, Helander and Rupp, 1984; Rupp, 1981).

A primary goal in engineering a visual display system is to "attain sufficient image quality to maximize the transfer of information from the display to the human operator" (Murch and Beaton, 1988). Numerous factors contribute to the overall image quality of VDTs. Among these factors are luminance contrast, raster modulation, and ambient illumination. The purpose of this thesis work is to examine the effects of these three factors on observer's ability to read text passages. Although these factors are known to affect the visual detection of targets presented on VDTs, the important contribution of this work is the investigation of the effects on text.

## REVIEW OF LITERATURE

### *Luminance Contrast*

The luminance contrast threshold refers to the ability of the human visual system to detect differences in luminance between an object and its immediate background. As Van Nes (1984) states, there are perceptual requirements in reading performance that affect display technology. In reading symbols or words from VDTs, one perceptual requirement involves the luminance contrast of the text. According to the ANSI/HFS100-1988 standard, character luminance modulation "shall be equal to or greater than 0.5 (contrast ratio of 3:1). A luminance modulation of at least 0.75 (contrast ratio of 7:1) is preferred." These values include the effects of ambient illumination on contrast. The various measures of luminance contrast are defined as,

$$\text{Luminance Modulation, } M = (L_{\max} - L_{\min}) / (L_{\max} + L_{\min}),$$

$$\text{Contrast Ratio, } CR = L_{\max} / L_{\min}, \text{ and}$$

$$\text{Contrast, } C = (L_{\max} - L_{\min}) / L_{\min}.$$

in which  $L_{\max}$  is the higher luminance and  $L_{\min}$  is the lower luminance.

Crook, Hanson, and Weisz (1959) and Shurtleff and Wuersch (1979) are cited as the technical justification for the ANSI/HFS 100-1988 requirement on luminance contrast. These studies presented symbol sets to subjects who were timed for reading speed. Shurtleff and Wuersch varied character size and contrast ratio in the design and selection of group display systems for command and control facilities.

They established three levels of criticality for these control centers in determining the parameters of character size and contrast ratio. They found that maximum speed and accuracy were achieved when symbols subtended at least 20 arcmin with a contrast ratio of 8:1. Smaller symbols (15 arcmin) required at least a contrast ratio of 9:1 to satisfy a "critical" level of performance (see Figures 1 and 2). The ANSI/HFS 100-1988 requirement for small letters was derived from the Crook, Hanson, and Weisz (1959) study.

Snyder (1986) states that the critical contrast ratio is at least 3:1. He also states that small characters should have a higher ratio than 3:1, and a ratio of at least 7:1 is preferred for all characters, regardless of size. Snyder and Maddox (1978) found that a luminance modulation of 0.75 (CR 7:1) for contextual displays and a luminance modulation of 0.9 (CR 19:1) or greater for noncontextual displays was optimal. Shurtleff (1980) states that a contrast ratio of 10:1 has become a generally accepted industrial standard. Meister notes that the minimum contrast ratio is a function of the absolute luminance level and the visual size of the symbols. He states that if the designer provides a contrast of at least 18:1, wide variations in stroke width and symbol height are possible over a range of luminance from 0.1 fL to 50 fL. Meister cites industry-wide standards for luminance contrasts. Contrast ratios of 4:1 to as high as 15:1 are found in the literature of various organizations, depending on the ambient illumination and display luminance.

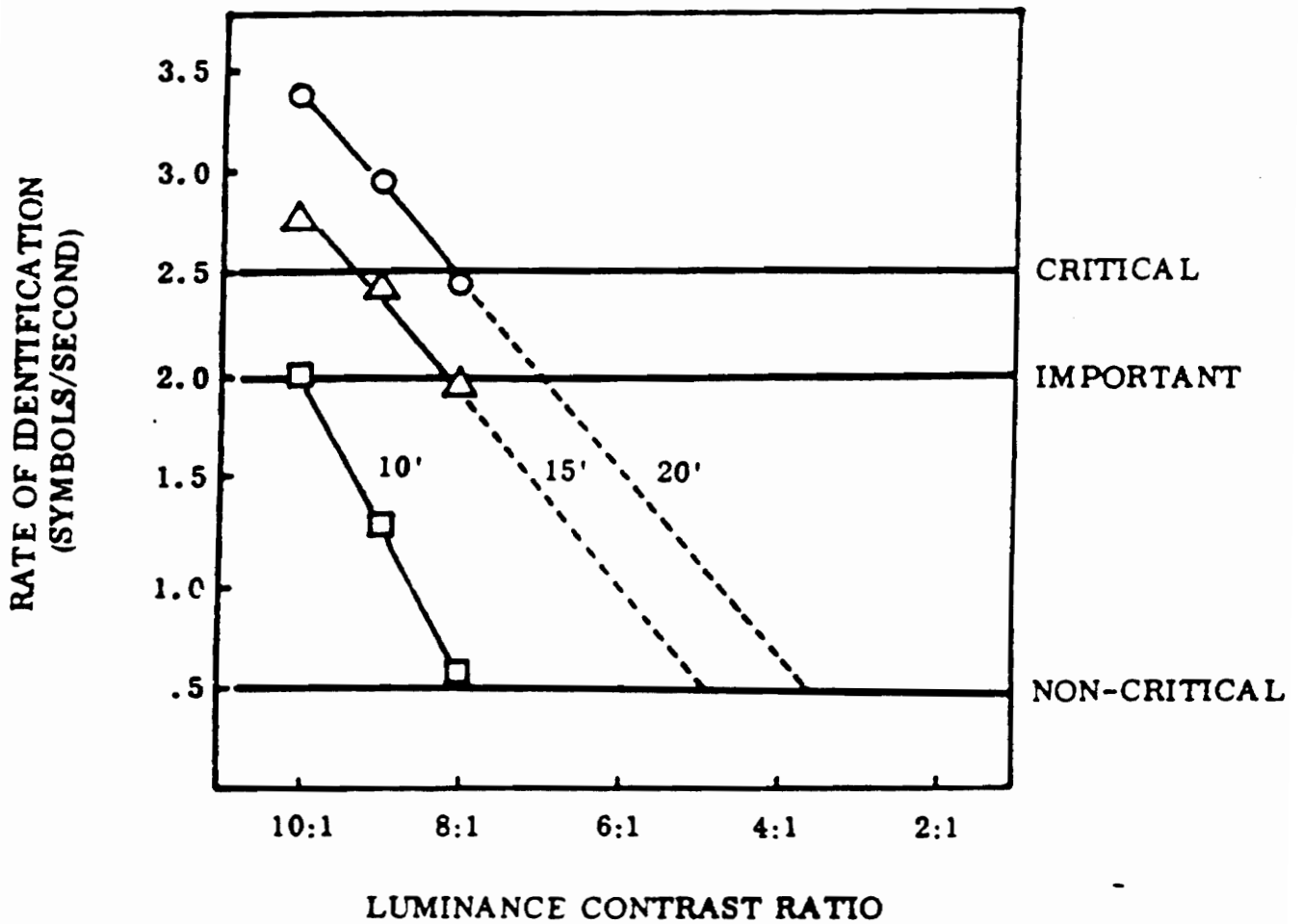


Figure 1. Obtained and Extrapolated Accuracy Values  
Adapted from Shurtleff and Wuersch (1979)

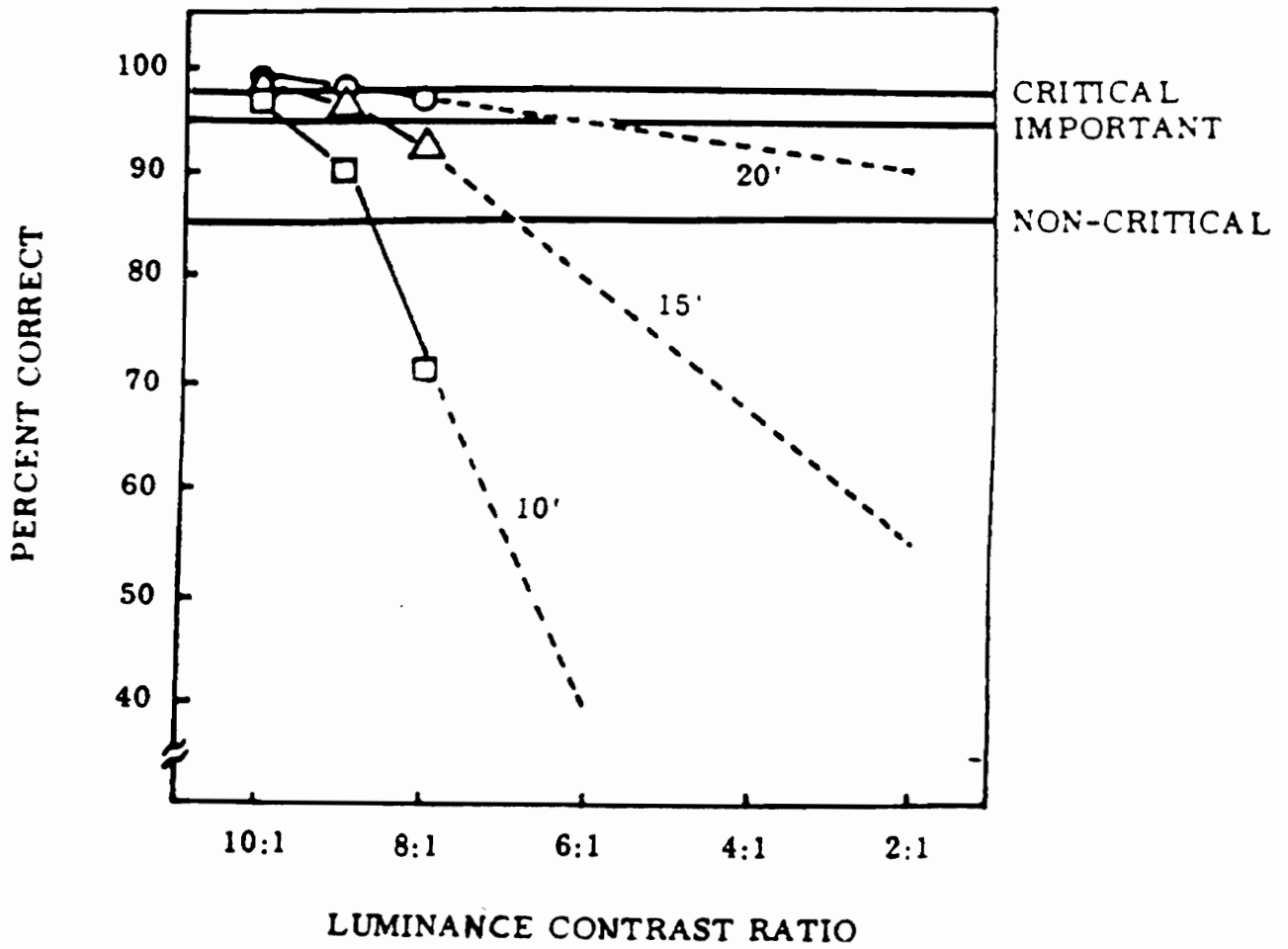


Figure 2. Obtained and Extrapolated Symbol Identification Rates.  
Adapted from Shurtleff and Wuersch (1979)

TUB (Technical University, Berlin) recommends a ratio of 5:1 to 10:1 with a background of at least 20 cd/m<sup>2</sup>. DIN recommends a minimum ratio of 3:1, while 6:1 to 10:1 is preferred and a maximum contrast of 15:1 is satisfactory. The Defense and Civil Institute of Environmental Medicine (DCIEM) uses a minimum ratio of 4:1 in an ambient light of 75 to 100 ft. candles. VDT ("The VDT Manual") recommends 3:1 as a minimum ratio, and 8:1 to 10:1 as an optimum ratio with a background luminance of between 15 and 20 cd/m<sup>2</sup>. Table 1 shows other luminance contrast recommendations (Helander and Rupp, 1984).

Zhu and Wu (1990) investigated character luminance and background screen luminance, and they found that optimal contrast varies as a function of screen luminance. They tested three luminance levels (20, 30, 40 cd/m<sup>2</sup>) and seven contrast ratios (3:1, 5:1, 7:1, 9:1, 11:1, 13:1, 15:1). Their results confirm that lower contrasts are optimal for high VDT screen luminance; and, conversely a higher contrast is ideal for low VDT screen luminance. Zhu and Wu conclude that optimal contrast range should not be thought of as a fixed parameter since it covaries with screen luminance. Shurtleff (1980) says a range is recommended because a minimum contrast is difficult to arrive at due to the various techniques used. Shurtleff recommends the range should be from 2:1 to 18:1. These studies have led to the conclusion that optimal contrast appears to be better defined as a range of contrast rather than as a single value.

TABLE 1. Luminance Contrast Standards

<b>ISO 9241 Part 3</b> ISO 9241 (1990): Ergonomic Requirements for Office Work with Visual Display Terminals (VDTs). Part 3: Visual Display Requirements.	<b>Minimum M 0.5 (CR 3:1)</b>
<b>MIL STD 1472-C</b> Military standard, human engineering design criteria for military systems, equipment and facilities, US Dept. of Defense.	<b>Minimum M 0.6 (CR 4:1)</b>
<b>DIN 66234</b> Characteristic values for the adaptation of workstations with fluorescent screens to humans, Parts 1 to 9. German DIN Association, 1981.	<b>Minimum M 0.5 (CR 3:1)</b>
<b>British HSE</b> Visual display units, Health and Safety Series booklet. London: British Health and Safety Executive, 1983.	<b>Minimum M 0.6 (CR 4:1)</b>

Helander and Rupp (1984)

The above studies on luminance contrast differ from the requirements in the ANSI/HFS 100-1988 standard. This probably stems from the fact that the recommendations were based on data compiled from several different studies. Also, with one exception, the above sources used higher minimum contrast ratios than the ANSI/HFS 100-1988 standard.

Knoblauch, Arditi, and Szlyk (1991) state that the influence of contrast upon reading performance is important because: (1) text of a wide range of contrasts is encountered in real-world situations and (2) many ocular conditions lower the effective contrast of the reading stimulus. Furthermore, Knoblauch, et al. suggest that reading performance is best when luminance differences between text and background is maximal. However, some researchers have suggested that the contrast between text and its background can degrade operator's performance, especially when the luminance contrast was too high or too low (Rupp, 1981). The literature (see, e.g. Van Nes and Jacobs, 1981) suggests that reading depends only weakly on contrast for text of medium to high contrast, but it may rely more heavily on contrast at lower levels.

Legge, Rubin, and Luebker (1987) measured reading rate as a function of contrast and character size. For characters subtending 1 degree at a contrast of 0.96, subjects had high reading rates (300 words/min). Reading rates slowly declined as

contrast was reduced. But, below a contrast of 0.10, reading rates declined much more rapidly, thereby supporting the statement that reading may rely more heavily on contrast at lower levels. For smaller characters (subtending .25 degree), contrast played a much more critical role. They concluded that for a luminance modulation of 0.5 (CR 3:1), no appreciable increase in performance existed for a relatively large range of character size (15 arcmin to 720 arcmin).

Rogers, Spiker, and Cicinelli (1986) studied the effects of luminance, luminance contrast, and illumination on legibility. They found previous literature to be inconsistent for the following reasons: (1) confounding of luminance and luminance contrast, (2) widely different levels of luminance and luminance contrast, (3) diversity of display devices, symbol types, and experimental tasks, and (4) effects of ambient illumination on the observer's adaptive state. They conducted three studies: Study 1 investigated luminance contrast effects in low ambient illumination (dark adaptation), Study 2 investigated contrast effects in moderate illumination (1081 lux), and Study 3 investigated contrast effects under high illumination. In each study, subjects were required to state the position of the break in a Landolt ring symbol. In studies 1 and 2, they found that small contrast ratios (1.2:1, 1.5:1, and 2:1) are sufficient for maximizing detectability under low and moderate illumination conditions. Study 3 was conducted to investigate the independent and interactive effects of adaptation, contrast ratio, and display background luminance on detectability.

Study 3 required subjects to gaze into the adaptation field until they were instructed to turn to the CRT and identify the location of the break in the symbol. They found that all the main effects (adaptation luminance, contrast ratio, and background luminance) were significant, as well as their interactions. The overall conclusions reached were that the symbols luminance had no effect on display legibility in studies 1 and 2. Also in studies 1 and 2, the contrast ratio of symbol luminance to background luminance affected symbol detection. No significant improvements were found with contrast ratios over 4:1 (low ambient illumination) or 5:1 (moderate ambient illumination).

#### *Summary of Luminance Contrast*

A summary of the luminance contrast literature is presented in Table 2.

TABLE 2. Summary of Luminance Contrast Literature

<b>ANSI/HFS 100</b> American National Standards Institute, 1988.	$\geq 3:1$ 7:1 is preferred
<b>Shurtleff and Wuersch, 1979</b>	8:1 9:1 for small symbols
<b>Snyder, 1986</b>	at least 3:1 7:1 strongly preferred
<b>Snyder and Maddox, 1978</b>	7:1 for contextual displays 19:1 for noncontextual displays
<b>Shurtleff, 1980</b>	2:1 to 18:1
<b>TUB</b> Technical University, Berlin, 1973.	5:1 to 10:1
<b>DIN 66234</b> German DIN Association, 1981.	6:1 to 10:1 15:1 maximum
<b>DCIEM</b> Defense and Civil Institute of Environmental Medicine, December 1978.	4:1 minimum in an ambient light of 75 to 100 fc
<b>VDT</b> The VDT Manual, 1979.	3:1 minimum 8:1 to 10:1 optimum
<b>Zhu and Wu, 1990</b>	varies with screen luminance
<b>Knoblauch, Arditi, and Szlyk, 1991</b>	performance best when luminance differences between text and background is maximum
<b>Legge, Rubin, and Luebker, 1987</b>	characters subtending 1 degree at a contrast of 0.96 had high reading rates; below 0.10 reading rates declined rapidly

### *Raster Modulation*

According to the ANSI/HFS 100-1988 standard, raster modulation is a significant factor in image quality. Images reproduced on CRT display systems are produced by scanning an electron beam horizontally across a raster line, then stepping downward and repeating the scan along the next line. The spot spread function (Figure 3) defines the width of each raster line as the beam progresses along the raster. When adjacent lines are written within the integrating time of the eye, the luminance in the overlapping portions of the two lines produce a visual sensation equal to the sum of the overlapping of the two individual luminance (Farrell and Booth, 1984).

The ANSI/HFS 100-1988 standard for percent raster modulation and percent active area states that "for a CRT having a pixel (picture element) density of fewer than 30 pixels per degree perpendicular to the raster (at the design viewing distance), the luminance modulation in the direction perpendicular to adjacent lines **shall** be equal to, or less than, 20 percent when all lines and pixels are in their 'on' state. For displays having a luminance control, this requirement is to be met when the pixel luminance is at one half the maximum luminance" (ANSI/HFS 100-1988, p. 18). It is stated that a raster modulation greater than 20 percent interferes with legibility of the displayed image. When the raster modulation is measured photometrically with all

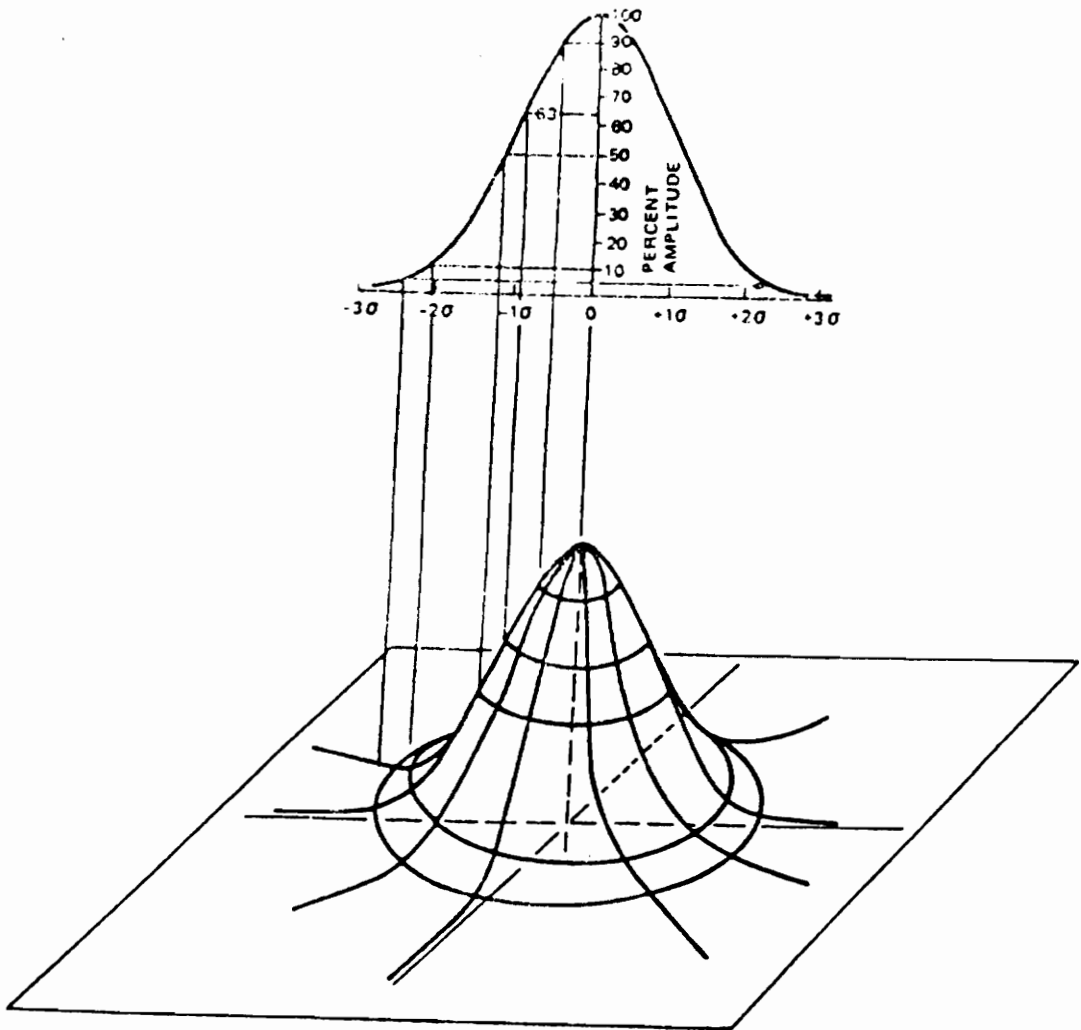


Figure 3. Spot width profile. (see Farrell and Booth, 1984)

of the rasters "on", the percent raster modulation can be calculated by combining the maximum measured luminance with the minimum measured luminance:

$$\text{Percent Raster Modulation} = 100 (L_{\max} - L_{\min}) / (L_{\max} + L_{\min})$$

According to Biberman (1973), if raster lines are not properly spaced, they can produce false imagery. Interaction of the signal in the raster line frequency with the frequencies present in the imagery causes the false imagery. Schade (1973) states that there are three factors affecting this problem: (1) the number of samples per image, (2) the signal-to-noise ratio per sample, and (3) the generation of spurious signals by the sampling process.

The TUB states that the "dot of a character should merge to create the impression of a line," and the DCIEM states that the percent active area should be 75% (Rupp, 1981). Rupp (1981) states that the percent active area does not appear to be an important factor unless the display is used under degraded conditions such as low contrast and low luminance. Under those degraded conditions, Rupp states that there is a relationship between legibility and percent active area up to about 30% active area. Rupp continues by stating that under typical viewing conditions, the percent active area appears to be more of a subjective than objective consideration.

"Image quality is a function of a number of factors. Most prominent among them are resolution and addressability. Those two factors are related to each other in the term 'raster modulation'" (ANSI/HFS 100-1988, p.18).

In their research on resolution and addressability, Murch and Beaton (1988) discuss two display criteria that underlie the design goal of maximizing the transfer of information from the display to the user. The first of the two criteria is the adjacent raster line (pixel) requirement. This requirement states that when an operator is at a normal viewing distance (46 cm), the raster structure of the display can not be detected by that operator. According to the authors, the adjacent raster line (pixel) requirement is intended to reduce the visible "noise" arising from the discrete picture elements of digital display systems. This "noise" contains no relevant information for an operator. Uniformly bright solid-filled areas and alphanumeric characters result when displays meet the adjacent raster line (pixel) requirement. Failure to meet the requirement results in visible raster modulation, which, according to Murch and Beaton, has a detrimental effect on "reading speed, visual search, and threshold detection of information component."

The second criterion is termed alternate raster line (pixel) requirement. This requirement states that individual lines (pixels) with an alternating on-off pattern must be visible to the operator from a normal viewing distance. The visibility of high

spatial frequency components is optimized when this requirement is met.

Adjacent and alternate criteria oppose each other in terms of favoring one, disfavoring the other. For example, increasing the displays addressability favors the adjacent raster line (pixel) requirement since the luminance contrast between adjoining raster lines is reduced. This advantage proves to be disadvantageous to the alternate raster line (pixel) requirement by reducing the detectability of individual lines within the on-off pattern. Similarly increasing resolution favors the alternate raster line (pixel) requirement because the smaller spot will increase the luminance contrast between pixels. However, this makes the raster structure visible when all the pixels are active.

To determine whether or not a display system meets the two criteria, the designer must first determine the modulation between adjacent and alternate raster lines (pixels) under various combinations of resolution/addressability ratio (RAR) values. The RAR value for the alternate criterion is equal to one-half of the RAR value for the adjacent criterion (see Murch and Beaton for calculations). The designer must determine the detectability of adjacent and alternate raster line (pixel) modulation by a human operator. The detectability is determined by use of the contrast sensitivity function (CSF). The CSF indicates the human visual capability to perceive the modulation between pixels on a raster display.

### *Resolution*

Resolution refers to the capability of a display to present fine detail. It is defined as the smallest discernable or measurable detail in a visual presentation. Resolution is measured as the width of a line drawn on the screen--the narrower the line, the higher the resolution. Thus, resolution is determined by the design of the CRT and is related to factors such as phosphor density, deflection fields, and electron-gun design (Murch, Virgin, and Beaton, 1985). Resolution can be indexed in a number of ways including lines per inch, line-spread function, MTF, and spot size. This study will use the line width at 50% of maximum luminance. In other words, resolution is defined as the width of a pixel at one-half the maximum luminance.

### *Addressability*

Addressability is the distance between raster lines scanned on a display or the distance between adjacent pixel sites (Murch, et al., 1985). Addressability is determined by the video controller logic used in the system. The display controller selects and addresses a specific point (pixel) or x,y coordinate. Addressability is defined as the peak-to-peak separation between adjacent lines (pixels).

### *Resolution/Addressability Ratio (RAR)*

The resolution/addressability ratio (RAR) was proposed by Murch, et al., (1985) to aid design decisions by incorporating both resolution and addressability into

one metric. Because resolution is determined by the design of the CRT and because addressability is determined by the video controller, these two display parameters are independent. However, according to Murch, et al., "certain relationships need to be maintained between them to produce high quality displays." For example, if resolution is greater than addressability, raster lines will not merge and the pixels will appear as separate dots. If resolution is less than addressability, successive lines will over-write adjacent lines producing artifacts (i.e., stripes and contours). Thus, the design goal is an RAR of around 1.0 for a monochrome CRT display with Gaussian-shaped pixels.

The following equation is used to determine RAR:

$$\text{Resolution/Addressability Ratio} = W/S$$

where  $W$  is the full width of a raster line (pixel) profile at one-half its maximum luminance and  $S$  is the peak-to-peak separation between adjacent raster lines (pixels). For example, a 48cm diagonal display with a height of 27.5cm and an addressability of 1024 lines has a peak-to-peak separation of  $27.5/1024 = 0.27$  mm/line. Assuming a 0.38 mm wide spot profile, the RAR value is 1.41.

The above equation often is used for evaluating displays over a range of resolution and addressability to determine the modulation between adjacent and alternate line (pixel) criteria.

*Ambient Illumination*

ANSI/HFS 100-1988 states that, "the ambient illumination **shall** be within a range that does not violate the image quality requirements stated in sections 6.1, 6.2, 6.3, and 6.4." (ANSI/HFS 100-1988, p. 11). The standard also states that in VDT workplaces, ambient illumination in the range of 200 to 500 lux normally is sufficient. Many investigators recommend 200 to 1000 lux for proper ambient illuminance (see Rupp, 1981). However, Snyder and Maddox (1978) recommend an ambient illuminance less than or equal to 125 lux for contextual displays, and less than or equal to 75 lux for noncontextual displays. Other recommended standards are shown in Table 3. In general, performance is found to be superior and modulation is enhanced with lower ambient illuminance levels than with higher illuminance levels (Burnette, 1976).

An important variable in ambient illumination research is the task used. Tasks requiring one to resolve fine detail require greater illumination. Thus, specifications should take into consideration the task to be performed in that environment. The display ergonomic standards shown in Table 3 confirm that the tasks to be performed affect the required illumination. The SNBOSH recommendations provide an ambient light environment that is satisfactory for many tasks and still permits a display contrast of about a 15:1 or more. This directive also states that additional lighting for source documentation may be used at the workstation. The U of L and DCIEM

recommendations are intended to provide adequate illumination for reading the source document and to follow general illumination recommendations for that kind of task. The ANSI/HFS 100-1988 standard on ambient illumination also states that task or local lighting may be needed for some demanding visual tasks. However, the illumination should be "sufficiently bright, uniform, and free from glare and flicker" (ANSI/HFS 100-1988, p. 11). Across the various ergonomic standards, it becomes obvious that there must be a compromise between the ambient illumination levels required to adequately read VDT screens and the higher levels required to read handwritten or pencil copy (Sanders and McCormick, 1987). Also, the use of proper displays and the use of glare filters can reduce the glare from local lighting sources.

Ambient illumination affects the visual performance by reducing displayed luminance contrast. Snyder and Maddox (1978) cited research that showed an ambient-to-display illuminance ratio of 10:1 was the point at which significant increases in the symbol-to-display background contrast ratio were required to compensate for increases in ambient illumination.

### *Summary of Literature Review*

The effects of luminance contrast, raster modulation, and ambient illumination on VDTs have been studied extensively in isolation and, to some extent, in select

TABLE 3. Ambient Illumination Standards

<b>TUB</b> Technical University, Berlin, 1973.	50 lux
<b>DIN 66234</b> Characteristic values for the adaptation of workstations with fluorescent screens to humans, Parts 1 to 9. German DIN Association, 1981.	300-500 lux for workstations with negative polarity displays 500 lux minimum for workstations with positive polarity 200 lux if display is tilted 20°
<b>U of L</b> University of London, 1978.	500 to 750 lux
<b>DCIEM</b> Defense and Civil Institute of Environmental Medicine; DCIEM Technical Report No. 78x46. December 1978	50 to 100 ft-c
<b>VDT</b> The VDT Manual, 1979.	300 to 500 lux
<b>SNBOSH</b> Swedish Board of Occupational Safety and Health Directive 136, 1979.	200 to 300 lux

Rupp (1981)

combinations (i.e., contrast and illumination; Rogers, Spiker, and Cicinelli, 1986). A lack of literature exists on the combined effects of all three factors. Since these factors are known to affect VDT operator performance, their combined influence should be examined.

Furthermore, many of the current display ergonomic standards for each factor stem from visual target detection studies. Because the primary use of VDTs is the display of text, the influence of the factors on readability needs to be examined.

### *Research Goals*

The major objective of this research is to determine the effects of the following on text readability:

- (1) luminance contrast
- (2) raster modulation
- (3) ambient illumination.

## METHOD

In this experiment, participants were asked to read text passages and to select the word from each passage that was out-of-context. These sentences appeared on a monochrome CRT and they varied in contrast and RAR. The ambient illumination of the room also was varied. The participants were timed on their task completion, evaluated on their response correctness, and asked to judge perceived image quality.

### *Participants*

Ten individuals, ranging from 22-26 years of age, with normal or corrected-to-normal vision from Virginia Polytechnic Institute and State University participated in the study, and they were paid \$5.00 for their participation. Before being asked to participate, each individual was screened for 20/20 near and far acuity and normal contrast sensitivity. The visual testing systems used were the VisiTech vision contrast test system and the Bausch and Lomb Master OrthoRater.

### *Equipment*

In the experiment, a Zenith 286-LP personal computer was used to control the conditions presented to the participants, as well as to record the data. An Arche 214 MH color CRT, with a 0.28 mm shadow-mask pitch, was used in this study. A Minolta Illuminometer was used to measure the ambient illumination of the room. Finally, because of the varying illumination and contrast levels, a glare filter was used.

### *Experimental Conditions*

Each participant received all the experimental conditions. Participants were seated 55 cm (21.5 in) from the computer screen. The computer screen was placed on a table in front of the participant. The mouse input device was placed next to the participant at a comfortable distance. To maintain a constant viewing distance, the participants were asked not to make any large head movements while performing the task.

### *Task Description*

Participants were asked to perform two tasks. One was a reading task, while the second was a subjective quality rating task. Participants received five practice trials to become familiar with these tasks. Also, before the practice trials, participants were instructed on how to use the mouse input device.

The Tinker Speed of Reading Test was developed by M.A. Tinker (1947) to study the effects of typographical and illumination variations on reading speed, and for measuring speed of sustained reading in situations where performance over a relatively long period of time is desirable (Tinker, 1955). This test was later modified by Carver (Feldman, 1972). Originally the test was constructed with two goals in mind: (1) a test that would measure reading speed without being confounded by difficulties in comprehension, and (2) a performance test that could be used for testing durations

of up to 30 minutes. This test has been used successfully in many visual display experiments (see, e.g. Ansley, 1991; Burnette, 1976; Downing, 1989; Hunter, 1988; Jorna, 1988; Poulton, 1969; Sayer, Sebok, and Snyder, 1990; Sebok, 1991; and Watkins, 1991).

The test consists of 500 short passages to measure reading time. Each passage contains one word, the "spoiler," that is clearly out-of-context in the passage. Subjects are required to read the paragraph and identify the spoiler word as quickly as possible. The time required to find the spoiler is a measure of reading speed. The following paragraph is an example of a Tinker passage (the spoiler word in this instance is "car"):

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

The Tinker passages were selected randomly and displayed in the center of the screen. The text was presented in mixed upper and lower case fonts that comply with ANSI (ANSI/HFS 100-1988) guidelines for size and spacing. Upon locating the spoiler word, the participant pressed the right button of the mouse device. Immediately after the button click, the words on the screen were replaced by blank outline blocks that enclosed the word positions in the Tinker paragraph. Using the

mouse device, the participants positioned the cursor inside the block that corresponded to the out of context word and depressed the mouse button. After the participant selected the block, the screen cleared and the following 9-point rating scale was displayed on the screen:

Best Imaginable (9)

Excellent (8)

Good (7)

OK (6)

Passable (5)

Marginal (4)

Poor (3)

Awful (2)

Worst Imaginable (1)

The nine-point scale has been used successfully in many studies (see Ansley, 1991; DeVilbiss, 1990; and Sebok, 1991). Each adjective corresponds to a number between 1 and 9, with 1 being "worst imaginable" and 9 being "best imaginable." To choose one of these adjectives, the subject used the mouse input device to highlight the desired word and then pressed the left button. After the subjective rating task, the word "READY" was displayed on the screen. When the participant was ready to begin the next trial, he or she pressed the left mouse button. Participants were instructed that, if needed, they may rest upon arriving at the "READY" screen. This

instruction prevented participants from taking a break after beginning a timed trial (when the Tinker passage is displayed). The instruction also prevented large response times not accurately representing reading rate.

The experimental tasks were the same as described for the practice sessions. The participants read the Tinker passage, selected the target word, and rated the image quality. The time required to find the spoiler word, the correctness of the response, and subjective ratings of the image were recorded by the computer. The participants' instructions are presented in Appendix A.

### *Experimental Design*

This study consisted of a three-factor, within-subjects design, as shown in Figure 4. All factorial combinations were presented randomly to each participant, with each condition being replicated three times for each participant. Each subject participated in 81 trials. Luminance contrast and ambient illumination were presented to the participant in blocks of nine trials. That is, LC and AI were set, the participant was allowed time to adapt to the illumination level, and RAR was manipulated after each Tinker passage. At the end of nine trials, all levels were changed.

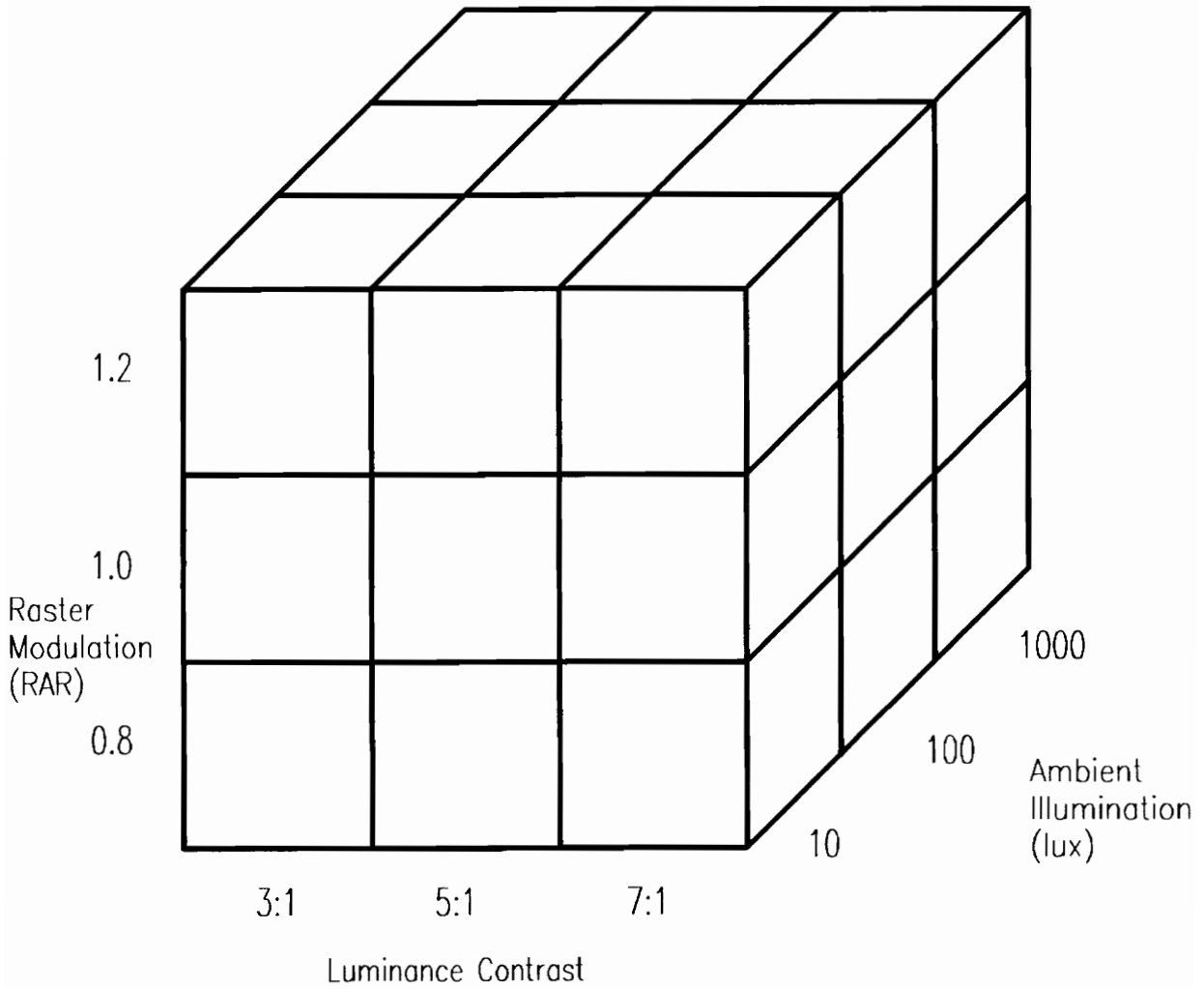


Figure 4. Experimental Design

### *Dependent Variables*

Reaction time was measured as the time required to identify the spoiler, in hundredths of a second. The computer measured this time. Two depressions of the mouse button signalled the start and end of timing.

The second dependent variable was error rate. Error rate was based upon the correctness of the subject's selection of the spoiler word. If the response was correct, a "0" was recorded by the computer. If the response was incorrect, a "1" was recorded.

The subjective quality of the image was the third dependent variable in this experiment. This rating was recorded as the number that corresponded with the descriptive adjective, as discussed previously.

### *Independent Variables*

The experimental design was a three-factor, within-subjects factorial: (1) Luminance Contrast (LC) with three levels, (2) Resolution/Addressability Ratio (RAR) with three levels, and (3) Ambient Illumination (AI) with three levels. All three variables were manipulated by the experimenter.

*Luminance Contrast (LC).* Three levels of luminance contrast were presented to each participant: 3:1, 5:1, and 7:1. The contrast levels were determined using the Minolta CS-100 Chroma Meter. The spot photometer is used by the Displays and Controls Laboratory (DCL) to determine the luminance of any given target.

*Resolution/Addressability Ratio (RAR).* Three ratios were presented to each participant: 0.8 (addressability greater than resolution), 1.0 (addressability and resolution equal), and 1.2 (addressability less than resolution). The measurement system used to make the resolution and addressability measurements was the DCL Gamma System. The Gamma System is a photometric system used to make most display measurements. The Gamma System consists of the GS-4100 Intelligent Radiometer, the GS-2110A Telemicroscope, the Aerotech Positioning System (a Unidex 11), and an IBM PC-XT.

*Ambient Illumination (AI).* Three levels of ambient illumination were present for each subject: 10 lux, 100 lux, and 1000 lux. The ambient illumination was measured with a Minolta T-1 Illuminance Meter. The illuminometer measures absolute luminance levels from continuous light sources.

## RESULTS

The three dependent variables -- error rate, reaction time, and subjective image quality -- were analyzed using separate Analysis of Variance (ANOVA) methods. Because the ANOVA components of variance models used within-subjects effects, the Greenhouse-Geisser correction (Winer, 1971) was applied to all tests. Significant main and interaction effects were examined using the Newman-Keuls post-hoc comparison test procedure.

### *Error Rate*

The ANOVA summary table for selection of the spoiler word is shown in Table 4. The main effect of luminance contrast ( $p < 0.05$ ) was significant. Figure 5 shows the error rates as a function of luminance contrast levels, and Table 5 lists the results of the Newman-Keuls post-hoc analysis. The critical difference results of the Newman-Keuls post-hoc analysis also are shown in Table 5. Figure 5 shows that the 5:1 luminance contrast level produced the most errors, while the 3:1 and 7:1 contrast produced the fewest errors. Across all observations, the error rate was 4.2% ( $\sigma = 20.08\%$ ). Further, the ANOVA Summary Table shows the LCxRAR interaction to be significant ( $p < 0.1$ ). Figure 6 plots this interaction.

TABLE 4. ANOVA Summary Table for Error Rate

Source	df	MS	F-Value	G-G
Subjects (Sub)	9	0.012		
Luminance Contrast (LC)	2	0.041	4.287	0.0313
LCxSub	18	0.010		
Resolution/Addressability Ratio (RAR)	2	0.003	0.160	0.8525
RARxSub	18	0.018		
Ambient Illumination	2	0.00	0.029	0.9618
AIxSub	18	0.014		
LCxRAR	4	0.042	2.972	0.0601
LCxRARxSub	36	0.014		
LCxAI	4	0.007	0.407	0.7560
LCxAIxSub	36	0.016		
RARxAI	4	0.011	0.942	0.4382
RARxAIxSub	36	0.012		
LCxRARxAI	8	0.013	1.345	0.2743
LCxRARxAIxSub	<u>72</u>	0.010		
Total	269			

Using the Greenhouse-Geisser correction (epsilon = 0.973),  
 $p < 0.05$  for LC.

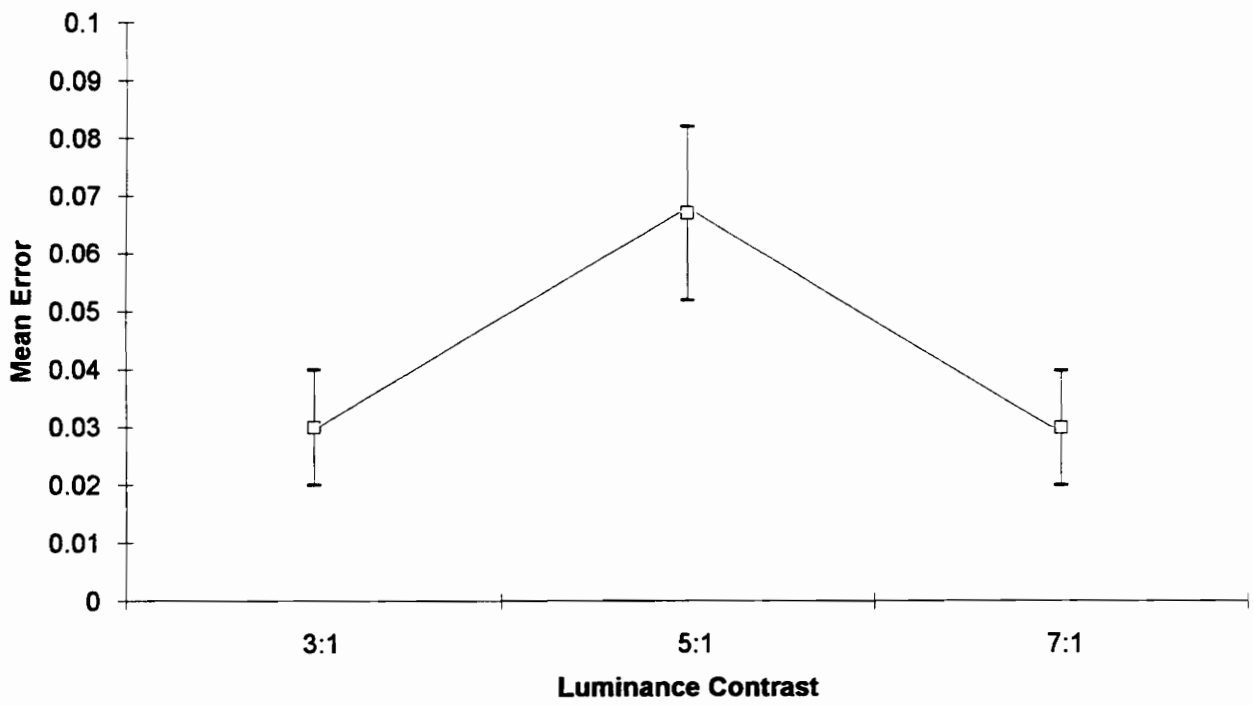


Figure 5. Luminance contrast main effect on error rate. Error bars indicate  $\pm 1$  standard error of the mean.

TABLE 5. Newman-Keuls Results for Luminance Contrast and Error Rate

Luminance Contrast	Mean Rating	Group
7:1	0.030	A
3:1	0.030	A B
5:1	0.067	B

Groups with the same letter are not significantly different,  $p < .05$ .

Newman-Keuls Critical Differences for Luminance Contrast and Error Rate

	1	2	3		
Treatments	3:1	7:1	5:1		
Means	.030	.030	.067	r	CD N-K
1	--	0	<b>0.037</b>	3	.039
2		--	<b>0.037</b>	2	.033

Bolded results are significant.

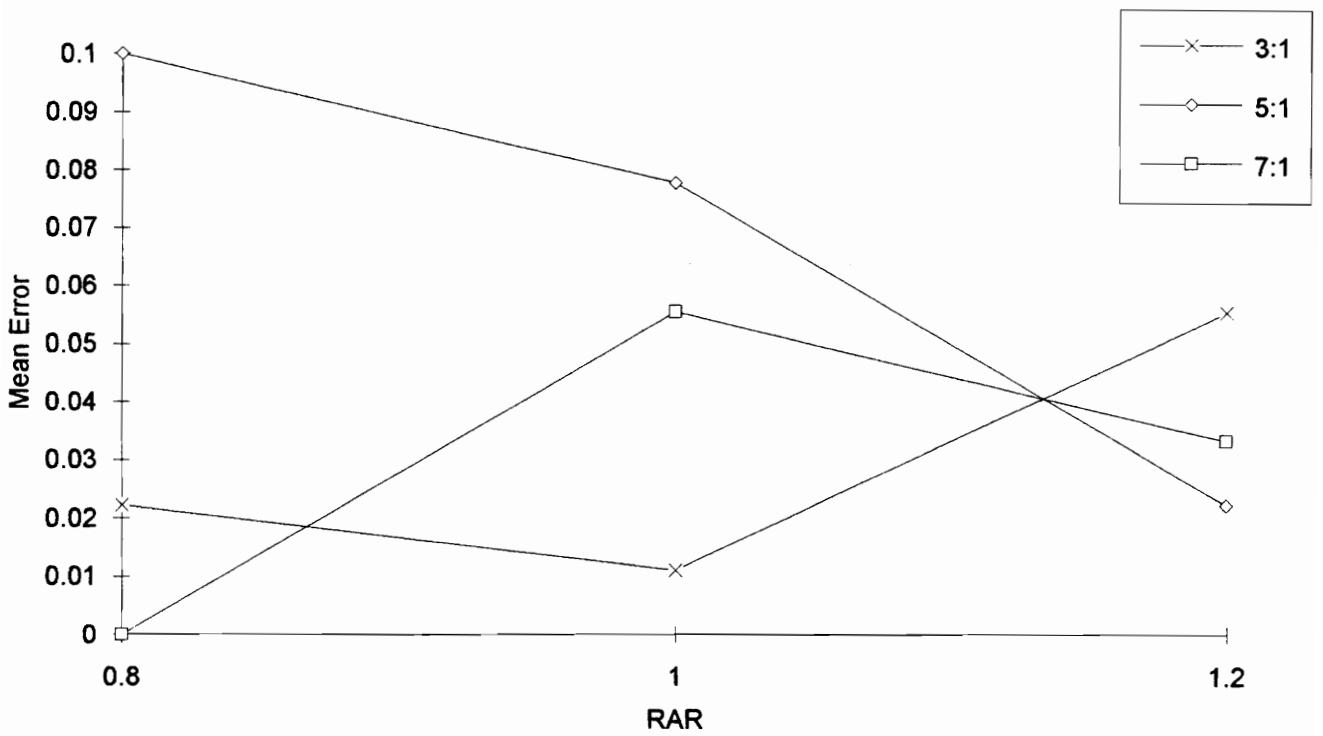


Figure 6. Luminance Contrast and RAR error rate interaction.

### *Reaction Time*

Table 6 shows the ANOVA summary table for the time to select the spoiler word. No main or interaction effects were significant ( $p < 0.05$ ). The mean time to read the Tinker passage was 5.88 seconds ( $\sigma = 0.022$  sec).

### *Subjective Ratings*

The ANOVA summary table for subjective image quality ratings is shown in Table 7. The main effects of luminance contrast, RAR, and illumination were significant, as was the two-factor interaction between luminance contrast and illumination. The mean rating given by subjects was 5.9 with a standard deviation of 1.6. Further, Table 7 shows that the two-factor interaction between luminance contrast and RAR was significant ( $p = 0.1$ ). Figure 7 plots this interaction.

*Luminance Contrast.* Figure 8 shows the main effect of luminance contrast on subjective image quality. Table 8 lists the Newman-Keuls post-hoc analysis results and the Newman-Keuls critical differences results. Figure 8 shows that the 5:1 and 7:1 luminance contrast conditions were rated higher than the 3:1 luminance contrast condition. The 7:1 and 5:1 conditions did not differ significantly.

*Resolution/Addressability Ratio.* The main effect of RAR on subjective image quality ratings is shown in Figure 9. The Newman-Keuls results show that image

TABLE 6. ANOVA Summary Table for Reaction Time

Source	df	MS	F-Value	G-G
Subjects (Sub)	9	10.548		
Luminance Contrast (LC)	2	1.766	0.983	0.3859
LCxSub	18	1.797		
Resolution/Addressability Ratio (RAR)	2	3.797	2.101	0.1683
RARxSub	18	1.807		
Ambient Illumination (AI)	2	0.986	0.522	0.6019
AIxSub	18	1.890		
LCxRAR	4	1.120	1.094	0.3674
LCxRARxSub	36	1.024		
LCxAI	4	1.395	0.492	0.6586
LCxAIxSub	36	2.838		
RARxAI	4	2.170	1.119	0.3554
RARxAIxSub	36	1.939		
LCxRARxAI	8	1.668	1.469	0.2359
LCxRARxAIxSub	<u>72</u>	1.135		
Total	269			

TABLE 7. ANOVA Summary Table for Subjective Rating

Source	df	MS	F-Value	G-G
Subjects (Sub)	9	34.136		
Luminance Contrast (LC)	2	21.668	18.745	0.0002
LCxSub	18	1.156		
Resolution/Addressability Ratio (RAR)	2	5.840	6.917	0.0120
RARxSub	18	0.844		
Ambient Illumination (AI)	2	9.187	6.459	0.0092
AIxSub	18	1.422		
LCxRAR	4	0.392	2.906	0.0690
LCxRARxSub	36	0.135		
LCxAI	4	24.653	19.387	0.0001
LCxAIxSub	36	1.272		
RARxAI	4	0.262	1.270	0.3047
RARxAIxSub	36	0.206		
LCxRARxAI	8	0.283	1.523	0.2204
LCxRARxAIxSub	<u>72</u>	0.186		
Total	269			

Using the Greenhouse-Geisser correction, the following results were obtained:

LC           epsilon = 0.792   p < 0.001  
 RAR         epsilon = 0.768   p < 0.05  
 AI           epsilon = 0.934   p < 0.05  
 LCxAI       epsilon = 0.523   p < 0.0001

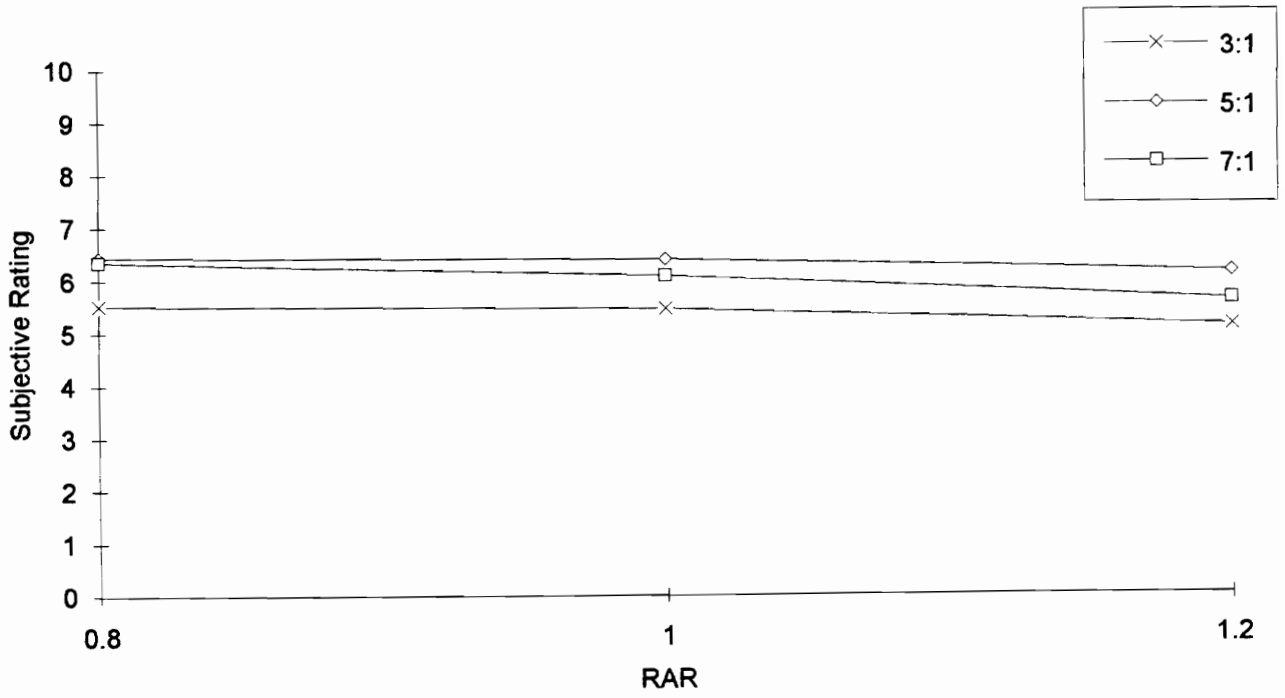


Figure 7. Luminance Contrast and RAR interaction on subjective rating.

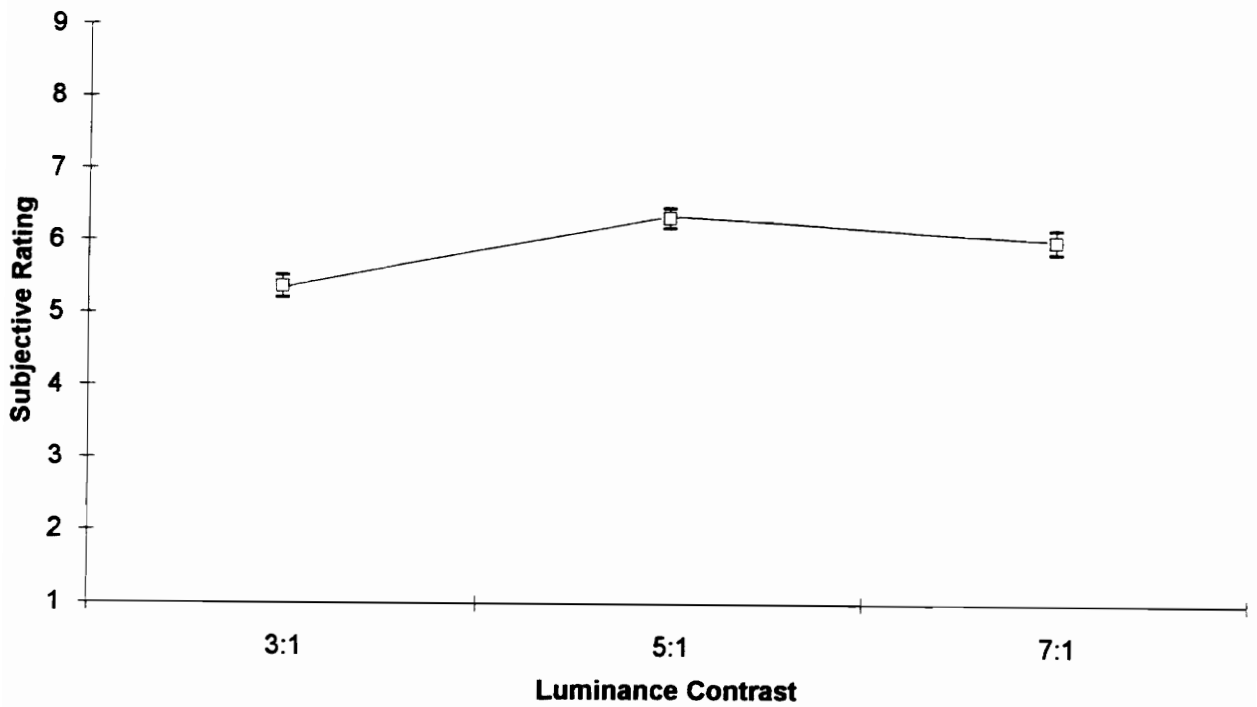


Figure 8. Luminance contrast main effect on subjective ratings. Error bars indicate  $\pm 1$  standard error of the mean.

TABLE 8. Newman-Keuls Results for Luminance Contrast and Subjective Rating

Luminance Contrast	Mean Rating	Group
3:1	5.367	A
7:1	6.019	B
5:1	6.328	B C

Groups with the same letter are not significantly different,  $p < 0.05$ .

Newman-Keuls critical differences for luminance contrast and subjective rating.

	1	2	3		
Treatments	3:1	7:1	5:1		
Means	5.367	6.019	6.328	r	CD N-K
1	--	<b>0.652</b>	<b>0.961</b>	3	0.531
2		--	0.309	2	0.459

Bolded results are significant.

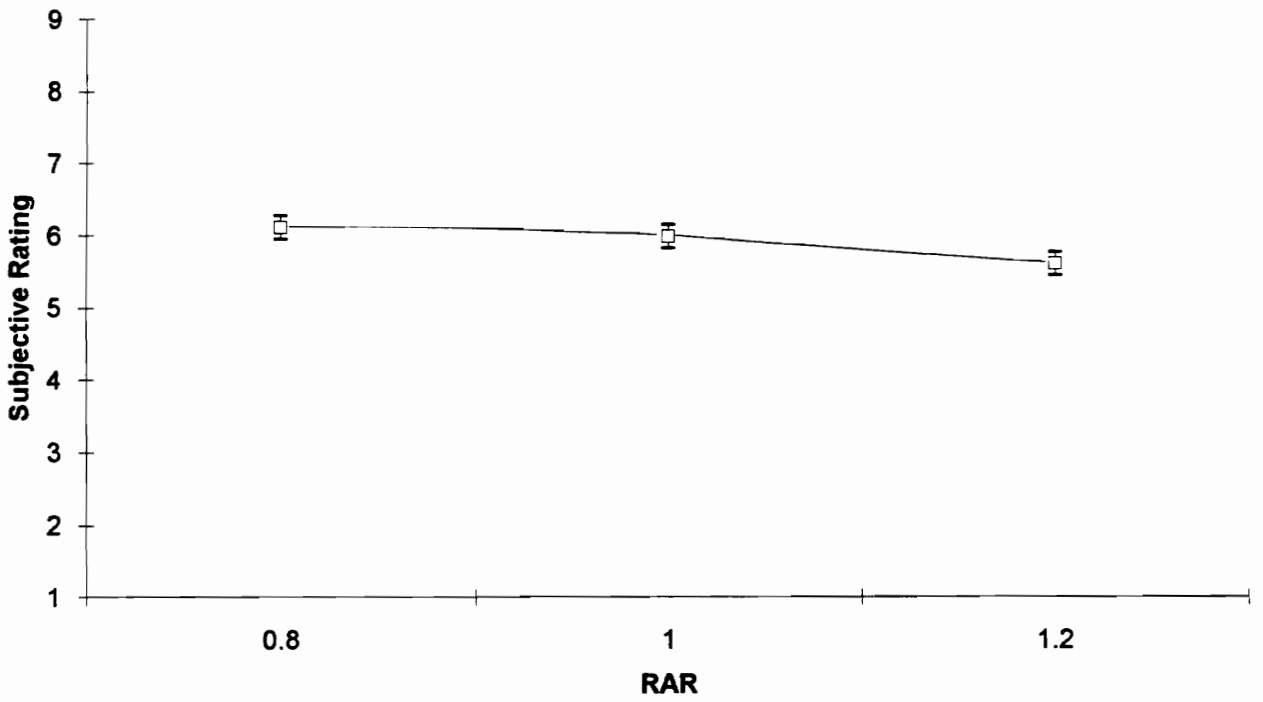


Figure 9. Resolution/addressability ratio main effect on subjective ratings. Error bars indicate  $\pm 1$  standard error of the mean.

quality decreased with increasing RAR. A RAR of 0.8 ratio was rated the highest and an RAR of 1.2 was rated the lowest ( $p < 0.05$ ). Since none of the interactions effects involving RAR were significant ( $p < 0.05$ ), the 0.8 ratio preference is maintained for all illuminations and luminance contrasts. Table 9 shows the Newman-Keuls results and critical differences.

*Illumination.* The main effect of illumination on image quality is shown in Figure 10. Table 10 lists the Newman-Keuls post-hoc analysis results and the critical differences. Figure 10 shows that 100 lux was rated higher than the 1000 lux condition. No significant differences were found between 10 and 1000 or 10 and 100 lux conditions.

*Luminance Contrast and Illumination.* Figure 11 shows the significant interaction between luminance contrast and illumination. Table 11 shows the associated Newman-Keuls results.

Figure 11 shows that the subjective judgements of image quality increase with increasing illumination within each luminance contrast level, with the exception of the 1000 lux condition at the 7:1 luminance contrast condition. Table 11 shows the 1000 lux/7:1 interaction to be rated significantly lower than all conditions except the 10/3:1

TABLE 9. Newman-Keuls Results for Resolution/Addressability Ratio and Subjective Rating

RAR	Mean Rating	Group
1.2	5.618	A
1.0	5.987	B
0.8	6.107	C

Groups with the same letter are not significantly different,  $p < 0.05$ .

Newman-Keuls critical differences for resolution/addressability ratio and subjective rating.

	1	2	3		
Treatments	1.2	1.0	0.8		
Means	5.618	5.987	6.107	r	CD N-K
1	--	<b>0.369</b>	<b>0.489</b>	3	0.35
2		--	0.12	2	0.288

Bolded results are significant.

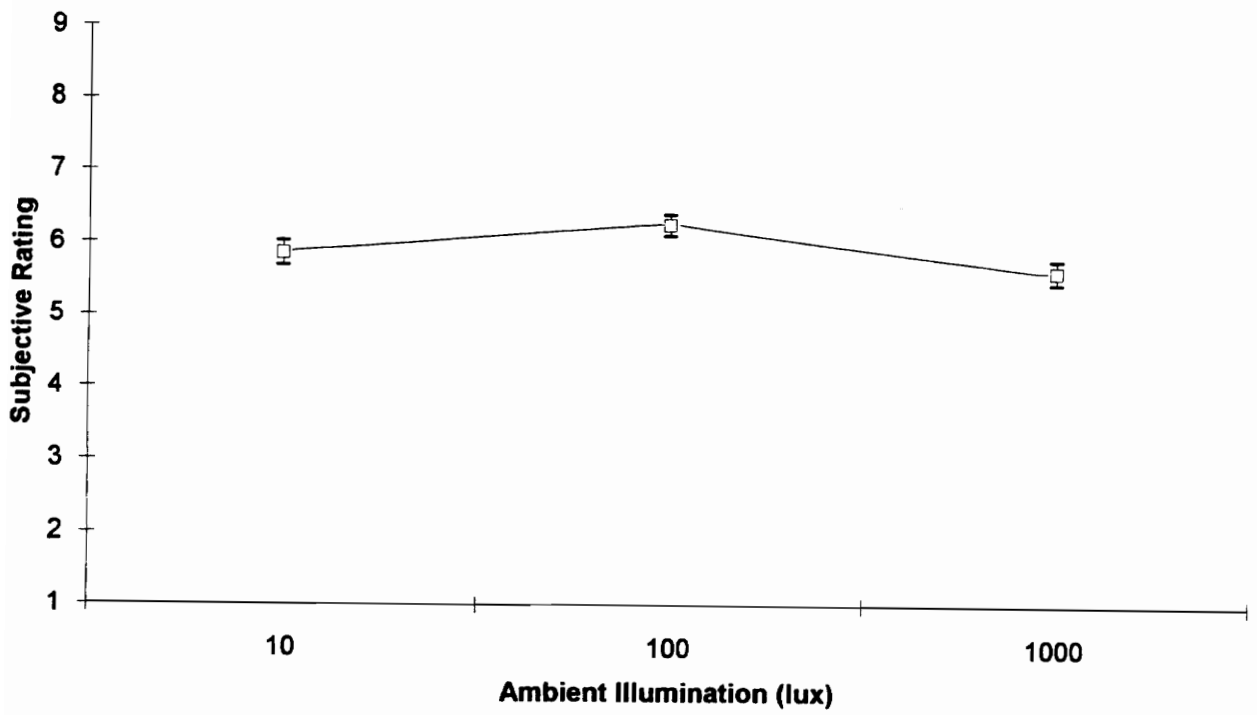


Figure 10. Illumination main effect on subjective ratings. Error bars indicate  $\pm 1$  standard error of the mean.

TABLE 10. Newman-Keuls Results for Illumination and Subjective Rating

Illumination (lux)	Mean Rating	Group
1000	5.617	A
10	5.848	A B
100	6.248	B

Groups with the same letter are not significantly different,  $p < .05$ .

Newman-Keuls critical differences for illumination and subjective rating.

	1	2	3		
Treatments	1000	10	100		
Means	5.617	5.848	6.248	r	CD N-K
1	--	0.231	<b>0.631</b>	3	0.592
2		--	0.4	2	0.513

Bolded results are significant.

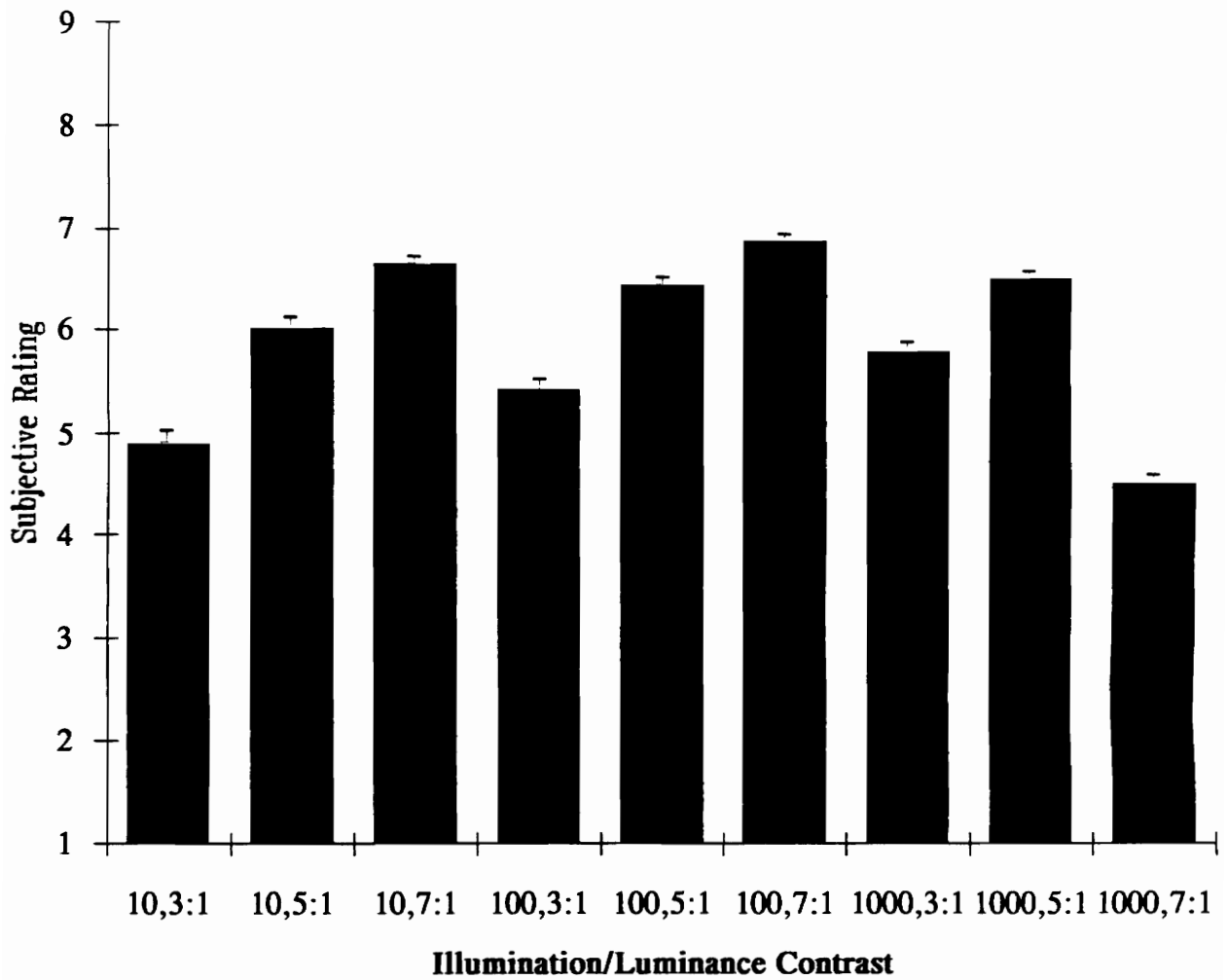


Figure 11. Illumination and luminance contrast interaction on subjective ratings. Error bars indicate  $\pm 1$  standard error of the mean.

TABLE 11. Newman-Keuls results for illumination and luminance contrast interaction and subjective rating.

Illumination/LC	Mean Rating	Group						
1000/7:1	4.533	A						
10/3:1	4.889	A	B					
100/3:1	5.422	A	B	C				
1000/3:1	5.789		B	C	D	E	F	
10/5:1	6.011			C	D	E	F	G
100/5:1	6.444				D	E	F	G
1000/5:1	6.528					E	F	G
10/7:1	6.644						F	G
100/7:1	6.878							G

Newman-Keuls critical differences for illumination and luminance contrast interaction and subjective rating.

	1	2	3	4	5	6	7	8	9			
Treatments	1000; 7:1	10; 3:1	100; 3:1	1000; 3:1	10; 5:1	100; 5:1	1000; 5:1	10; 7:1	100; 7:1			
Means	4.533	4.889	5.422	5.789	6.011	6.444	6.528	6.644	6.878	r	CD	N-K
1	--	<b>0.356</b>	<b>0.889</b>	<b>1.256</b>	<b>1.478</b>	<b>1.911</b>	<b>1.995</b>	2.111	<b>2.345</b>	9	1.149	
2		--	0.533	0.9	1.122	<b>1.555</b>	<b>1.639</b>	<b>1.755</b>	<b>1.989</b>	8	1.127	
3			--	0.367	0.589	<b>1.022</b>	<b>1.106</b>	<b>1.222</b>	<b>1.456</b>	7	1.098	
4				--	0.222	0.655	0.739	0.855	<b>1.089</b>	6	1.067	
5					--	0.433	0.517	0.633	0.867	5	1.028	
6						--	0.084	0.2	0.434	4	0.979	
7							--	0.116	0.35	3	0.908	
8								--	0.234	2	0.795	

Bolded results are significant.

and 100/3:1 conditions. Table 11 also shows that the 100/7:1 interaction was rated significantly higher than the 1000/7:1, 10/3:1, 100/3:1, and 1000/3:1 conditions.

## DISCUSSION

This research found that luminance contrast significantly affected errors in the Tinker Speed of Reading task, although RAR and illumination did not significantly increase the number of errors. The Newman-Keuls results show that the 3:1 and 7:1 luminance contrast conditions resulted in the lowest error rates and the 5:1 condition resulted in the highest error rates.

This finding is in agreement with Snyder and Maddox (1978) who found that a 7:1 luminance contrast for contextual displays was optimal. Other technical publications, including ANSI/HFS 100-1988 and Snyder (1986), also state a preference for the 7:1 contrast ratio. A luminance contrast of 7:1 is lower than some accepted optimum ratios. Shurtleff (1980) suggests a ratio of 10:1, while VDT suggests that luminance contrasts between 8:1 and 10:1 are optimum.

None of the main effects were found to significantly increase the time required to complete the Tinker Speed of Reading paragraph. This finding agrees with Legge, Rubin, and Luebker (1987) who found that for a luminance contrast of 3:1, no appreciable increase in reaction time existed. Although, that study did find that reading rates declined as contrast was reduced. However, the luminance contrast levels most affecting reading rates in the Legge et. al. (1987) study were lower than the 3:1 luminance contrast level used in the present research. The reaction time

results appear to stem from the fact that all text images were supra-threshold (i.e. above detection level).

The finding that there was no appreciable reaction time findings is consistent with other studies from the Displays and Controls Laboratory who used the Tinker Speed of Reading Test (see Ansley, 1991 and Sebok, 1991). This consistency of results suggests that the procedures followed in conducting the Tinker Speed of Reading Test may affect reaction time. This is one possible explanation for the lack of reaction time significance in the present thesis work. A closer examination of the Tinker task procedures is suggested.

Another possible explanation for the lack of reaction time significance for the luminance contrast main effect, is the fact that none of the three levels exceeded threshold. The 3:1 luminance contrast condition is the minimum luminance contrast condition required by most standards. Thus, no appreciable increase in reaction time would be expected.

The 0.8 RAR consistently was rated higher than either the 1.0 or the 1.2 RAR conditions. The high rating was consistent over all luminance contrast and illumination levels. This trend indicates a general preference for the 0.8 RAR condition.

This research found that the subjective ratings differed across illumination levels. The 100 lux condition resulted in significantly higher ratings than the 1000 lux condition. The 10 lux condition did not significantly differ from the other two conditions. The range of the subjective ratings was from 6.25 to 5.618. Figure 7 shows that ratings were affected by ambient illuminations levels that were either too dark (10 lux) or too bright (1000 lux). This finding is consistent with research that recommends ambient illumination levels in the mid-range of 200-500 lux (see Rupp, 1981).

The LCxAI interaction showed that image quality increased for all illumination levels within luminance contrast except for the 7:1/1000 lux interaction. The low-rated 1000 lux condition declined sharply at the 7:1 luminance contrast condition. The decline was found to be significant, suggesting that high ambient illumination levels require special attention.

An investigation of Figure 8 shows that the 3:1 luminance contrast condition was consistently rated lower than the other two luminance contrasts levels. This is true over all ambient illumination levels. The main effect result also shows the 3:1 luminance contrast condition to be given a low rating. It can be concluded that participants did not prefer the 3:1 luminance contrast condition, regardless of the error rate results.

## CONCLUSIONS

This research shows that the time required to perform a Tinker Speed of Reading task is not affected by luminance contrast or illumination. Also, the illumination does not increase the error rate. Further, this research shows that RAR does not affect reading time or error rate.

However, luminance contrast does affect the errors made while performing the Tinker Speed of Reading task. A luminance contrast of 7:1 suggested. Because the 3:1 luminance contrast did not produce significantly more errors than the 5:1 luminance contrast condition, one cannot suggest that contrasts 5:1 and lower increase errors and should be avoided. However, subjects consistently gave the 3:1 luminance contrast level a low rating. Generally a luminance contrast of 7:1 will produce fewer errors.

Participants rated the 0.8 RAR higher than the 1.2 RAR. One could argue that this is so because the characters in the 0.8 RAR paragraph were slightly larger (addressability was greater than resolution) than the characters in the 1.2 RAR. This larger character size potentially leads to more noise. However, prior to the study it was determined that character size was not a confounding factor since all characters met threshold

requirements. The range of RAR from 0.8 to 1.2 was .296 mm/pixel to .420 mm/pixel, respectively.

Display designers can conclude that 7:1 is the preferred contrast ratio based upon the findings that 3:1 and 7:1 produced the fewest errors and 5:1 and 7:1 produced the highest subjective image quality ratings. This recommendation holds over a RAR range of 0.8 to 1.2 and an ambient illumination range of 10 to 100 lux. Because of the low image quality ratings for the 7:1/1000 lux interaction, high illumination levels would require special attention.

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**APPENDIX A**

**PARTICIPANTS' INSTRUCTIONS**

## PARTICIPANTS' INSTRUCTIONS

### *Pre-Screening Instructions*

The purpose of this study is to examine the effect of luminance contrast, raster modulation, and ambient illumination on reading performance. Your contribution to the study will be to view a display under various levels of contrast, raster modulation, and illumination. Before participating in this experiment, you will be asked to take two vision tests to make sure you will be able to see the display clearly. If you have any questions regarding the purpose of this experiment, please ask them at this time.

### *Experimental Instructions*

During this experiment you will be viewing a passage of text on the monitor placed in front of you. You will see a screen that says "Ready?" Once you are ready to begin, press the left mouse button and the passage will appear on the screen. Next, you will read the passage and find the word that does not belong, i.e., it does not make sense in the context of the rest of the passage. When you have found the word press the right mouse button. At this point the words will be replaced with boxes. Move the cursor over the box corresponding to the out of context word and hit the left mouse button.

After you select the box, a list of adjectives will appear. Move the cursor next to the word which best describes the image quality of the paragraph you just saw. Press the left mouse button to select this word.

After selecting the adjective, the "Ready?" screen will appear again. There will never be more than one word that does not belong.

After every "Ready?" screen, please stop so that I may make some quick adjustments. Once I have made those adjustments, I will instruct you to begin again, at which time you will depress the left mouse button.

Please work as quickly and as accurately as possible. It is important that you try to keep your head as still as possible. That is, do not make any large head movements while you are looking for the out-of-context word. You will be given some practice trials to get used to this experiment before actually starting. If you get tired or just want to take a break, go ahead and do so. But, wait until you get to the "Ready?" screen before you stop. Remember always press the left mouse button except when you find the word in the paragraph.

Do you have any questions?

## VITA

### Emily Jean Wells

Emily Wells was born in Sioux Falls, South Dakota on November 27, 1968. She received her bachelor of science in psychology, concentrating on human factors, in 1991 from the University of South Dakota in Vermillion, South Dakota. In August, 1991 Emily entered Virginia Polytechnic Institute and State University to pursue her master's in human factors engineering within the Department of Industrial and Systems Engineering. Emily currently is employed by Gateway 2000 and is a member of the Health, Safety, and Ergonomics Committee. She intends to be involved in the development of a Human Factors division there. Emily is a member of the Human Factors and Ergonomics Society and Psi Chi.