Effect of Ambient Light on Electronically Displayed Medical Images as Measured by Luminance Discrimination Thresholds

Technical Report 87-004

1987

Stephen M. Pizer Diane C.
Rogers R. Eugene Johnston

The University of North Carolina at Chapel Hill
Department of Computer Science
New West Hall 035 A
Chapel Hill, N.C. 27514

Effect of Ambient Light on Electronically Displayed Medical Images as Measured by Luminance Discrimination Thresholds

Diane C. Rogers [1], R. Eugene Johnston[1], and Stephen M. Pizer[1,2]

[1]Departments of Radiology and [2]Computer Science,
University of North Carolina, Chapel Hill, NC, 27514

ABSTRACT

Two-alternative forced-choice experiments were conducted to determine the effects of ambient light on luminance discrimination thresholds. The luminance levels displayed on the monitor screen were chosen so as to include typical light levels encountered in medical images, about 0.01 to 120 ftL. The ambient light levels of 4 to 40 lux used represent the range found in a typical radiologic reading room where video displays are used and efforts are made to control the ambient light. Test targets were 1 cm squares centered in a uniform background field so that when no ambient light was present the mean luminance from the central region of the display was held constant at about 2 ftL. When the ambient light was 4 or 40 lux no effect on the observers' discrimination thresholds was found. Alterations in discrimination thresholds which were found at the higher ambient light level of 148 lux are attributed to diffuse reflections from the CRT face. Since the diffuse reflections sum with the intensity emitted from the CRT to deterimine the luminance characteristics of a digitally stored image, as ambient light levels increase the displayed intensity increases and the display contrast decreases.

INTRODUCTION

In the world of medical imaging represented primarily, but not entirely, by the field of radiology, the use of electronic devices to display images stored in a digital format has come into common use. The newer imaging modalities such as X-Ray computed tomography (CT), magnetic resonance imaging (MRI) and Ultrasound have digitally acquired images where the most direct transform for display to the human observer is by electronics.

A digitally acquired image is stored in a computer as an array of numbers, each number representing a recorded intensity for a specific portion of the image. Before the image is displayed, it may be modified by contrast enhancement techniques. The transformed image numbers, now referred to as scale indicator intensities, are mapped by a lookup table into physical driving intensities, i.e., digital driving levels. A D/A converter uses this as input and produces the video signals. The display device then converts the video signal into displayed intensities, i.e., luminance. The term greyscale refers to the path transversed from minumum to maximum displayed intensity (photometric luminance) as a function of digital driving level. The final image transformation is that which occurs within the human visual system and yields the perceived intensity or brightness.

With the proliferation of electronic displays and the introduction of picture archiving and communications systems (PACS), radiologists will be looking at images on multiple screens and consulting with colleagues in different locations. We have been concerned that as images are displayed on different devices and in different locations, the information transferred to the radiologist observer remain constant and not altered by the display device or viewing environment. In cases where display devices have different photometric intensity ranges, each device should employ its full range. But consequently, the images displayed on different devices may not be physically identical. In such cases, perceptual constancy rather than physical constancy is the objective. That is, the brightness of any point within an image should bear a constant relationship to the brightness of the rest of the image, despite variations in the absolute intensity at which the image is displayed. Given that the observer is the final processor of information, characteristics of the human visual system must be determined by controlled experiments and factored into the final choice of display parameters.

To maintain displayed images that are physically invariant, or alternatively, displayed images which yield equivalent perceptions across diverse display devices, we have developed a methodology to "standardize the display device" (Pizer 1981).

The specific standardization methodology we are implementing is termed "perceptual linearization". It is based on empirically determined visual discrimination thresholds (just noticeable differences or jnds) of displayed intensity. Using signal detection theory paradigms we define a jnd as that difference in luminance that is detectable by the observer with a 50% true positive rate and a 5% false positive rate on ROC curves (Pizer 1980, 1981). For our two-alternative forced-choice experiments a jnd is equivalently described by the luminance difference which can be detected 87.8% of the time.

Jnds are determined at various luminance levels throughout the luminance range of a video display. As reported by others (e.g., Koenig and Brodhun, 1889, cited by Blackwell, 1972,), we found that for all but very low luminances, jnds increase monotonically as a function of luminance, with a rate less than Weber's law. This jnd function is used to define a conversion table between the scale indicator intensities and the digital driving level intensities such that the resultant greyscale is "perceptually linear" under our display conditions. We define a linearized greyscale to be one in which the jnd vs digital driving level function is described by a horizontal line. That is, equal changes in recorded intensity result in luminance changes which when viewed on the display screen are equally discriminable, independent of location in the display scale path.

A number of factors may influence jnds, (and therefore the linearization function,) including interobserver variations, image structure, and viewing environment. Their effect should be considered when defining the linearization process used to construct greyscales. In an earlier study (Johnston et al., 1985) we maintained a fixed image structure and a controlled viewing environment to look at interobserver and intraobserver variability. These studies were conducted at a low ambient light level, 4 lux, for target luminances ranging from 0.01 to 26 ftL. Under these conditions the curve for jnd vs driving level intensity, and therefore linearization, was independent of observer, within the statistical variation of individual observers.

If the viewing environment varies, i.e., the ambient light is not the same as in our test conditions, or the ambient light at two different display stations is different, how does this affect what the radiologist sees and interprets? The present experiments are an initial attempt to answer this question.

Ambient light

The effects of ambient light on display and perception of images are complex and include the following. First, there are two classes of reflections, specular, or mirrorlike, and diffuse. Their magnitude depends on characteristics of the particular CRT screen, but "there are no accepted, standardized procedures to measure either of these parameters" (Rinalducci, et al., 1983, p. 92). Their impact can be reduced with certain filters.

Specular reflections occur when light emitted by objects (e.g., lightboxes) or reflected off of objects (e.g., papers or keyboards) forms images at the front surface of a CRT. Because reflected images are located at the surface of the CRT and displayed images are located slightly further away, at the back surface of the CRT screen, accommodation and convergence may fluctuate as the visual system alternately focuses on the two sets of images. Consequently, the displayed characters would be intermittently blurred (Rinalducci, et al., 1983).

Diffuse reflections is the term used to indicate the fairly uniform increase in luminance, by reflection, at all points across the CRT. This increase is proportional to the amount of ambient light incident at the CRT face. The diffuse reflectance characteristic of a monitor can be determined by measuring the percentage of incident light (of known quantity) which is reflected from the blank screen. Diffuse reflections, by increasing the luminance for all points, reduce the contrast within an image, and the image may appear to be washed out. This perceptual effect may, however, be subtle at low ambient light levels.

A second effect of ambient light is glare, also called veiling glare. This occurs when a light considerably more intense than the object under scrutiny is in the field of view. It can severely reduce sensitivity to a target image and, even if sensitivity is not reduced, it can be a source of discomfort. Its occurrence depends on light location and intensity.

Third, there is concern that changes in ambient light level will adversely affect the observer's sensitivity to a given display by shifting the adaptation level away from intensities of the displayed images. Light adaptation refers to the processes of adjusting to the prevailing environmental luminance. For gross changes in luminance (above about 3 log trolands), the first step of adaptation is the relatively slow process of receptor photopigments reaching a state of equilibrium. Once the visual system has reached equilibrium it is said to be in steady-state adaptation. Increases in retinal illuminance during steady-state adaptation will cause a decrease in the receptor response to a given stimulus increment with a corresponding decrease in sensitivity. This shift in the operating curve, for threshold vs intensity, is called "response compression" and has been described as instantaneous. The effects would be fairly local were it not for both voluntary and involuntary eyemovements which occur with normal vision. Luminance or contrast discrimination is best when the ambient light levels (hence the visual system adaptation level) and the display are of similar intensities (Craik, 1938). If the ambient light is very different than the display intensity, or if the display comprises a broad range of intensities, then the amount of light (delta I) necessary to elicit a criterion response may be shifted.

In addition, there are secondary effects of adapting level, in terms of the degree of summation and resolution which occurs for both temporal and spatial vision (see review by Barlow, 1972). With adaptation to higher intensity levels, resolution increases and summation decreases.

Finally, for CRTs or other self-luminous displays, it is a common observation that when room lights are increased the displayed images appear to darken, that is, the brightness, or perceived intensity, of the display relative to the entire visual field decreases. This occurs because our visual system is sensitive to contrast, not absolute illumination level. Thus perceptions of blackness and whiteness are not determined by absolute intensity but by an object's intensity relative to the rest of the visual field. This phenomenon known as brightness constancy is usally adaptive, but it may impose limitations on CRT viewing environments. For example, increasing ambient light can greatly broaden the intensity range in an environment. If brightness is based on intensities in the entire visual field instead of intensities within some functionally defined portion, such as a CRT, then, with even moderate ambient light levels, the range of perceived intensities displayable on a monitor may be greatly narrowed and brightness constancy for the display could be disrupted.

The effects of ambient light are obviously a concern when displaying medical images. Detection of low contrast targets displayed in film/lightbox systems has been found to decrease with increasing levels of ambient light. Baxter et al. (1982) relate this effect to the differential adaptation level which would exist across the retina if the retina is stimulated by an image with a wide range of intensities. Alter, et al. (1982) suggest that light scattering in the eye is the major cause of decreased performance. Finally, Merrild-Hanson and Ratjen (1952) also reported that increasing ambient light decreased detection. They argue that some (unidentified) factor other than glare, produced by illuminated but uncovered portions of lightboxes, is the cause of this degradation. All of this work was carried out using the film/lightbox system in which target and surround luminances are an order of magnitude greater than those of a video display. We know of no experiments addressing the impact of ambient light on CRT displays.

We measured ambient light levels in radiology clinics where image interpretation is done from video monitors and found that the radiologists usually attempt to reduce the light to fairly low levels, ranging from about 2 to 5 lux. Frequently however, video monitors are located in the same room as film lightboxes, and often films are being viewed on the lightboxes while others use the video monitors. With films covering most viewboxes and the overhead lights off or dimmed, we found the ambient light level at the video console to be in the range of 5 to 40 lux. The typical monochrome video monitor when displaying a CT image generates an average screen luminance in the range of a few footlamberts. The range of luminance within an image for a typical CRT is from about 0.01 up to about 30 ftL. This is in contrast to film viewing where the uncovered lightbox operates at around 1000 ftL. and light transmitted through a film image is in the range of 10 to 500 ftL.

EXPERIMENTAL METHODS

Images were generated by a Comtal Vision 1020 processor with a VAX 11/730 host computer. Two different monitors were used in the experiment, one obtained from GE with a P45 phosphor was operated in the range from 0.0006 ftL to 72 ftL. The other, a Conrac with a P4 phosphor, was operated from 0.05 to 150 ftL. Photometric measurements were made before every experimental session to assure proper calibration of the monitor.

Three observers, including two of the authors, served as subjects. The experimental paradigm was basically that used in our earlier studies. To avoid problems of image interpretation, we selected a simple display and observer task. The test objects were two squares, 1 cm on a side, located one above the other, and separated by 0.75 cm. The squares were located in the center of the video screen on a background field of uniform luminance. The top, or standard square, was at the digital driving level intensity under test and was always at the same luminance for an experimental run. The luminance of the bottom, or comparison square, was equal to or increased in luminance from the top square. Discrimination thresholds were determined for four standard target intensities, 0.0006, 18.4, 57.5 and 118 ftL. The background luminance for each standard target condition was set so that the space-averaged luminance of the test objects plus the luminance from the immediate surround, a region of 8.8 cm diameter centered between the target squares, was constant at about 2.5 ftL. We chose this value to be in the range of what we measured from typical CT images displayed on video monitors. By maintaining a constant mean luminance, the contrast of target to surround luminance changed as we varied the target luminance. We assumed this to not be unreasonable since in medical images there is a wide range of contrast in different regions of the image. Figure 1 shows schematically the four stimulii used, with the actual values indicated to the right. A fixation

Insert Figure 1 about here

point was not provided for the display and though viewing distance was not constrained it was typically about 50 -80 cm.

A signal detection experiment consisting of 120 trials without feedback was designed as a two-alternative forced-choice procedure. For a trial, the two test squares were presented on the screen for a duration of 2 sec, followed by a 0.5 sec pause, before a second pair of test squares was presented. In one interval, the two squares were identical in intensity, and in the other, the comparison square was increased in intensity by one of two increments. (These increments were selected in pilot runs so as to bracket the estimated jnd.) The observer's task was to choose the interval, first or second, in which the comparison square was of increased intensity. The jnd is, by our definition, that difference in luminance which an observer detects 87.8% of the time.

All our previous experiments were conducted with an ambient room light of 4 lux generated by a lightbox located behind the video monitor and pointed toward the wall. This light source did not generate a very uniform room light, so for the present experiments we switched to incandescent ceiling lights which did give a more uniform ambient light. Three ambient light levels were chosen based on measurements observed in different clinic settings: 1) 4 lux, which is representative of the 2 -5 lux range we found in CRT reading rooms where efforts are made to control light, 2) 40 lux, which is still low, but more comfortable for paper reading; it represents the higher end of ambient light levels observed in clinic settings which are predominantly CRT-based; and 3) 148 lux, still a relatively low light level, is found in dark lightbox environments. Ambient light levels were calibrated with a photometer (United Detector Technology, model 161) by positioning a cosine diffuser with a 180^{o} angle of acceptance at the position the observer typically sat during the experiments and directing it towards the blank CRT face. As the ambient light was increased, and especially at 148 lux, the observers were bothered by specular reflections on the viewing screen. To minimize these, we draped the viewing room walls behind the observer and the table tops with black felt. Additionally, the observers were draped with black felt to avoid specular reflections from their clothing.

RESULTS

Each subject ran in each of the twelve conditions of the experiment. A brightness jnd was calculated separately for each run. The same trends were seen for all subjects and the results for one subject are shown in Figure 2.

Insert Figure 2 about here

Calculated jnds, measured in digital driving levels, are plotted as a function of each of the four standard target intensities, also measured in digital driving levels. The four standard target levels are indicated on the graph as stimulus 1, 2, 3, and 4. Only the data for stimulus 4 were obtained using the Conrac monitor. It's digital driving levels represent higher photometric values than those generated by the GE monitor which was used to generate the data for stimuli 1 - 3 in the figure. The other data points shown on the graph are from runs with other standard-target intensities and show how the jnd varies as a function of digital driving intensity. Results obtained with the different ambient light levels are denoted by the different symbols.

The effect of an increase in ambient light on brightness discrimination is not uniform, but depends differentially on the target for which discrimination is measured. Taken one by one, the results for our stimuli are as follows. For our stimulus 1, a dark target on a bright background (a configuration also referred to as negative contrast) increasing ambient light from 4 to 148 lux raises the jnd, that is sensitivity is decreased. For our stimulus 2, a moderate intensity on a moderate and somewhat brighter background, performance is equivalent for the three ambient light levels tested. For our stimulus 3, a bright target on a dark surround (a positive contrast display), we were surprised to find that performance is actually better at the higher than the lower ambient light levels. Finally, for our highest intensity target, there appears to be little effect of ambient light.

As seen by the error bars, there is considerable intrasubject variation. As shown in Figure 3, it also appears that substantial individual differences

Insert Figure 3 about here

exist. Here data for all three subjects are presented. It is clear that there is a difference between individuals as indicated by groupings of datapoints and associated error bars. For a given subject, the variations in brightness jnds caused by introduction of from 4 - 40 lux ambient light are within intrasubject variation and would probably be acceptable in a clinical environment. At ambient light intensities of 148 lux, the jnd function appears to be altered. Presumably at still higher ambient light levels, thresholds would be more severely altered and our linearization function would need to be amended. However, given the variation which typically occurs within a CRT viewing environment, about 2 - 40 lux, it appears that the effects of ambient light do not have serious consequences. A larger factor at these light levels appears to be individual differences.

DISCUSSION

We had expected the impact of ambient light to be more severe, or at least uniform across the target intensities. To understand these findings, we reconsider the experimental conditions and the possible influences of ambient light as described in the introduction to this paper. First, whether or not perceived intensity (brightness) of the stimuli was altered, was not measured and is not relevant to the discrimination task of this experiment. Second, both glare and specular reflections were minimized by lighting configurations and the use of black felt in the viewing environment. Third, the question of whether adaptation levels which existed during the different ambient light conditions differed enough to alter sensitivity is somewhat more difficult to answer.

Since observers were allowed free viewing of the room, it is not clear how the nonuniformities across the visual environment would have influenced steady-state adaptation. To estimate the potential range of adaptation levels under the different ambient light conditions, luminance measurements were made for different positions across the walls; these values were similar to the mean intensity measured for the CRT. We compared these intensity values to the data of Craik (1938), in which contrast sensitivity for different intensities was measured as a function of adaptation level, and felt that the threshold changes in sensitivity found for our experimental stimuli could not be fully accounted for by the potential variation in adaptation level.

The remaining variable is diffuse reflections from the monitor face, i.e., a fairly constant increase in luminance across all points of a display. Since the light intensity from an image point is the sum of the emitted intensity (defined by digital driving level) and the reflected intensity, contrast, which is a proportional measurement of the intensity range within an image, is reduced as ambient light, thus diffuse reflections increase. Perceptually, diffuse reflections may cause an image to appear "washed out".

Luminance jnds, as measured in our experiment, increase monotonically as a function of both target intensity and target contrast. Since ambient light changes these in opposite directions, that is, increases target intensity, but decreases target contrast, we reanalyze the data in terms of the photometric values of the targets to evaluate their influence.

The first step of this reanalysis was to determine, by measuring diffuse reflections at the CRT face, how much the image luminance was increased by the different levels of ambient light. These values, which are somewhat different for the two monitors, are presented in Table 1. At 4 lux, the increase was

Table 1. Luminance added to display by ambient light.

Ambient Light	GE monitor	Conrac monitor
4 lux	0.05 ftL	0.088 ftL
40 lux	0.5 ftL	0.89 ftL
148 lux	2.5 ftL	3.4 ftL

less than 0.1 ftL, while an ambient light level of 148 lux produced an increase between 2.5 and 3.5 ftL. for all points in a display. This is a large difference, particularly for our stimulus 1, which had an intensity of 0.0006 ftL. when measured with no ambient light. Since the intensity of the displayed image is the sum of the recorded image intensity and the diffuse reflections, these experiments measured brightness discriminations for only four recorded images, but for twelve different displayed images.

To compare sensitivity for different target intensities threshold measurements are indicated by delta I/I. We have calculated this fractional jnd for our data and find that by increasing the ambient light, the sensitivity (1/delta I/I) of the observer to luminance differences actually increases. The reason for this can be found by looking at how the contrast for each target is also changed with ambient light. We calculated contrast for each target at each ambient light level using the equation

$$C = (Lmax - Lmin)/(Lmax + Lmin) \qquad (1)$$

where C is contrast between the background and the standard target, Lmax and Lmin are, respectively, the greater and lesser intensity between background and standard target. Table 2 indicates the decrease in contrast which occured

Table 2. Stimulus contrast at different ambient light levels.

CONTRAST (between standard and background)	AMBIENT LIGHT (lux) 4	40	148
Stimulus 1	.96	.71	.38
Stimulus 2	.98	.96	.71
Stimulus 3	.78	.74	.63
Stimulus 4	.97	.96	.92

for each stimulus as a function of increasing ambient light. This decrease was quite large for stimulus 1, from 0.96 to 0.38.

To illustrate the combination of these two factors, changing target intensity and changing contrast, we have replotted the data. The results for one subject are shown in Figure 4. The fractional jnd, delta I/I is plotted

Insert Figure 4 about here

as a function of stimulus contrast. Data for the different stimuli are differentiated by symbols. A single monotonic function can reasonably well describe (delta I/I) for almost all points. In agreement with the literature on brightness jnds (e.g., Blackwell, 1972) this suggests that the effects of ambient light which we have observed can be attributed to the greater brightness discrimination sensitivity which occurs at lower contrast levels.

Consider just the data points for stimulus 1. Recall from Figure 2, where jnds are presented in terms of digital driving levels, that sensitivity appears depressed by higher ambient light levels. This would be a correct conclusion if digital driving level were the only contributor to the displayed intensity and diffuse reflections were not a factor. Now consider what is actually happening. The upper right point for stimulus 1 in Figure 4 was obtained at 4 lux, the lower left point, at 148 lux. The delta I for 4 lux is significantly lower ($p < .05$) than that of 148 lux, but because the displayed target intensity is so low here, due to a very small contribution of diffuse reflections, the delta I is proportionately large. Thus the subject is less sensitive to the stimulus 1 configuration displayed under 4 lux than as displayed under 148 lux ambient light. We can attribute this to the higher contrast which was present at 4 lux since brightness jnds for a fixed stimulus intensity are increased as a function of contrast.

In addition to magnitude of ambient light, one might consider how different light sources with differing spectral characteristics affect sensitivity. Our minimal data on this consist of comparing our prior and current results in which ambient light levels of 4 lux were generated by a fluorescent tube in a single lightbox, or by incandescent lights positioned overhead, respectively. No difference in the measured jnd values were observed across target luminances for these two lighting conditions.

CONCLUSIONS

The changes in sensitivity we have found here for brightness discrimination in a computer stored image can be explained by photometric changes of the image resulting from diffuse reflections. It may be that ambient light per se is also having some effect on sensitivity, due perhaps to shifts in adaptation level. We expect, however, that at these ambient light levels and with the limited intensity range for a typical CRT this would not be a very large effect. To investigate this issue, we would need to conduct further experiments in which the secondary effects of ambient light are controlled. That is, different recorded images would be presented at different ambient light levels in order that the displayed image is constant and only the ambient light level varies.

The ambient light levels which typically occur in CRT based reading rooms, do not appear to alter brightness discrimination thresholds as measured in our experimental paradigm and from a practical viewpoint, the linearized greyscale remains linearized over levels of 4 - 40 lux.

Acknowledgements- This research was partially supported by NIH Grant No. 1 R01 CA39059 and NATO Collaborative Research Grant No. RG. 85/0121.

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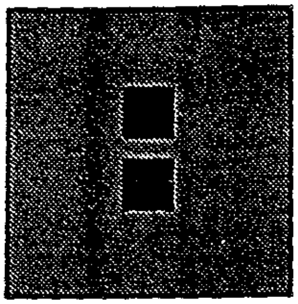
Figure Legends

Figure 1. Schematic of experimental stimuli to show relative intensity of test squares and backgrounds. Values for each stimulus are indicated in terms of digital driving levels (dl) and photometric intensity (ftL), as measured with no ambient light.

Figure 2. Brightness discrimination thresholds for subject DCR measured in units of digital driving levels are plotted as a function of standard target intensity, measured in digital driving levels. Measurements were made under three ambinet light conditions, 4 lux (●), 40 lux (▲) and 148 lux (o) for the four experimental stimuli. Additional datapoints obtained in earlier experiments at intermediate intensities are included in the graph to better indicate the shape of the function. The function is discontinuous for stimulus 4 since these data were obtained with a different monitor which produced higher photometric intensities for a given digital driving level.

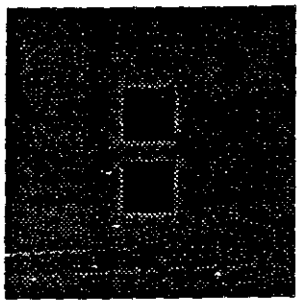
Figure 3. Discrimination data for the three subjects at the three ambient light levels tested.

Figure 4. Data from Figure 2 for DCR summarized and replotted with fractional jnd shown as a function of display contrast. This plot incorporates the changes in luminance characteristics of displayed image which result from diffuse reflections from CRT face.



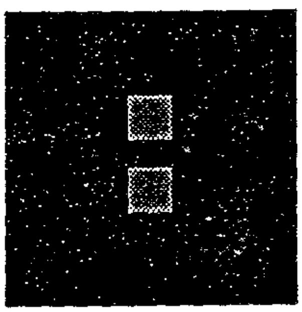
STIMULUS 1

Target = 0 dl
0.0006 ftL
Background = 79 dl
3.0 ftL



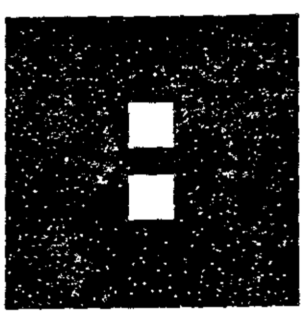
STIMULUS 2

Target = 148 dl
18.35 ftL
Background = 72 dl
2.24 ftL



STIMULUS 3

Target = 230 dl
57.46 ftL
Background = 45 dl
0.46 ftL



STIMULUS 4

Target = 225 dl
118 ftL
Background = 30 dl
1.3 ftL

Figure 1.

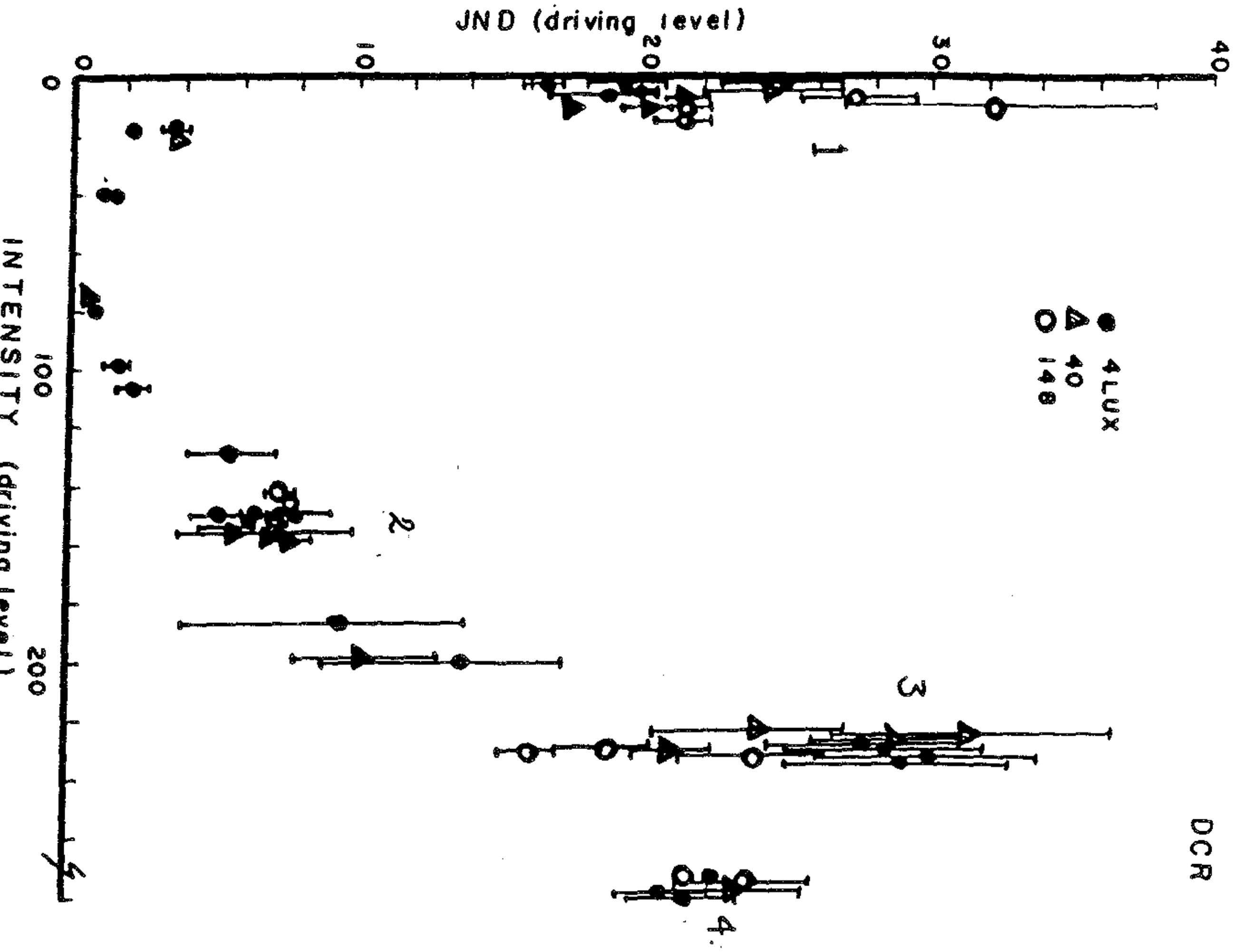

JND (driving level)
0
10
20
30
40
INTENSITY (driving level)
0
100
200
4 LUX
40
148
DCR
1
2
3
4

Figure 2.

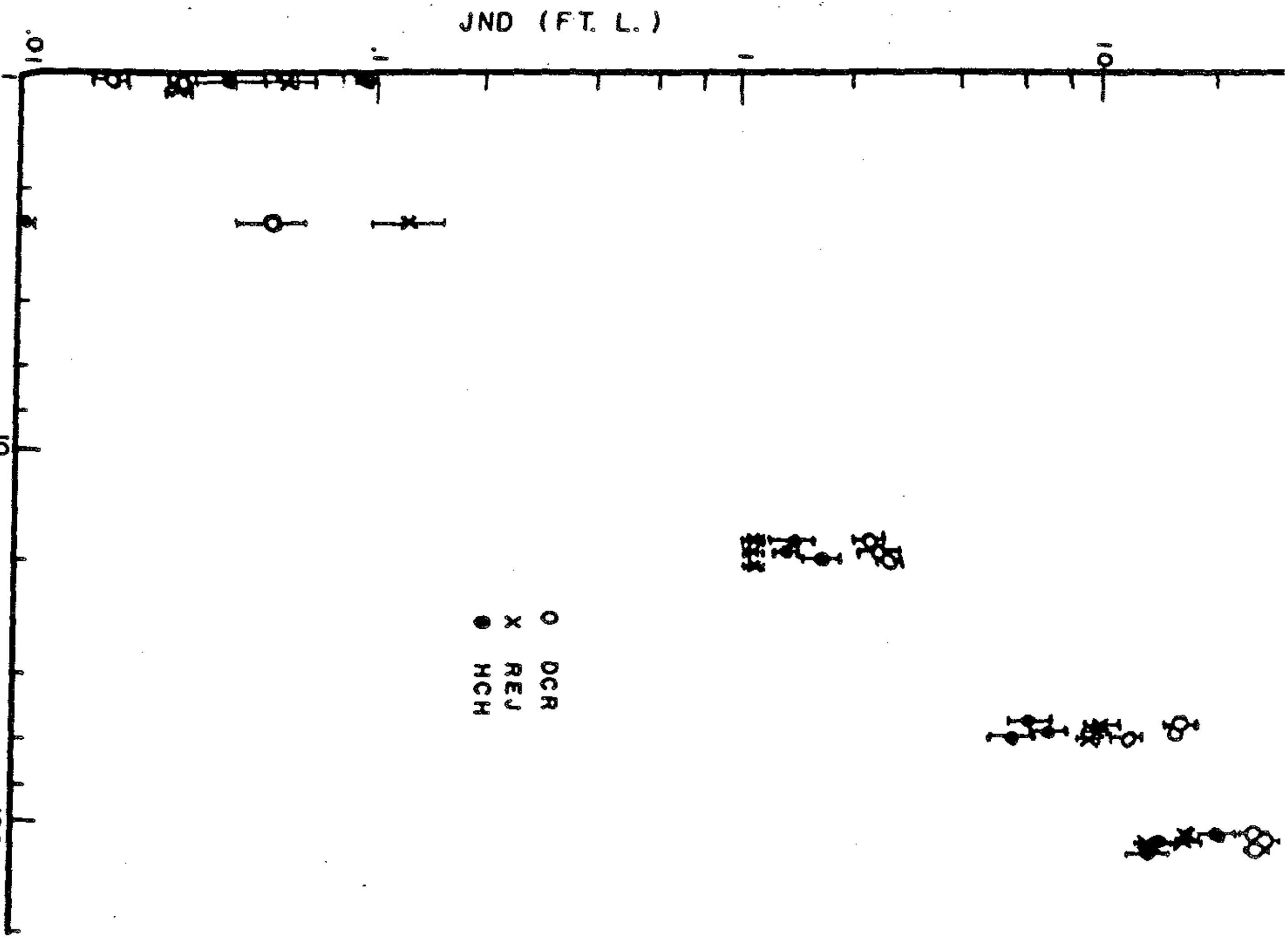


Figure 3.

FIGURE 4