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EVALUATION OF BRAKE-LAMP PHOTOMETRIC REQUIREMENTS

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16. Abstract

The objectives of this research were to (1) evaluate the luminance of current brake and presence lamps, (2) determine the relevant photometric parameter for brake lamps, and (3) determine minimum brake-lamp photometric requirements.

Six studies were performed. The first study used a photographic spot meter to obtain average luminance values, and photodensitometry to obtain luminance maps, for rear lamps of 40 automobiles. In the second study, equivalent luminance of a set of stock lamps was derived for use in later studies. Equivalent luminance was derived from brightness matches between the stock lamps and lamps of the same size and shape but of uniform luminance. The third and fourth studies investigated minimum brake-lamp photometrics for signal detection under high levels of ambient illumination. The fifth and sixth studies assessed the effects of lamp photometrics on the differentiation between brake and presence signals under low levels of ambient illumination.

On the basis of these studies, it is recommended that (1) luminous intensity be retained as the relevant photometric parameter of automobile brake lamps, and (2) 80 cd be retained as the minimum brake-lamp luminous intensity.

17. Key Words Brake lamps, rear lights, photometrics, luminous intensity, luminance, specifications, detection, identification, daytime, nighttime, reaction time

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Objectives

The objectives of this research were as follows:

(1) Evaluate the luminance of current brake and presence lamps.

(2) Determine the relevant photometric parameter for brake lamps.

(3) Determine minimum brake-lamp photometric requirements, based on daytime detection and nighttime signal-identification considerations.

To meet these objectives, the following studies were performed:

Task 1

This study used a photometrically calibrated photographic spot meter to obtain average luminance values, and photodensitometry (coupled with computerized image processing) to obtain luminance maps for rear lamps of 40 automobiles.

The average-luminance measurements showed an overlap of the brake-lamp and presence-lamp distributions: The lowest brake-lamp luminance was lower than the highest presence lamp luminance. Photodensitometry revealed that the lamps differed greatly in luminance uniformity: While some lamps were relatively homogenous, others showed substantial "hot" spots. (Within the area of a lamp, the variations in the luminance were up to 100:1.)

Task 2

The objective of this task was to provide luminance data on a set of stock lamps for use in later tasks. To deal with the spatial non-uniformities of stock lamps, a device was built that had the capability of presenting "lamps" of a variety of sizes and shapes, and of uniform luminance. Subjects were required to match the brightness of the stock lamps with that of the uniform lamp of the same size and shape. The luminance of the uniform lamp at the brightness match provided an "equivalent luminance" for the stock lamps. Using this approach, equivalent luminance data were obtained for six stock lamps at two viewing distances and two ambient illuminations. (The selected levels of viewing distance and ambient illumination corresponded to the levels used in the later tasks.)

(Continue on additional pages)

Task 3A

This task had two objectives. The first was to determine the minimum lamp photometrics for signal detection under a reasonably worst case of viewing. Such a case involves having the lamp oriented toward the sun. Consequently, this experiment was performed under conditions simulating sun shining on the rear of the vehicle. The second objective was to assess the relative power of luminous intensity, equivalent luminance, and average luminance to predict performance in a signal-detection paradigm.

Subjects in this study performed two simultaneous tasks. The primary task was detecting lamp signals in the near periphery of the visual field. The secondary, loading task consisted of a compensatory tracking task, necessitating involvement of the foveal (central) visual field.

The results of this study indicate that luminous intensity was a statistically significant predictor of both the reaction time to lamp signals and frequency of missed signals. Equivalent luminance, derived in Task 2 (and shown to be distance dependent), did no better in predicting the performance, while average luminance did worse. These findings support retaining luminous intensity as the relevant parameter of brake lamps.

Reaction time to lamp signals was generally a decreasing function of lamp intensity in the region from 40 to 80 cd, arguing against reducing the current brake-lamp minimum of 80 cd. However, no differences were obtained between 80 and 100 cd, thus providing no support for increasing the minimum.

Task 3B

The objective of this task was to provide a qualitative field validation of the findings in the laboratory Task 3A. Consequently, this experiment was performed under conditions analogous to those of Task 3A, but outdoors, and used only a limited number of conditions and subjects. (The subject, seated in a stationary automobile, performed the same two simultaneous tasks as in Task 3A.)

The data from this outdoor task were in good qualitative agreement with those in the corresponding laboratory Task 3A. Consequently, the data from the more extensive Task 3A (in terms of tested lamps, intensity levels, viewing distances, and subjects) can be relied upon in making recommendations.

Task 4A

This task had two objectives. The first was to determine the relationship between lamp photometrics and presence/brake signal differentiation. To assess this relationship, signal identification was evaluated as a function of lamp photometrics under simulated dusk/dawn conditions. The second objective was to assess the relative predictive power of luminous intensity, equivalent luminance, and average luminance to predict performance in a signal-identification paradigm.

On each trial two identical lamps were simultaneously energized so that they simulated either a non-separated or separated dual-lamp configuration. The subject's task was to indicate whether the signal presented was "presence" or "brake." To investigate the effects of past experience on signal identification, one group of subjects consisted of recently arrived West Europeans.

The findings from this study indicate that luminous intensity is a statistically significant predictor of signal identification. While equivalent luminance (derived in Task 2) and average luminance were also significantly related to signal identification, luminous intensity accounted for more variance of signal identification than the other two predictors.

In the range tested (100 to 18 cd), the likelihood of identifying a signal as a brake signal proved to be a monotonic function of lamp intensity. Furthermore, reaction time was inversely related to the degree of subjects' uncertainty (as measured by the relative likelihood of brake and presence responses): Reaction time was slowest when the likelihood of both types of response was close to 50%, and it decreased as the likelihood of brake responses increased or decreased away from 50%. These results argue against reducing the current minimum brake-lamp intensity of 80 cd.

The present study found no significant effect of the lamp configuration on the likelihood of brake responses, but there was a statistically and practically significant effect on reaction time: The mean reaction time for the non-separated lamp configuration was 0.19 sec faster than for the separated configuration. This disadvantage for the separated system is possibly the result of an increased duration of the decision process that requires comparison of two spatially separated areas (i.e., two lamps), in comparison to the decision process that could rely on only one of the two available spatial areas.

No differences were found between the performance of U.S. and European subjects who arrived recently in the U.S., suggesting that prior experience does not significantly affect brake/presence differentiation.

In summary, the results of this task provide support for retaining luminous intensity as the relevant parameter of brake-lighting specification. Furthermore, these results argue against reducing the current minimum of 80 cd for the brake-lamp luminous intensity.

Task 4B

The objective of this task was to evaluate for a color-coded rear-lighting system the potential effects of decreasing the intensity difference between presence and brake lamps from 18 vs. 100 cd to 18 vs. 40 cd. A signal-identification paradigm, analogous to the one in Task 4A, was used. This was an exploratory study, using a limited number of subjects.

The main finding of this study is that when rear lights are color-coded, decreasing the intensity difference between presence and brake lights from 18 vs. 100 cd to 18 vs. 40 cd does not increase the error rate of signal-identification responses, but it results in a small (0.03 sec) but statistically significant increase in reaction time.

Recommendations

On the basis of these studies, it is recommended that

(1) luminous intensity be retained as the relevant photometric parameter of automobile brake lamps, and

(2) 80 cd be retained as the minimum brake-lamp luminous intensity.

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INTRODUCTION

The objectives of this research were as follows:

(1) Evaluate the luminance of current brake and presence lamps.

(2) Determine the relevant photometric parameter for automobile brake lamps.

(3) Determine minimum brake-lamp photometric requirements, based on daytime detection and nighttime signal-identification considerations.

To meet these objectives, the following studies were performed:

Task 1:	evaluating luminances of actual presence and brake lamps,
Task 2:	calibrating test lamps for use in later tasks,
Task 3A:	investigating, in a laboratory setting, the effects of lamp photometrics on daytime detection of brake signals,
Task 3B:	providing field validation for Task 3A,
Task 4A:	studying the effect of lamp photometrics on signal identification, and
Task 4B:	studying the effect of lamp photometrics on signal identification for a color-coded rear-lighting system.

TASK 1: MEASUREMENT OF LUMINANCES OF PRESENCE AND BRAKE LAMPS BY PHOTODENSITOMETRY

Introduction

The goal of this task was to determine the range of luminance values of presence and brake lamps on a sample of vehicles on the road, measured from the eye point of a following driver.

Method and Procedure

Photodensitometry coupled with computerized image processing was used to obtain luminance value distributions. Average luminance values were obtained with a photometrically calibrated photographic exposure spot meter. Vehicle selection, test geometry, photographic considerations, data collection, and data processing are described below.

Vehicle selection. Forty vehicles were sampled according to the following categorization:

(1) Eight vehicles which had presence and brake lamps as separate physical structures in their rear-lamp assembly.

(2) Twenty eight vehicles which had presence and brake lamp functions within the same physical structure, designated as non-separate.

(3) Four vehicles with quasi-separated systems, where one or more lamp cavities on each side functioned as in the separated systems, and one or more lamp cavities on each side functioned as in the non-separated systems.

The sample included a variety of makes and models manufactured between 1974 and 1984 (see Tables 1 and 2). The sample included only passenger cars, with no vans or pickups.

Test geometry. Measurements were taken from positions relative to rear-lamp assemblies corresponding to the driver eye-to-lamp geometry in a real-world situation. This geometry is defined by the lamp-to-eye distance, lamp height above the ground, driver's seated eye height, and lateral separation from straight ahead.

The following assumptions were made:

TABLE 1

CAR MODELS TESTED IN TASK 1

Model	Frequency
GM	11
CHRYSLER	6
FORD	5
DATSUN	2
HONDA	2
SAAB	2
TOYOTA	2
VW	2
ALFA ROMEO	1
AMC	1
BMW	1
JAGUAR	1
MERCEDES	1

TABLE 2

CAR MODEL YEARS IN TASK 1

Model Year	Frequency
1984	5
1983	6
1982	4
1981	5
1980	2
1979	3
1978	4
1977	3
1976	2
1975	3
1974	3

(1) The vehicle is located in the center lane of three 12-foot-wide traffic lanes.

(2) The driver is 50 ft back from the vehicle in one of the three traffic lanes.

(3) The center of the rear-lamp assembly is 26.5 in from the road surface.

(4) The driver eye point is 42 in from the road surface.

These assumptions, along with the requirement of filling the frame of a 35-mm film with a 15-in wide lamp (using a 300 mm, f/5.6 catadioptric lens) determined the positions of the camera and the spot meter. The "center" position (for both the camera and the spot meter) was at the centerline of the lamp, 133.5 in from the lamp, and 30 in from the ground. The "left" and "right" positions (for the spot meter only) were 32 in (13.5°) left and right from the centerline, but at the same distance from the lamp and height from the ground as the "center" position.

Photographic considerations. In addition to many modern photoelectric devices presently used for photometry and radiometry, an important and widely-used technique is the use of the photo-sensitive emulsion in photographic film. The sensitometric characteristics of modern photographic films have applicability across a very wide spectral range from the infra-red to high energy x-rays. This study considered only a part of the visible spectrum, the red, beginning at approximately 600 nanometers, to determine luminance over an extended incandescent source.

Exposure and development of photographic film produces an image consisting of areas having different transmittances of light, depending on the number and size of the silver grains present. If the transmittance is measured by the ratio of the intensity of the undeviated light passing through the film to that of the incident collimated light, then the transmittance is called diffuse transmittance. In ordinary photodensitometry, as was performed in this study, semi-diffuse transmittance was measured, because each component was present, but some of the scattered light could not be collected by the optics of the densitometer.

The opacity, O, is defined as the reciprocal of the transmittance. The density, D, is defined as $\log_{10}$ O. Hence, depending upon the area of the aperture which defines the light and the number and size of the silver grains present in the developed emulsion, there is a corresponding density resulting from a particular exposure. Density measurements in this study were made with a Macbeth TD-500 Quantalog densitometer using a 1-mm diameter aperture. The densitometer was calibrated with a standard three-step tablet of three known densities: 0.8, 1.5, and 3.0.

The exposure, E, may be expressed as the time integral of the focal plane illuminance, I_f, or radiant intensity per unit area incident on the film (intensity is energy per unit time per unit solid angle), so that

$$E = C \int_0^t \int_{\lambda_1}^{\lambda_2} V(\lambda)\, I_f(\lambda)\, d\lambda dt,$$

where the film performs the integration. The quantity $V(\lambda)$ is the relative visual spectral response function, also known as the CIE curve (from the Commission Internationale Eclairage agreement of 1931), and C is a constant involving conversion factors. The units of E are customarily expressed in meter-candle-seconds, or more recently, lux-seconds. The above expression takes note of the fact that photographic film is a spectrally selective detector as well as an integrating detector, since film does not have a uniform response over a spectrum.

If a lens is adjusted to focus a surface, or extended source of luminance, in its focal plane, there is a definite relation between field luminance and focal plane illuminance. Focal plane illuminance, I_f (on the lens axis) depends primarily on the luminance of the source, L, and the solid angle that it subtends as defined by the lens aperture and focal distance, as follows (Kingslake, 1967).

$$I_f = L/A^2,$$

where A is the ratio of lens focal length to lens diameter.

Film and processing-procedure selection. The best format for collection of the photodensitometric data was deemed to be 35-mm roll film, black and white, for reasons of low cost, availability, and ease of handling, both in camera and chemical processing.

An important consideration in film type selection for the purpose of this study was its spectral sensitivity. The film must have a reasonably good spectral sensitivity to tungsten light in the wavelength region from 610 to 670 nanometers, defined as "red" in SAE Standard J578d, "Color Specification for Electric Signal Lighting Devices." There are four classes of spectral sensitivity in photographic emulsions: blue-sensitive, orthochromatic, panchromatic, and infra-red sensitive. Only panchromatic-sensitive film met the above spectral sensitivity requirement, and corresponds approximately to the photopic spectral response characteristics of the human eye to tungsten light at a color temperature of 2,854°K.

Another important consideration in film-type selection was exposure latitude, which is also strongly influenced by development time, temperature, and developer concentration and type. In this study, exposures were to be obtained from lamps ranging approximately from 2 to 300 candelas. Resulting density data should fall as nearly as possible on the most linear portion of the film characteristic curve, which relates density to exposure (intensity x time). A film was sought that had a long linear exposure range.

Three panchromatic black-and-white film types were subjected to a series of exposure and processing tests. They were Kodak Panatomic-X, Kodak Plus-X, and Kodak Tri-X.

Exposure and processing tests were conducted on at least twelve samples of each film type with the camera and lens that were subsequently used for data collection. The camera was an Olympus OM-1 with a 300-mm, f/5.6, fixed aperture, catadioptric lens. This camera-lens combination allowed exposure control only on shutter speed, because the aperture was physically fixed at f/5.6. A Kodak Wratten #25 filter was placed in front of the lens to allow only light wavelengths from 600 nanometers on to strike the film. A known light source consisting of a Photo Research Corp., Spectra, regulated, diffuse, brightness lamp was photographed at each shutter setting at a distance of 133.5 in. Shutter times in seconds available on this camera were as follows: 1/1000, 1/500, 1/250, 1/60, 1/30, 1/15, 1/8, 1/4, 1/2, and 1. Each exposure at a given shutter speed for each film type occupied a single frame.

Two processing procedures were compared for reproducibility. Both procedures used Kodak D-76 developer, diluted in a ratio of 1:1, at a temperature of 68°F. One procedure consisted in developing films in a small tank, agitated for 5 sec. at 30 sec. intervals. Panatomic-X and Plus-X films were developed for 7 min; Tri-X was developed for 10 min., as recommended by Kodak to achieve a contrast index of 0.53 for all three types. The second procedure used constant agitation for 5.5 min., for Panatomic-X and Plus-X, and 7.5 min. for Tri-X, also recommended by Kodak to achieve a contrast index of 0.53. (The contrast index of 0.53 was chosen because this value would give the widest exposure latitude with a reasonable expectation of uniformity.) Processing times less than the recommended ones put uniformity expectations at risk (Eastman Kodak Co., 1976).

Densities were measured on each exposure and plotted to compare uniformity and exposure latitude. The small-tank method was performed in-house. The constant agitation method was performed by machine at a local processor, Precision Photographics, Inc., which handles much scientific and professional photography in Ann Arbor for the University and industrial research organizations. It was immediately found that the processing by machine was clearly superior in terms of reproducibility than the small-tank method. The commercial processor was then subjected to further testing for uniformity by submitting additional films of all three types exposed in the normalized manner described above.

The results of the film selection tests are shown in Figure 1. Ranges of variation in density at each exposure point are seen to vary considerably for Tri-X, particularly at higher exposures. Panatomic-X is seen to have reasonably good uniformity, but a very narrow exposure latitude, and hardly any linearity at all. Plus-X was the film of choice because it had a long linear exposure latitude and good uniformity. The processor was then subjected to further random checks on reproducibility using Plus-X film exclusively. These quality control tests indicated that processing consistency could be reasonably expected; hence, it was decided to use Plus-X film, developed to a contrast of 0.53 by machine processing at Precision Photographics.

Camera-film system calibration. Focal plane illuminance, I_f, has already been defined as the ratio of the luminance of the source, L, to the square of the relative aperture of the lens, or f-number, squared:

$$I_f = L/A^2 \text{ (meter-candles)}$$

Exposure, E, has already been defined as the product of illuminance and time, hence,

$$E = I_f t = Lt/A^2 \text{ (meter-candle-sec),}$$

if the luminance, L, is expressed in candelas per square meter (cd/m^2).

In a real camera and lens, however, all of the light incident on the lens does not fall on the film, because there is some scattering of the light off the axis of the lens, and some absorption of the light in the lens. Also, these effects are wavelength-dependent. These attenuating effects must be taken into account with a transmission factor, k, in the exposure equation, so that

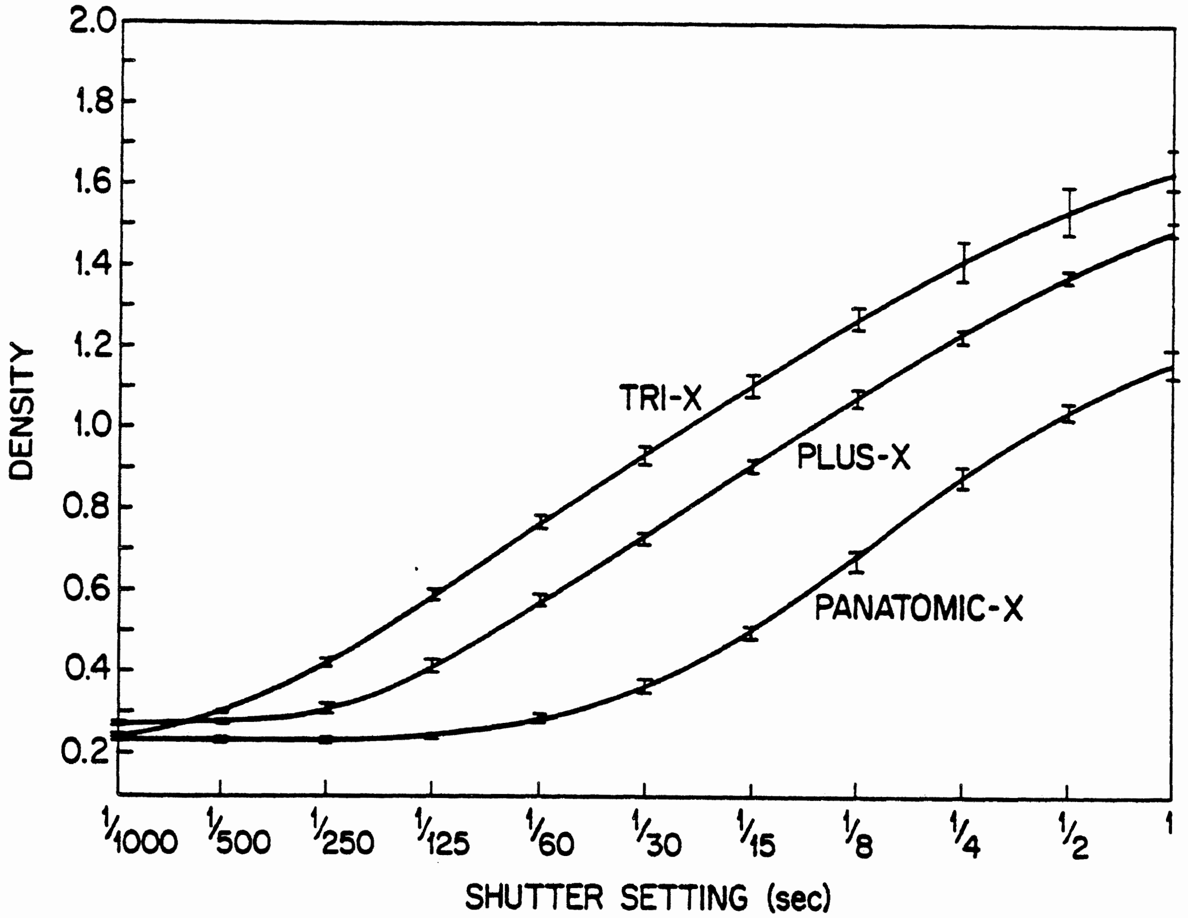

Figure 1. Comparison of Tri-X, Plus-X, and Panatomic-X films to normalized exposure and processing. (All at f/5.6, Wratten #25 filter, D-76, 1:1, 68°F, constant agitation.)

$$E = kLt/A^2 \text{ (meter-candle-sec)}.$$

In addition to the above-described optical effects, there is for every still camera a so-called "effective" shutter time, because a shutter, whether focal-plane or leaf type, cannot accelerate and decelerate instantaneously across the camera aperture. The quantity, t, in the exposure equation must be corrected for known deviation from the camera-indicated shutter speed. Another factor concerning shutter behavior, particularly a focal-plane type that was used in this study, is the uniformity of its traverse across the aperture. A serious non-uniformity can give rise to a bias in photographic density across the film. If it exists, it must be corrected for in film density measurements. Lastly, concerning the f-number of the lens, it generally has to be assumed that the lens manufacturer has produced a highly accurate instrument, and that the f-numbers are accurate to a much greater degree than any of the other above-described factors.

A value for the k factor in the exposure equation was determined for the camera and lens used in this study by measuring the ratio of light (filtered with a Wratten #25 filter, to take into account wave-length effects) transmitted to the focal plane, to the filtered light incident on the lens. Measurements were made with a Spectra Pritchard photometer. A 99.9% reflective plate was at the rear of the camera as nearly as possible at the focal plane, with the camera back open, the mirror locked up, and shutter open. The transmission factor for this camera and lens was determined to be 0.720, in the wave region of interest.

Shutter time behavior was examined with a Camline Shutter Analyzer, Model 22. This is an instrument that determines shutter speed photoelectronically at three places along the path of a focal-plane shutter in motion: (1) at opening, (2) at the center, and (3) at closing. The arithmetic mean of the three shutter time points is defined as the effective shutter time. The three speed values also give an indication of possible exposure bias. All of the shutter speed settings on the Olympus OM-1 camera used in this study were tested for repeatability and for exposure bias. The two shutter speeds used in data collection were 125 and 500. The nominal time for 125 is 0.008 sec., and for 500 is 0.002 sec. Effective shutter times for 125 and 500 were found to be 0.007 sec. and 0.0024 sec., respectively. These are differences of 12.5% for 125 and 16.7% for 500, hence considerable error could arise in the exposure equation if nominal shutter speed time values had been used. Variation in shutter motion across the image plane from opening, center, and closing was found to be, for 125, 3%, and for 500, 1%. These variations were considered to be insignificant for density bias corrections. Repeatability on the measurements was nearly 94%, to three significant figures.

Having determined the optical and time characteristics of the camera and lens, it remained only to determine the relationship between photographic density and exposure for the selected film. This was done by the sensitometric method described below.

A 100-ft roll of Kodak Plus-X negative film was obtained for the calibration, and for subsequent rear-lamp luminance data collection, so that there would be minimal variation in photographic response due to manufacturer's variation in emulsion preparation; this would not have been the case had individual off-the-shelf, manufacturer-loaded cassettes been used. The film exposure tests used random, off-the-shelf individual rolls of film to provide worst-case conditions for the investigation of uniformity of photographic response and reproducibility of development.

The film calibration consisted of: (1) exposure of strips of the bulk Plus-X film through a Kodak #2 step tablet in contact with the film to a known illumination of a known spectral distribution, and for a known time; (2) development of the film under the same controlled conditions already established; and (3) measurements of density with the Macbeth TD-500 Quantalog densitometer.

A Kodak photographic step tablet is a "stepwedge" consisting of 21 densities running from about 0.05 to about 3.05. Each step differs from the preceding step by a density difference of about 0.15, corresponding to an exposure difference of 1.414, or the square root of 2. The step tablet densities were checked with the Macbeth densitometer and found to be in accordance with its specifications, as shown in Figure 2.

An Omega enlarger was used to make the exposures, because light intensity could be controlled conveniently by changing magnification, and time could be accurately controlled with an electronic timer. The light source was filtered with a Wratten #25 filter to give a spectral distribution corresponding to the SAE Standard J578d definition of "red" (Eastman Kodak Co., 1968). Illuminance on the baseboard of the enlarger was measured with a Gossen Panlux meter calibrated in foot-candles. Magnification and time were adjusted so that all 21 steps were visible in the developed film. Illuminance and time measurements were converted to meter-candle-seconds. Resulting densities were measured on the Plus-X film strips, developed by the established procedure, and plotted to give the characteristic curve, shown in Figure 3. Exposure values are expressed in millilux-sec to avoid dealing with negative logarithms. Base plus fog density (D-min) was found to be 0.28; D-max was 1.86. The slope of the most linear part of the curve, gamma

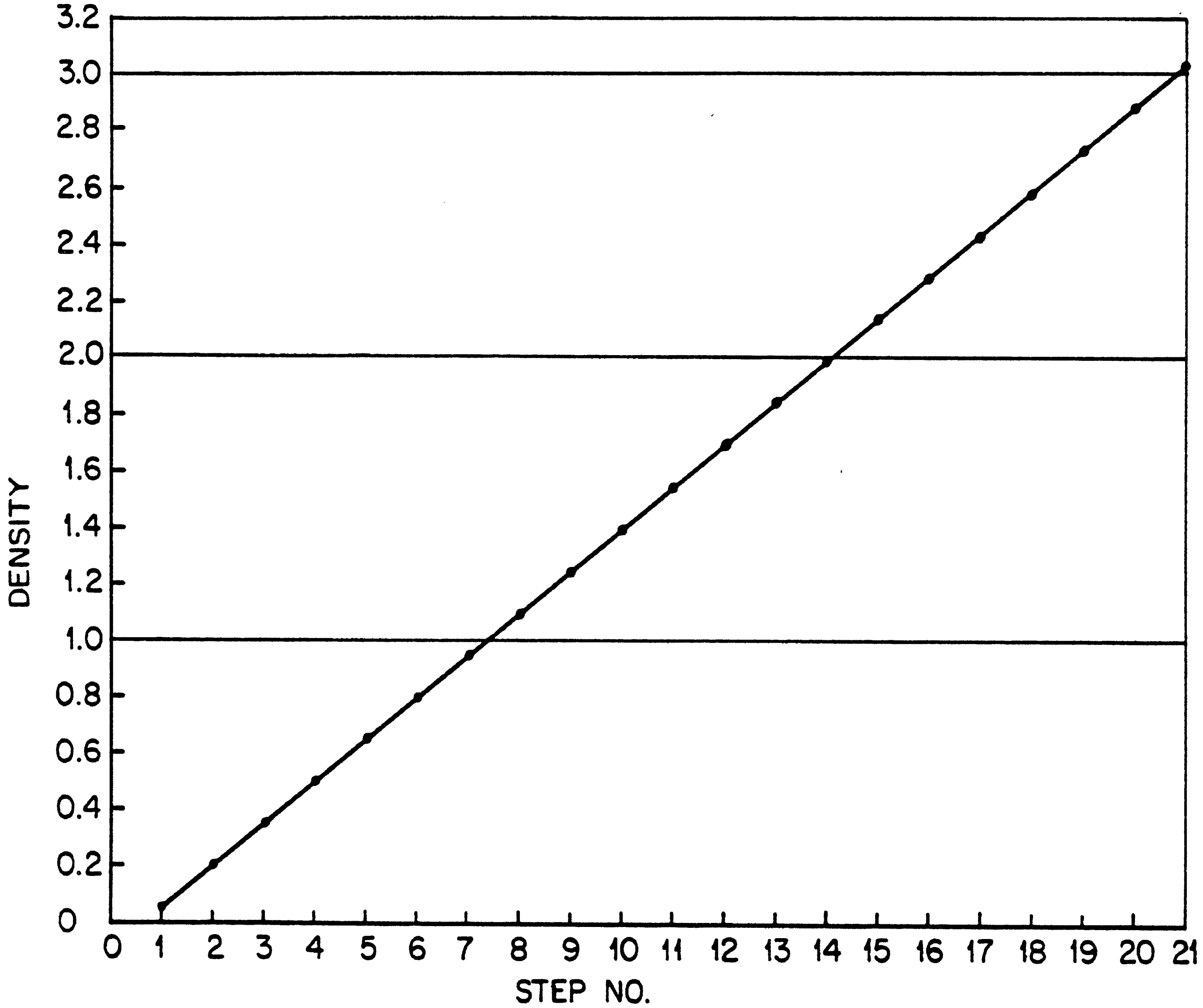

Figure 2. Density vs. step number for Kodak #2 step tablet.

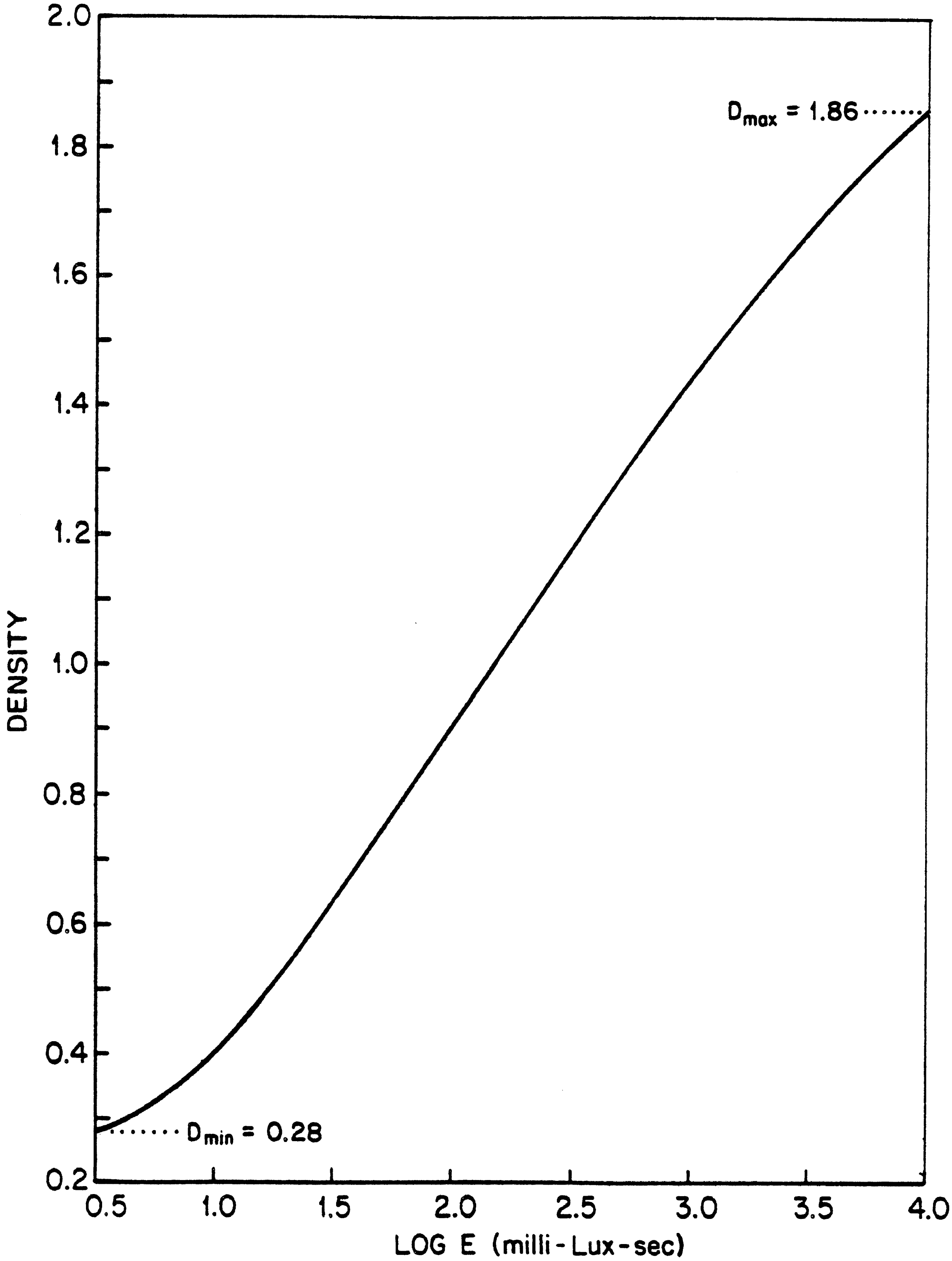

Figure 3. Characteristic curve for Plus-X film. (Wratten #25 filter; processed with D-76, 1:1, 68°F, 5.5 minutes, constant agitation.)

(γ), was found to be 0.527, which indicated that the processing procedure continued to be consistent. The camera and film system to be used for data collection was then considered to be calibrated.

Data collection procedure. Two forms of rear-lamp luminance data were collected from the sample of forty vehicles: (1) average luminances, and (2) photographic recordings of luminance variations over the areas of the lamps. These data were taken for both presence and brake lamp functions for each vehicle, according to the procedures described below.

A large chamber into which a car could be driven, and which could be darkened for the photography, was made available to the project. On the floor of this chamber two yellow lines perpendicular to car direction were painted to assure reproducibility in geometry for each subject vehicle. Each vehicle was identified in a numerical sequence, beginning with no. 1 on through no. 40. Each subject was directed to drive into the chamber so that the subject's rear-lamp assembly was positioned directly above the yellow line. Immediately following this, the car's exhaust system was vented to the outside atmosphere with a blower and pipe. The left-side lamp assembly was then cleaned, since all measurements were taken from the left assembly. The driver was then instructed to start the car's engine and let it run at its idle speed. The second yellow line, parallel to the first, at a distance of 133.5-in. rearward, provided the base-line for positioning of the camera and line of sight for the average luminance measurements, all to correspond with the geometry considerations previously described. All data were taken with engines running at idle.

Average luminance measurements. Average luminance measurements were made with a 1° Pentax spot meter used as a brightness photometer. The spot meter was calibrated with a known brightness source; the brightness source was measured in foot-lamberts with a Spectra-Prichard photometer. The conversion function of spot meter units to to cd/m^2 is shown in Figure 4.

The metering angle of the Pentax spot meter is 1° of arc, and the meter gives an average value of brightness of the area of the source subtended by this angle. In some cases the brightness of a lamp assembly could be obtained with a single reading, if the source just filled the viewing circle. In other cases, more often than not, lamp lenses were sufficiently large in area that several readings were required. Some lamp lenses were so large that up to six readings across the total area were required. In all cases where multiple readings were made, the data were averaged to give a single average value for the lamp assembly. Each presence and brake lamp for all 40 vehicles were measured in

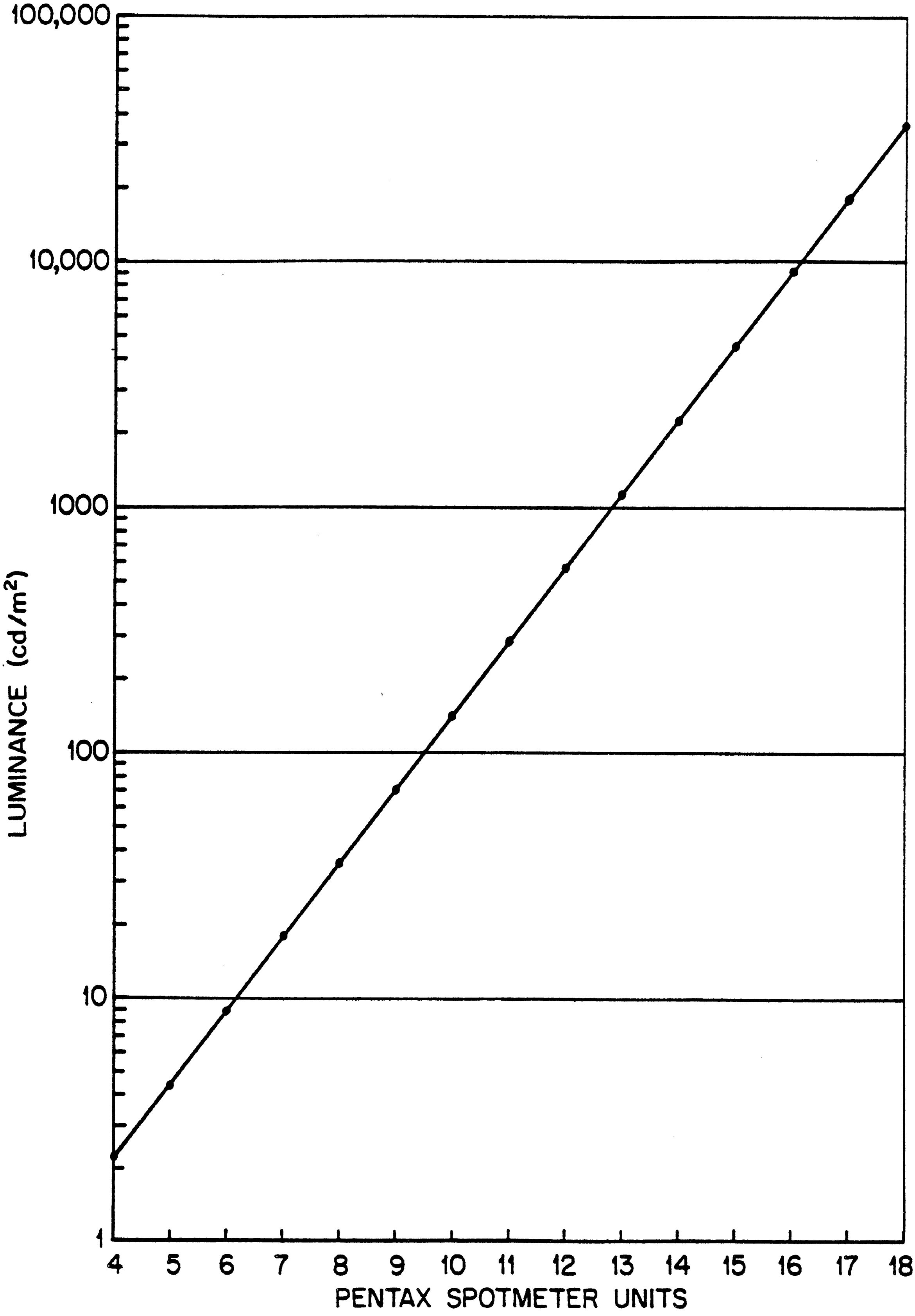

Figure 4. Conversion data of Pentax spot meter units to luminance.

this manner, at each of three positions behind the vehicle: center, right, and left, resulting in a total number of 240 average luminance values expressed in cd/m^2. For purposes of data processing, a fitted function was obtained for the data in Figure 4:

$$\log_{10}L = 0.30083S - 0.86334,$$

where L is luminance in cd/m^2, and S is the spot meter unit reading.

Photographic data collection. Presence and brake lamps for 40 vehicles were photographed at the center position for each lamp, giving a total of 80 black and white, negative photographs for the vehicle sample.

The Olympus OM-1 camera was mounted on a tripod so that the lens axis was 30-in. above the ground, in accordance with the previously discussed geometry. The lens was not filtered. A data-recording back was used on the camera so that film frames could be identified in correlation with the vehicles. The same numerical sequence as in the average-luminance-data collection (of 1 through 40) was used.

In anticipation of the much greater dynamic range of lamp luminances between presence and brake lamps than the dynamic range of the film, two shutter speed settings were used: 125 for presence lamps, and 500 for brake lamps. The lens aperture was fixed at f/5.6, because the catadioptric lens used did not have the capability for aperture variation.

The shutter speed settings of 125 and 500 for the presence and brake lamps were arrived at by preliminary photographic tests of various vehicles, using lower and higher shutter speeds. Densities were measured on these films with the Macbeth densitometer, using a 1-mm aperture, to ascertain that the resulting densities over different areas of the lamps corresponded to the useful exposure latitude of the film. This requirement was considered to be met best by the shutter speeds specified.

The data were collected on nine rolls of the calibrated, bulk-loaded film from the 100-ft roll. The rolls were processed in two batches of four rolls in one batch and five rolls in another. The first and last frame of each roll contains a photograph of the Kodak #2 step tablet, which was illuminated by a Kodak 650H projector, through a plate of 0.25 in. thick, #048 white plexiglass, to provide a uniform and diffuse light source, and filtered with the Wratten #25 filter. Densities were measured on each of the test frames on each roll to assure that the processing was uniform within each roll, and from roll to roll.

The total maximum spread between the maximum and minimum base plus fog densities in the first batch was 3.3%, and in the second batch, 2.9%; these data included frames within a roll, and from roll to roll. Film calibration for the data collection was regarded as having been maintained essentially constant.

Computerized image processing. Forty presence-lamp and forty corresponding brake-lamp photographs, taken on the center line of the lamp assemblies, were processed on the U-M computerized image processing research network (CIPRNET) to produce area luminance distributions for each lamp.

The CIPRNET consists of a DeAnza system which uses a Digital Equipment Corporation DEC-VAX 110 machine, with a UNIX operating system. The DeAnza system was programmed to do the following: (1) digitize the images of the lamps; (2) produce computer-generated pseudocolors, which corresponded to particular gray levels in the black-and-white digitized images; and (3) display the color distributions on a color video monitor.

Photographic lamp images were scanned on a light table by a Fairchild CCD (charge coupled device) video camera with a 75 mm, f/1.4 Cosmicar television lens. A 20-mm lens extender tube was used to provide a magnification ratio such that the width of a 35-mm film frame just encompassed the width of the video monitor. In this way, all lamp image dimensions with respect to height and width in relation to each other were preserved.

A completely filled video frame has a resolution capability of 512 x 512 pixels, height and width, to give a total of approximately 262,000 pixels, or unit picture elements for a given image. Since the lamp images did not completely fill the 35-mm film frames, except for a few cases where the width of the assembly was larger than 15 in, the number of pixels per lamp image was considerably less. The scanning resolution was 7 x 7 pixels, but this was sufficiently small to display detailed fine structure in the construction of the lenses in the rear-lamp assemblies. These details can be seen in the photographically recorded data of the computerized-processed images, presented as 2 in x 2 in color slides.

The computer had the capability of dealing with 256 levels of gray shades, counting zero, from white to black, but the dynamic range of the Fairchild video camera and the dynamic range of the film imposed limitations on this capability. An image of the Kodak #2 step tablet taken from one of the rolls in the data collection allowed 155 gray levels, which was considered to be quite good. Thirteen of the twenty-one steps of the step tablet were visible on the film by eye and on the video display after digitization by the computer. It was then necessary to assign luminance values to the steps, to constitute a calibration of the luminance distribution. The thirteen steps of the step tablet were displayed as a color bar of discrete steps of colors, ranging from red for higher values of luminance down through orange, yellow, green, blue, and violet for descending values of luminance.

Two color calibration bars were required, one for the photographs of the presence lamps taken at a shutter speed of 125, and the other for brake lamps taken at 500.

The presence lamp calibration bar legend was prepared as follows:

(1) Densitometer measurements were made on selected frames of the photographic data to seek the highest densities. (The data obtained with a 1-mm aperture was an average over the aperture area. The photography yielded images of fine detail of lens structure in which densities could be [and probably were] higher. This would have involved microphotodensitometry, as is used in astronomical spectroscopy, but such a procedure was outside of the scope of this project.) Maximum densities found in this manner were of the order of 1.35.

(2) The film calibration curve yields an exposure value of log E = 2.83 for a density of 1.35. The antilog of 2.83 is equal to 676 millilux/sec., or 0.676 lux/sec.

(3) From the exposure equation given previously:

$$E = kLt_{eff}/A^2$$

The luminance, l, in cd/m^2, is

$$L = E\ (\text{lux/sec})/0.000161\ \text{cd/m}^2$$

for $t_{eff} = 0.007$ sec, and $A^2 = 31.36$; (f/5.6).

(4) The corresponding decrements in exposure, for the thirteen steps, are given in Table 3.

Since the densitometer could only be read to three significant figures, all data are rounded off to three significant figures. (The luminance value for step 1 should be interpreted as greater than or equal to 4,210 cd/m^2, and the luminance value for step 13 as less) than or equal to 66.6 cd/m^2.

The analogous thirteen steps for the brake lamp calibration bar legend are given in Table 4. (Here, $t_{eff} = 0.0024$ sec, and the maximum densities—averaged over the 1-mm

TABLE 3

PRESENCE LAMP LUMINANCES CORRESPONDING TO STEP IN TASK 1

Step	Log E_{step}	Millilux-sec	Lux-sec	L(cd/m^2)	Log L(cd/m^2)
1	2.83	676	0.676	4,210	3.63
2	2.68	479	0.479	2,980	3.47
3	2.53	339	0.339	2,110	3.32
4	2.38	240	0.240	1,490	3.17
5	2.23	170	0.170	1,060	3.02
6	2.08	120	0.120	747	2.87
7	1.93	85.1	0.0851	530	2.72
8	1.78	60.3	0.0603	375	2.57
9	1.63	42.7	0.0427	266	2.42
10	1.48	30.2	0.0302	188	2.27
11	1.33	21.4	0.0214	133	2.12
12	1.18	15.1	0.0151	94.0	1.97
13	1.03	10.7	0.0107	66.6	1.82

densitometer aperture—were on the order of 1.67.) As with the presence lamp data, three significant figures are presented. (Here, also, step 1 luminance should be interpreted as greater than or equal to 57,400 cd/m^2, and for step 13 as less than or equal to 910 cd/m^2.)

The video display of the luminance distribution for each presence and brake lamp, together with its corresponding color calibration bar, was photographed with a Minolta SRT-101 35-mm camera, using Kodak Ektachrome 200 color slide film, with a Kodak color compensating filter CC40R. A 35-mm focal-length lens with a +1 diopter close-up lens was used to fill the film frame width with the width of the video display, so that the scanning magnification ratio would be preserved in the slide format. The slide format was chosen because it is the most convenient for presentation. Each frame carried the vehicle identification, and whether it is presence or brake by a "P" or "B" following the identification number.

It is particularly important that the lowest number in the presence calibration legend be interpreted as "less than or equal to," because some parts of the violet region may represent base density plus fog in the black and white data, or some low value of luminance to give rise to film density near base plus fog.

The question as to whether or not the base density plus fog value should be subtracted from density data was considered. In certain applications in astronomy and spectroscopy, this is usually done, because densities are in general much lower than were encountered in this study. In exposure regions of very high densities, it is not entirely clear what the base plus fog density is, so it was not subtracted. In any event, base plus fog density means zero luminance.

TABLE 4

BRAKE LAMP LUMINANCES CORRESPONDING TO STEP IN TASK 1

Step	Log E_{step}	Millilux-sec	Lux-sec	L(cd/m^2)	Log L(cd/m^2)
1	3.50	3,160	3.16	57,400	4.76
2	3.35	2,240	2.24	40,600	4.61
3	3.20	1,580	1.58	28,800	4.46
4	3.05	1,120	1.12	20,400	4.31
5	2.90	794	0.794	14,400	4.16
6	2.75	562	0.562	10,200	4.01
7	2.60	398	0.398	7,220	3.86
8	2.45	282	0.282	5,110	3.71
9	2.30	200	0.200	3,620	3.56
10	2.15	141	0.141	2,560	3.41
11	2.00	100	0.100	1,820	3.26
12	1.85	70.8	0.0708	1,280	3.11
13	1.70	50.1	0.0501	910	2.96

Results

Average luminance values. Average luminance values for the total set of 40 cars are described in Table 5. Table 6 provides the analogous information by the type of rear-lighting system.

Photodensitometry. Eighty 2 in x 2 in color slides were prepared and submitted to the sponsor.

Discussion

The main findings are as follows:

Average luminance values

(1) There is an overlap of the brake-lamp and presence-lamp distributions: The lowest brake-lamp luminance is lower than the highest presence-lamp luminance, and this holds true for measurements taken at 0°, 13.5° Right, and 13.5° Left.

(2) The range of brake-lamp luminance values was 20:1 at 0°, 19:1 at 13.5° Right, and 26:1 at 13.5° Left.

(3) The range of presence-lamp luminance values was 22:1 at 0°, 13:1 at 13.5° Right, and 26:1 at 13.5° Left.

(4) The ratios between the brake-lamp luminance and presence-lamp luminance ranged from 8:1 to 53:1 at 0°, from 4:1 to 45:1 at 13.5° Right, and 6:1 to 53:1 at 13.5° Left.

(5) There is a substantial luminance drop moving from 0° to 13.5° Right or Left.

(6) "Separated" systems tended to have higher (a) brake-lamp luminances, (b) presence-lamp luminances, and (c) ratios between the brake-lamp luminance and presence-lamp luminance.

Photodensitometry

(7) The sample showed a substantial range of luminance uniformity: While some brake and presence lamps were relatively homogenous, others showed substantial "hot" spots.

(8) The geometry of the hot-spot areas varied from car to car.

(9) Within the area of a lamp, the variations in the luminance were up to 100:1.

TABLE 5

AVERAGE LUMINANCE VALUES IN TASK 1 (cd/m^2)

Light	N	Angle	Minimum	Maximum	Mean
Brake	40	0°	2,660	54,100	19,989
Presence	40	0°	261	5,620	1,163
Ratio Brake/Presence	40	0°	9	53	19
Brake	40	13.5° Right	1,880	35,700	9,355
Presence	40	13.5° Right	166	2,090	652
Ratio Brake/Presence	40	13.5° Right	4	45	14
Brake	40	13.5° Left	1,390	35,700	10,956
Presence	40	13.5° Left	118	3,760	725
Ratio Brake/Presence	40	13.5° Left	6	53	16

TABLE 6

AVERAGE LUMINANCE VALUES BY TYPE OF REAR-LIGHTING SYSTEM IN TASK 1 (cd/m^2)

NON-SEPARATED					
Light	N	Angle	Minimum	Maximum	Mean
Brake	28	0°	2,660	35,700	14,904
Presence	28	0°	261	1,580	837
Ratio Brake/Presence	28	0°	9	38	18
Brake	28	13.5° Right	1,880	25,800	7,053
Presence	28	13.5° Right	166	890	517
Ratio Brake/Presence	28	13.5° Right	5	44	14
Brake	28	13.5° Left	1,390	26,300	7,843
Presence	28	13.5° Left	118	1,120	518
Ratio Brake/Presence	28	13.5° Left	6	27	15
SEPARATED					
Brake	8	0°	3,760	54,100	36,995
Presence	8	0°	413	5,620	2,339
Ratio Brake/Presence	8	0°	9	53	22
Brake	8	13.5° Right	2,990	35,700	17,433
Presence	8	13.5° Right	254	2,090	1,090
Ratio Brake/Presence	8	13.5° Right	4	45	17
Brake	8	13.5° Left	2,100	35,700	23,650
Presence	8	13.5° Left	263	3,760	1,517
Ratio Brake/Presence	8	13.5° left	8	53	21
QUASI-SEPARATED					
Brake	4	0°	10,400	50,500	21,575
Presence	4	0°	471	2,400	1,093
Ratio Brake/Presence	4	0°	12	30	20
Brake	4	13.5° Right	3,760	21,200	9,315
Presence	4	13.5° Right	333	1,580	713
Ratio Brake/Presence	4	13.5° Right	11	14	13
Brake	4	13.5° Left	3,160	15,000	7,362
Presence	4	13.5° Left	280	1,200	587
Ratio Brake/Presence	4	13.5° Left	10	17	13

TASK 2: LUMINANCE CALIBRATION OF TEST LAMPS

Introduction

The purpose of this task was to provide luminance data on a set of stock taillamps for use in later tasks. However, the photometric work described in the preceding chapter has shown that the taillamps employed on vehicles typically have non-uniform surface luminance. It is also clear that the degree of uniformity varies greatly from unit to unit. This non-uniformity, together with different lamp sizes and shapes, means that the luminance of a taillamp cannot be readily measured by conventional photometric instruments.

Since luminance data were essential to the conduct of later tasks in the program, an alternative means of obtaining them was required. To do this a device was fabricated that had the capability of presenting "taillamps" of a variety of sizes and shapes, but of relatively uniform luminance. Subjects were required to match the brightness of this device to that of the stock lamps of interest. Then photometry of the simulated lamp provided an "equivalent luminance" for the stock lamps.

Method

Introduction. Six stock taillamps were selected for testing. These were part of a collection of 18 lamps that had been evaluated by a panel of lighting experts brought together by the Motor Vehicle Manufacturers Association (MVMA). The lamps had been divided into groups based on surface area, and ranked for surface brightness uniformity under both daylight and dark conditions. For this test the most and least uniform lamps in two size categories were selected. Following the numbering scheme of the MVMA panel, the six lamps were labeled as 1, 2, 3, 6, 9, and 14. Table 7 is a listing of the lamps, together with associated dimensions information.

Independent variables. The following is a listing of the independent variables.

Lamp size. Two sizes of lamps were included in the study. These will be referred to as small and large, respectively. There were four small lamps (from 11.9 to 14.7 in^2) and two large lamps (24.4 and 29.6 in^2). All six lamps were single bulb units.

Surface luminance uniformity. Two levels of uniformity were used. Three of the test lamps (two small ones and one large one) were relatively uniform, the other three (again two small ones and one large one) were relatively non-uniform. All of the lamps, except one, were fairly typical in terms of surface luminance uniformity, and would be exemplified by those surveyed in Task 1. The exception was lamp No. 2 which had a

TABLE 7

LAMPS USED IN TASK 2

Lamp Designation	Size (in^2)	Size Designation	Surface Brightness
1	11.9	SMALL	UNIFORM
2	29.6	LARGE	NON-UNIFORM
3	14.7	SMALL	NON-UNIFORM
6	24.4	LARGE	UNIFORM
9	12.1	SMALL	NON-UNIFORM
14	12.8	SMALL	UNIFORM

center section about 1.5 inch in diameter that was very bright, with the peripheral area being much dimmer.

Unit intensity. Four levels of intensity were used. The maximum for each unit was that provided by the brake filament, operating at 12.8 volts. The maxima ranged from 75 to 155 cd., measured at H-V. The minimum values tested were 3.5% of the maxima (see Table 8). Not all levels were used in all test conditions, as will be shown later.

TABLE 8

INTENSITY LEVELS FOR THE 50-FT CONDITIONS IN TASK 2 (cd)

Filter	Lamp Number					
	1	2	3	6	9	14
100.0%	155.0	75.3	151.0	113.0	96.0	102.0
50.0%	77.6	37.7	75.4	56.5	48.0	51.0
25.0%	38.8	18.8	37.7	28.3	24.0	25.5
3.5%	5.4	2.6	5.3	4.0	3.4	3.6

Ambient illumination. Two levels of ambient illumination were used. They were selected to represent extremes of difficulty for the subject. In the "dark" condition, the illumination at the surface of the lamps was about 0.2 foot-candles, approximating a dawn-dusk situation. In the "light" condition the normal room lighting was supplemented by high-intensity sources directed toward the lamps, providing about 6,000 foot-candles of illumination on the surface of the lamps. This corresponded to the type of situation one might encounter on a bright day. The illumination at the subject's eyes was approximately 0.2 foot-candles in the "dark" condition and 40 foot-candles in the "light" condition.

Viewing distance. Two viewing distances were used, 50 and 145 ft. At the shorter distance all the lamps should function as extended sources. At the longer distance, at least some of the smaller lamps should approach point sources. Since the lab used is only 75 ft long, the viewing distance of 145 ft was obtained by placing the test lamps and observer at one end of the lab. Subjects then viewed the lamps in a large mirror positioned at the other end of the lab.

Subjects. Twenty subjects participated in the test. All had visual acuity of 20/40 or better. The subjects ranged from 18 to 79 years of age. (Their actual ages were 18, 19, 20, 20, 22, 22, 22, 22, 25, 32, 34, 35, 39, 67, 70, 70, 73, 75, 75, and 79.) There were eleven females and nine males.

Dependent variable. The dependent variable was the intensity and luminance of a uniform comparison unit at the point where the subjects said it was the same brightness as the test lamp.

Uniform source. This unit had to meet several criteria:

(1) Its surface luminance should be as uniform as possible.

(2) It should be able to duplicate all the sizes and shapes of lamps to be tested.

(3) It should be able to present a broad range of surface luminances.

(4) It should be portable.

(5) It should be simple to construct and reliable in operation.

A schematic of the uniform source is shown in Figure 5. The light source was a 35-mm slide projector. Neutral density filters in the slide tray of the projector allowed controlled, step changes in output. The light passed through a color filter, a dispersion filter, and a neutral density filter. A mask, cut to the size and shape of the lamp being tested, was placed on the side of the dispersion filter facing the subject.

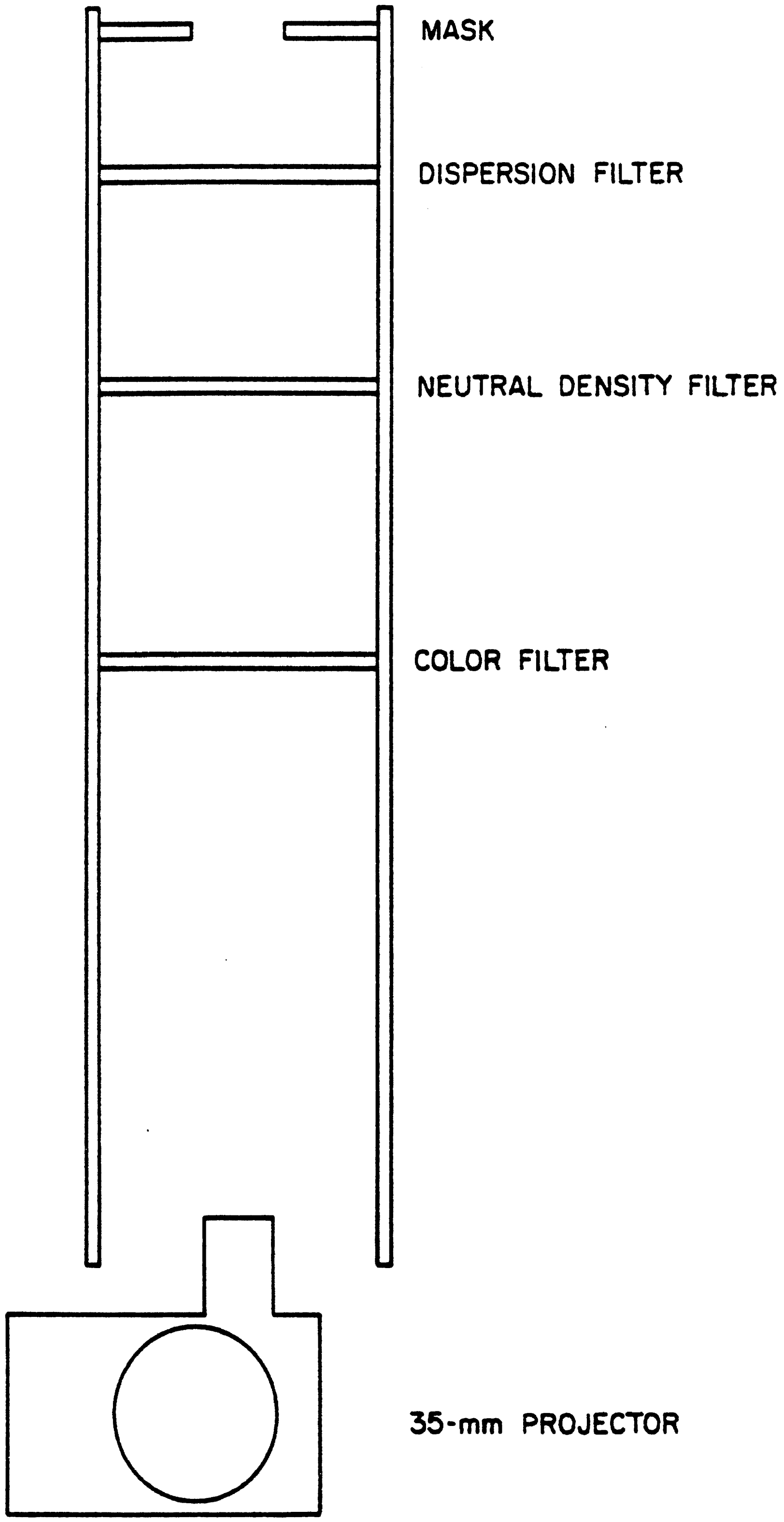

Figure 5. Schematic of the uniform source in Task 2.

In order to achieve the combination of surface luminance and uniformity desired, two positions were provided for the dispersion filter. The position closest to the light source was for the four smaller lamps, which required higher luminance levels in order to achieve the desired intensity. The further position was for the two larger lamps.

Although it appeared homogeneous to the eye, the surface luminance of this unit varied somewhat, especially in the larger, rectangular lamps. Based on measurements with a Pritchard Photometer, the difference from maximum to minimum was about 20%.

Test setup. The test lamps were attached to fixtures that held them in the correct orientation and at the same height as their counterpart in the uniform source. The uniform source and the test lamps were arranged side by side on a table, facing toward the subject. A rack to hold neutral density filters was positioned in front of the test lamp. A schematic of the setup is shown in Figure 6.

Ambient illumination. As noted earlier, two levels of illumination were used. In the lower level the intent was to approximate a dawn/dusk situation. To achieve this condition the laboratory lights were switched off and a fluorescent desk lamp was switched on, with its illumination directed toward the ceiling. This produced a general, diffuse illumination.

At the higher level all the laboratory lights were turned on. Additional illumination was directed on the simulated and test lamp by high-beam headlamps mounted above and below each unit and high-intensity photographer's lamps. The latter could be moved back and forth to keep the same distance between it and the surface of the unit. In sum, the combination of lamps provided about 6,000 foot-candles on the surface of the units.

Lamp filters. Four lamp intensity levels were used. As noted earlier, the maximum was whatever each lamp could provide at 12.8 volts. Three neutral density filters were used to achieve the lower levels. The transmissivity of these filters was 50%, 21%, and 3.5%. Table 8 is a matrix of the candela values at H-V actually provided by each test lamp in both of the 50-ft conditions. The candela values for the 145-ft condition are equal to 84% of the corresponding values measured at 50 ft. (The mirror that was used to obtain the 145-ft viewing distance had reflectivity of 84%.)

Filters having the same value as those listed in Table 8 were placed in front of the uniform source as well. The actual candela values provided by the uniform source depended on the filters in front of the lamp combined with those in the projector.

Photometry. All photometric measurements were made using UMTRI's Model 1970 Pritchard Photometer. Surface luminance of the simulated taillamps were measured directly, positioning the instrument on the subject's eye to lamp axis. Candela values were

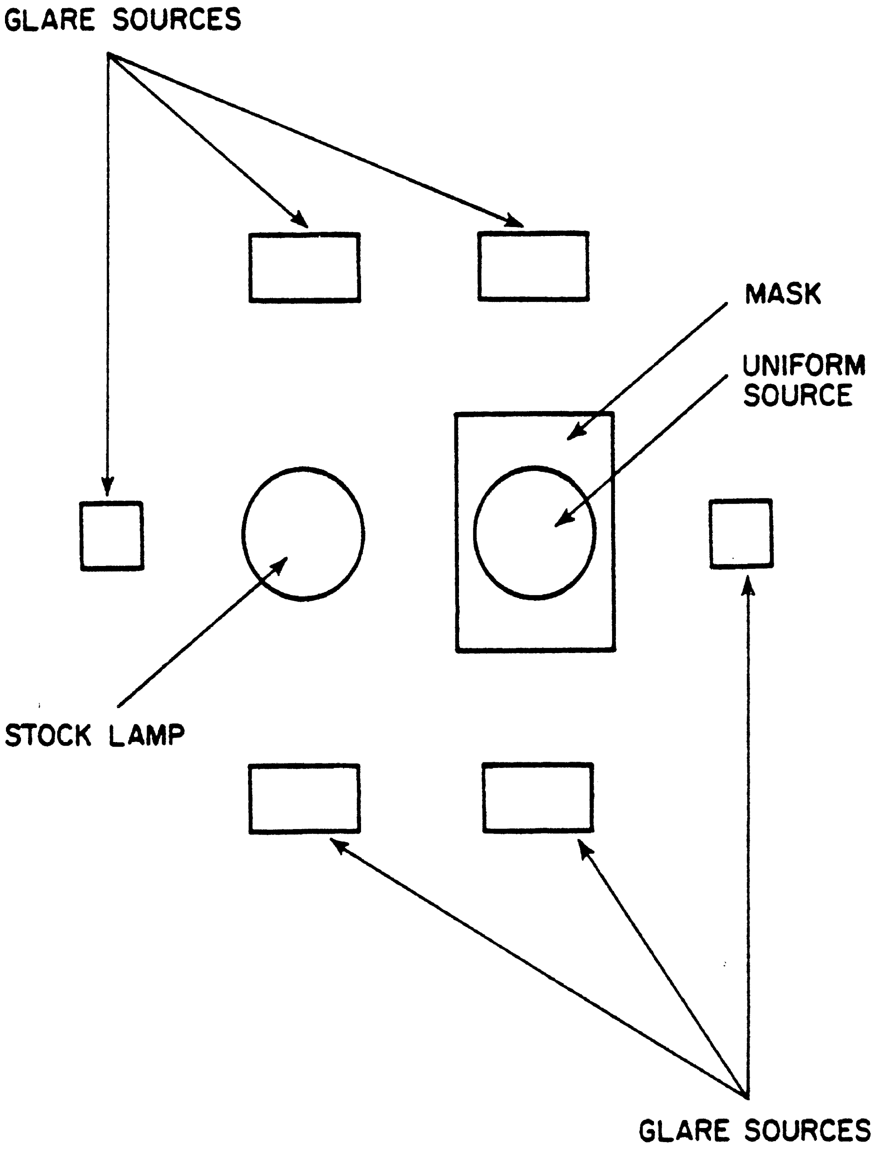

Figure 6. Schematic of the experimental setup in Task 2.

measured with the same instrument by positioning the standard diffuse reflective white target at a known distance, reading the luminance, multiplying by the target's correction factor and then by the square of the distance.

Test design. To keep the test within reasonable time limits, not all combinations of the variables were used. Only the 50-ft viewing distance was used in the dark condition, but both the 50- and 145-ft viewing distance were used in the light condition. In addition, the 50% filter was used only in the dark condition, so that subjects worked with three levels of source intensity rather than four in the light condition.

Each subject was exposed to a total of 60 different conditions in this test, with four replications of each. Depending on how fast the subject worked, it took two to three hours to complete the test.

Procedure

Subjects were run individually. They were brought into the laboratory, seated in a chair positioned appropriately for the first viewing distance that would be used, and the instructions were read to them. Any questions were answered and, if necessary, a dark adaptation period of five minutes was allowed.

The test started with the experimenter switching on one of the test lamps at a pre-established intensity. The uniform unit was then turned on, at an intensity level noticeably brighter or dimmer than the test lamp. The subject indicated whether the comparison unit should be made brighter or dimmer by pressing the corresponding button on a clipboard. The experimenter complied, making the comparison unit one step brighter or dimmer. This process was continued until the subject indicated that the two units appeared equally bright. The experimenter then reset the comparison unit to the opposite side of equal and the subject started in again. This process was repeated four times for each intensity level.

Results

Intensity comparisons. Figures 7 through 12 show the relationship between test unit and uniform source intensity (in candelas) for each of the six test lamps. The solid, diagonal line on each plot is where the points would fall if the units are set to equal intensity.

As evidenced in the figures, the subjects tended to set the uniform source to a higher level of intensity under most conditions. However, this seems less true at the highest intensity levels, particularly at the 145-ft distance.

There are some interesting differences between lamps. For example, lamp No. 14 (small, uniform) was judged by the experimenters to be the most uniform of the entire sample. The results for this lamp are the most consistent and depart least from the equal line. On the other hand, lamp No. 2 (large, non-uniform) was judged by the experimenters to be the most non-uniform of the sample. The differences in settings of the uniform source for various conditions at the same intensity are greatest for this lamp.

Equivalent luminance. The main purposes of this task was to develop "equivalent luminance" data for each of the test lamps. Figures 13 through 15 illustrate the relationship between the intensity of the stock lamps and the luminance of the uniform source at the "brightness" match. Each figure is for a different combination of viewing distance and ambient illumination.

The general trend in the figures is what was expected. That is, the larger lamps require higher intensities than the smaller lamps in order to achieve a given equivalent luminance level. (If two lamps have equal intensity but unequal area, the larger lamp will have lower luminance [Luminance = Intensity/Area].) However, the extent of the change is dependent upon ambient illumination, with much greater differences evident under higher ambient illumination.

A least-square regression line was fitted for the data from each condition. These equations were needed in the remaining tasks, where interpolation was necessary to estimate equivalent luminance values for a range of intensity values. These equations provided excellent fit to the data: The variance accounted for was 99% or more in 17 out of 18 conditions and 97% in the remaining condition.

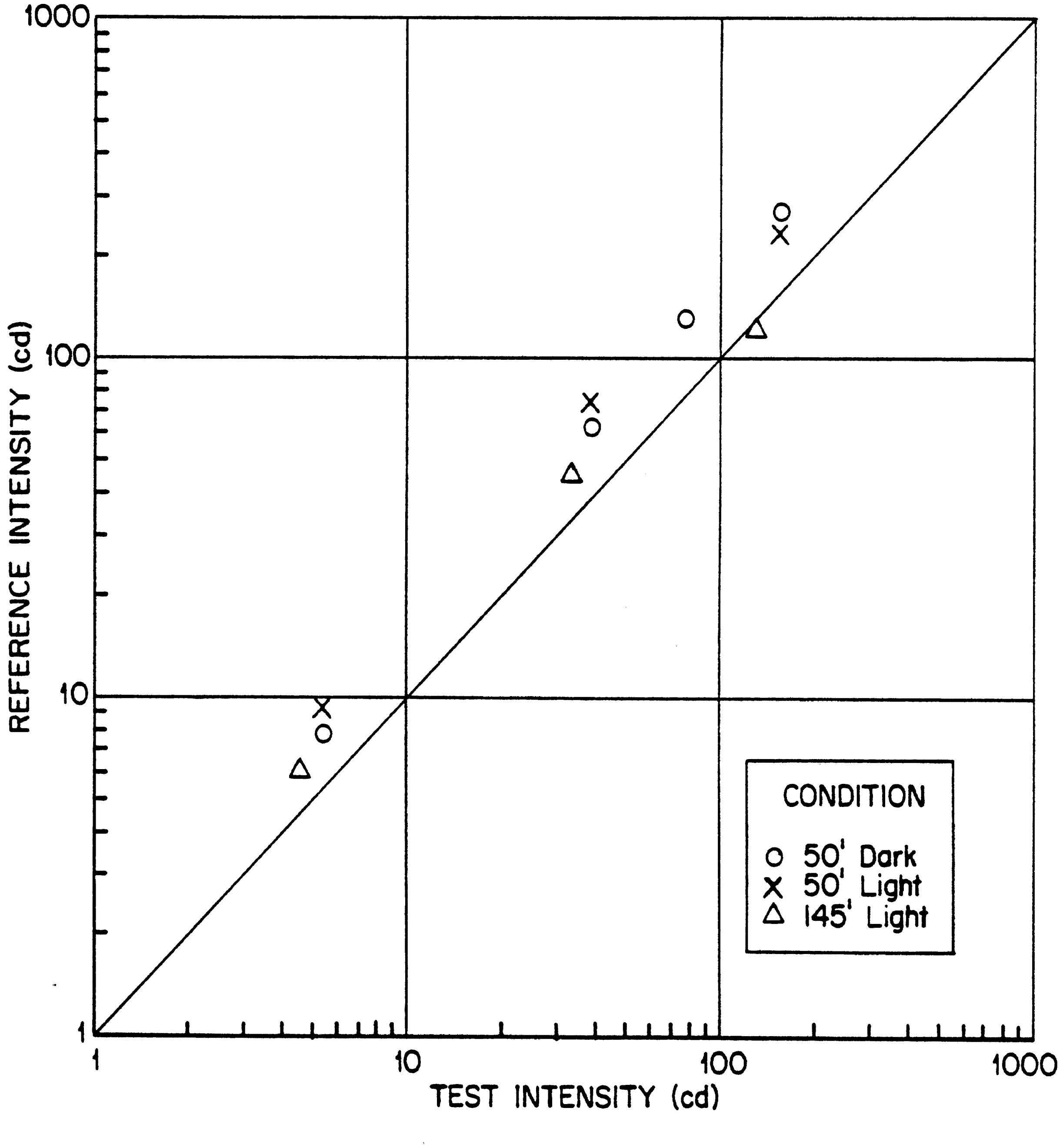

Figure 7. Relationship between the intensity of Lamp 1 and the intensity of the uniform source.

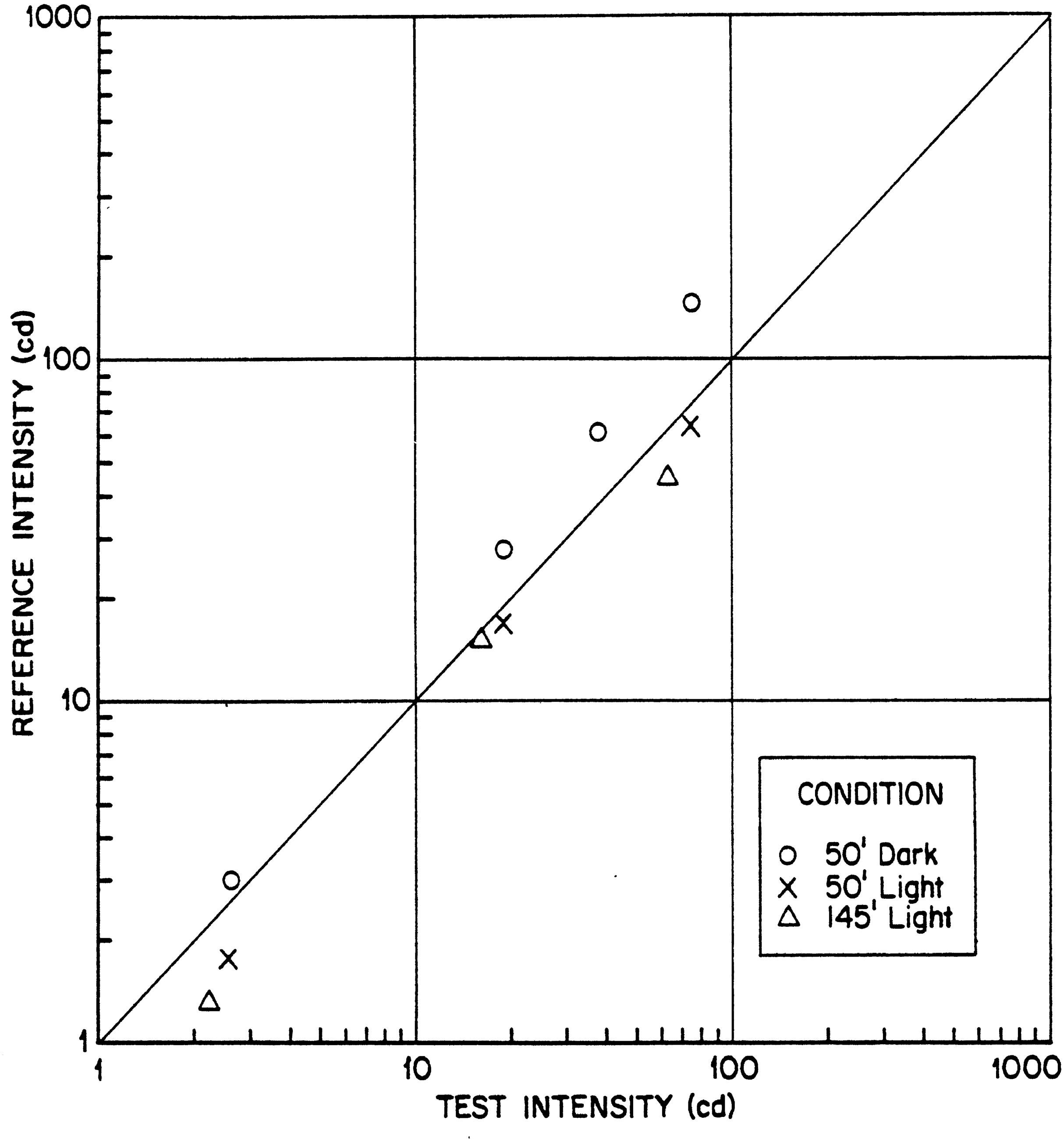

Figure 8. Relationship between the intensity of Lamp 2 and the intensity of the uniform source.

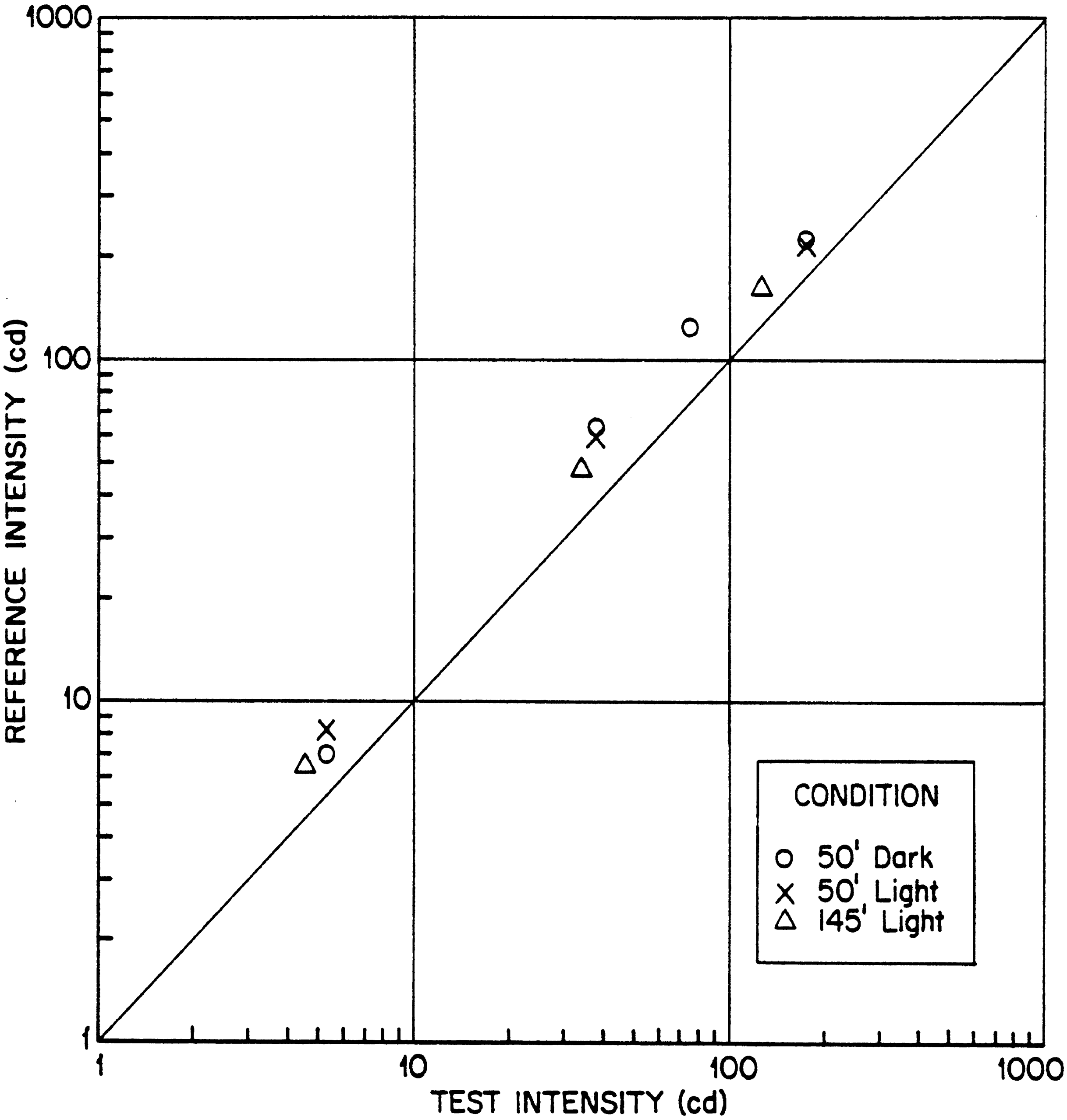

Figure 9. Relationship between the intensity of Lamp 3 and the intensity of the uniform source.

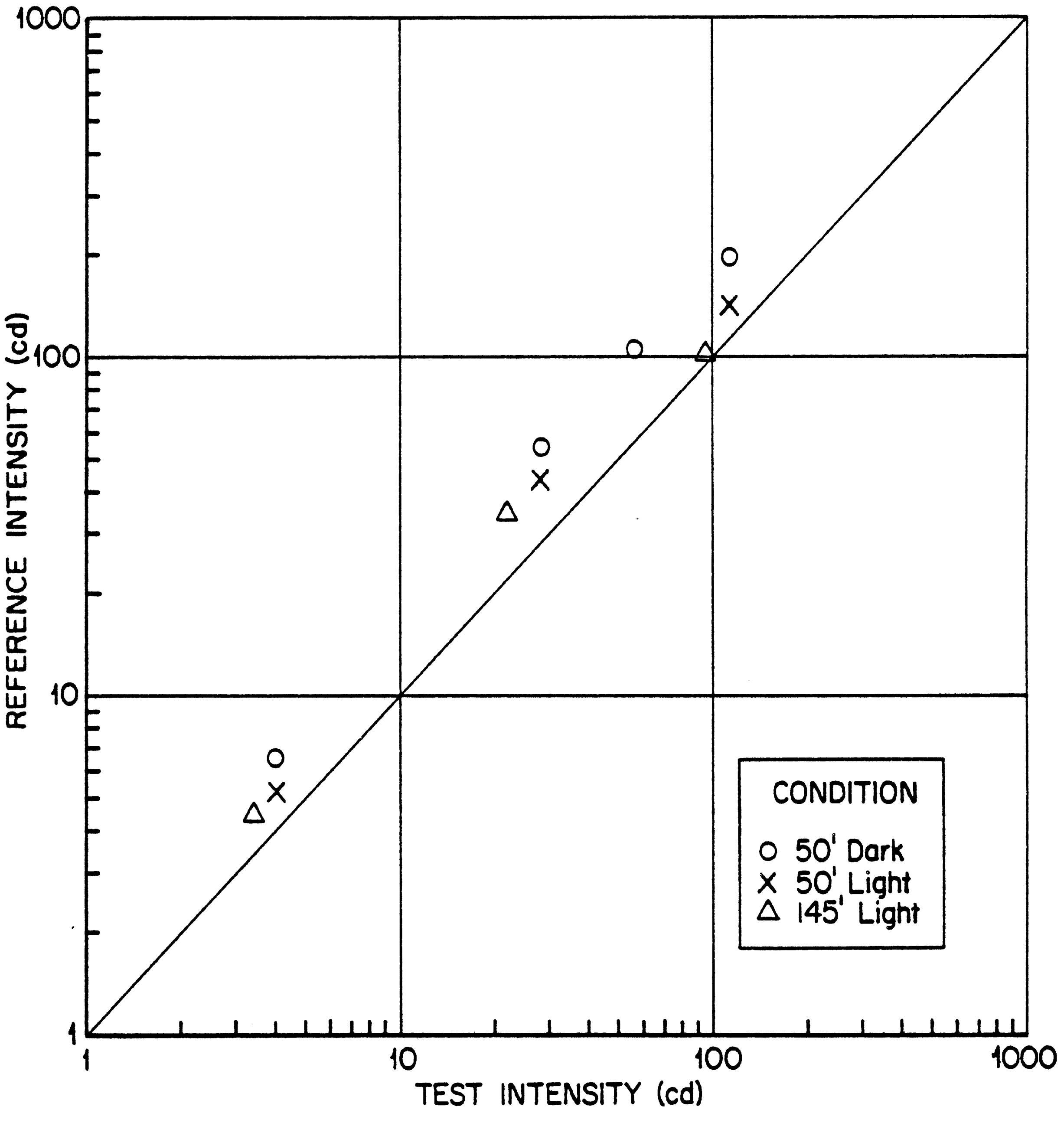

Figure 10. Relationship between the intensity of Lamp 6 and the intensity of the uniform source.

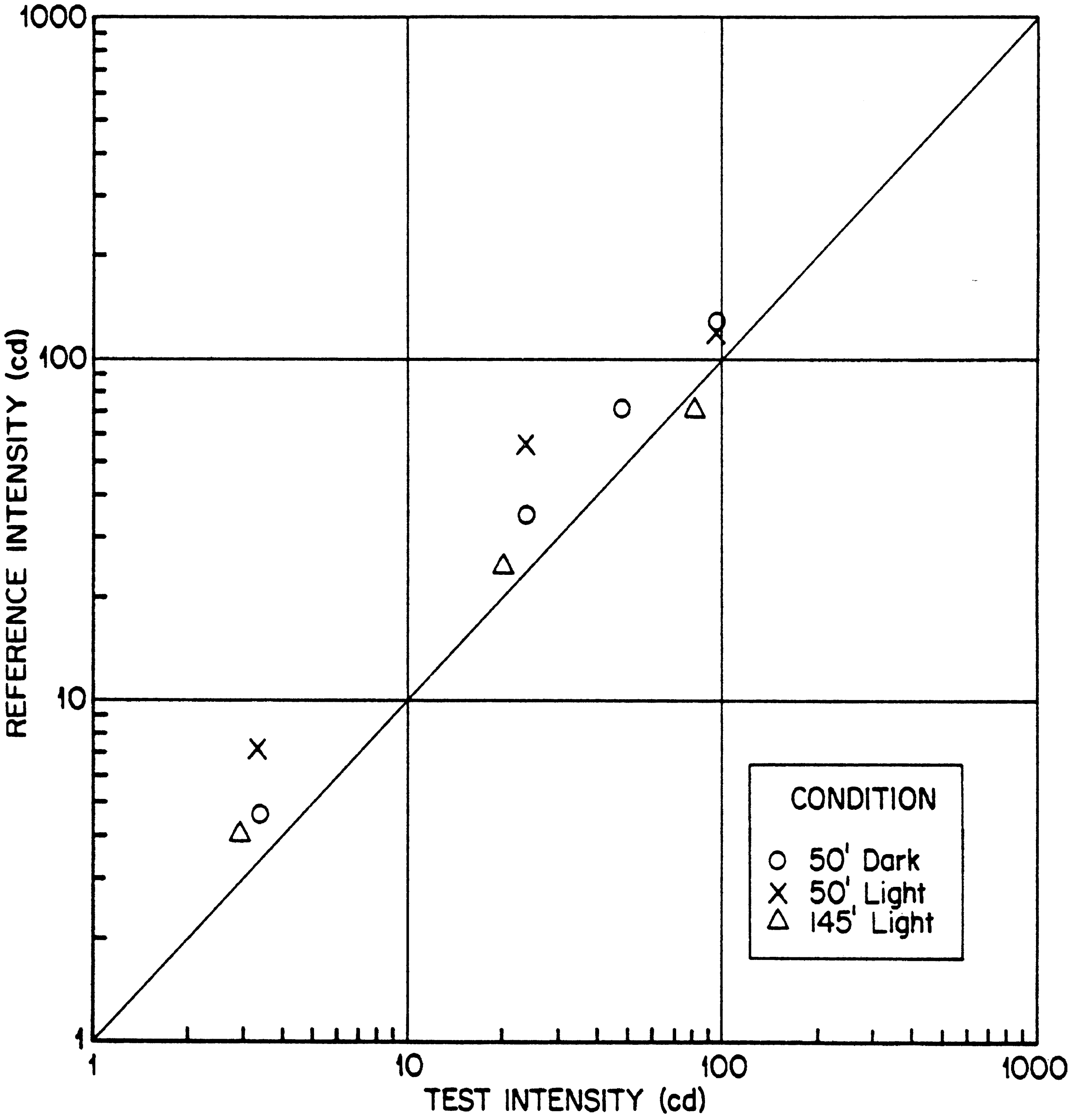

Figure 11. Relationship between the intensity of Lamp 9 and the intensity of the uniform source.

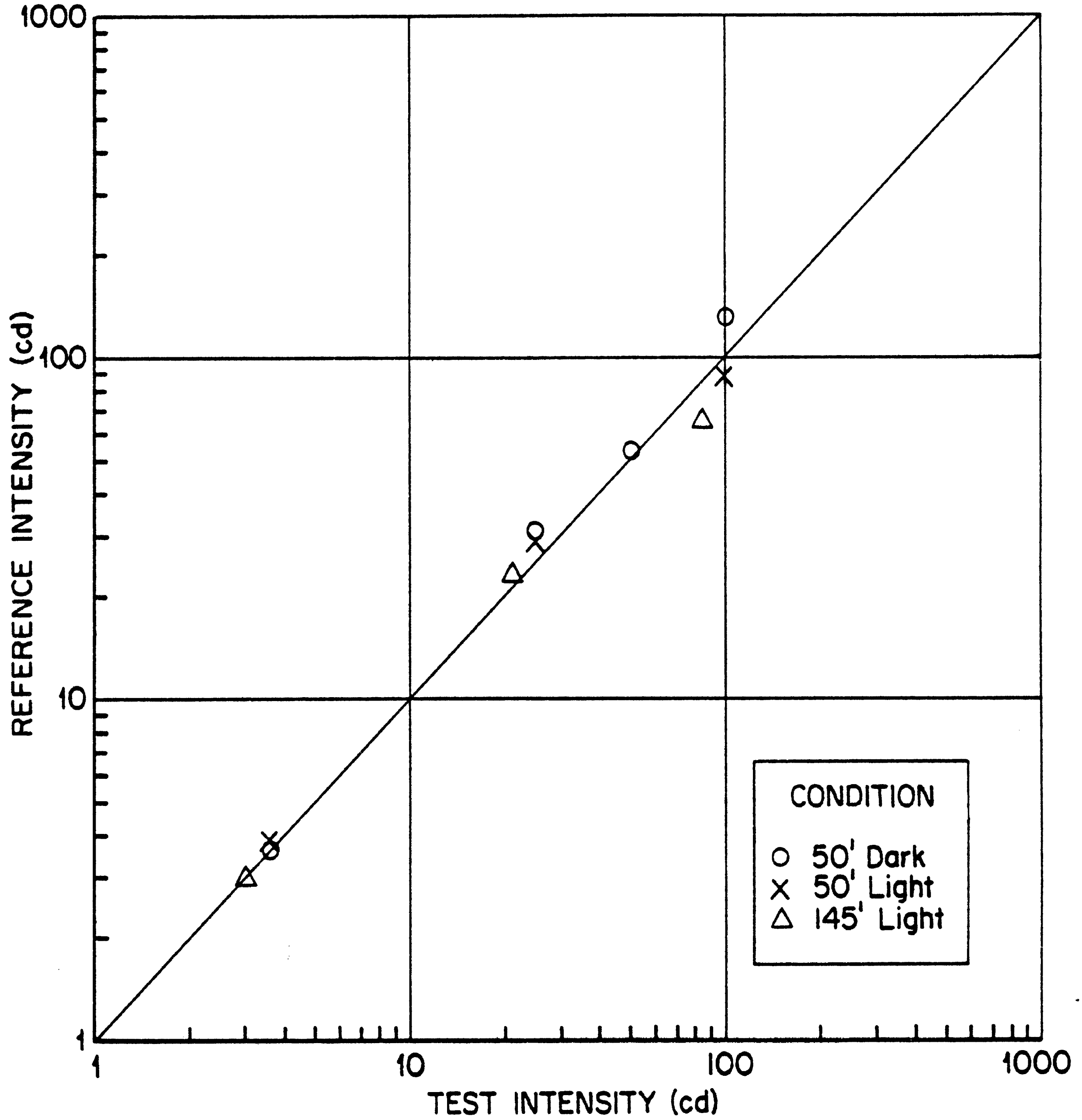

Figure 12. Relationship between the intensity of Lamp 14 and the intensity of the uniform source.

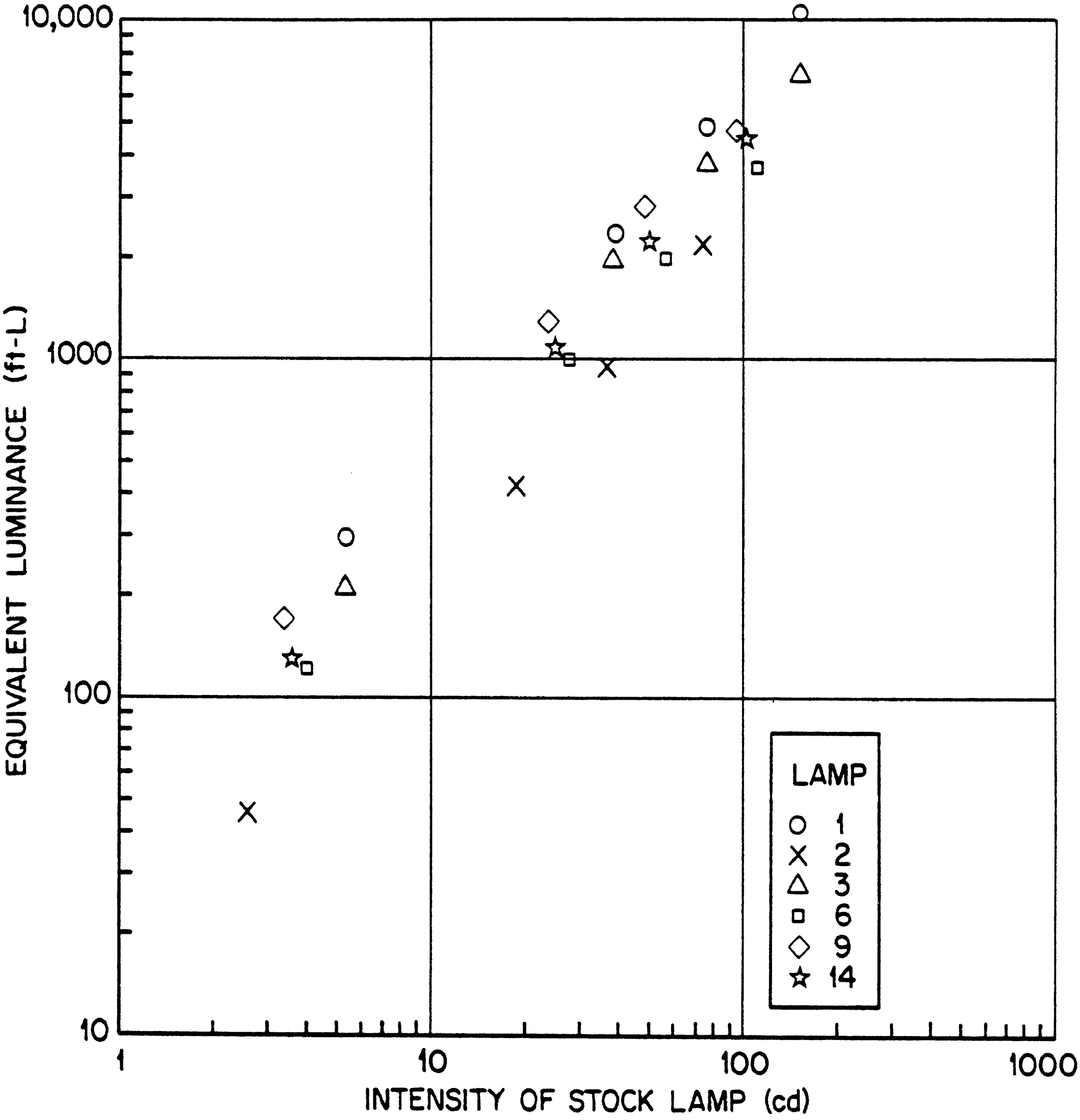

Figure 13. Relationship between the intensity of test lamps and the equivalent luminance. (50-ft viewing distance, “dark” ambient illumination)

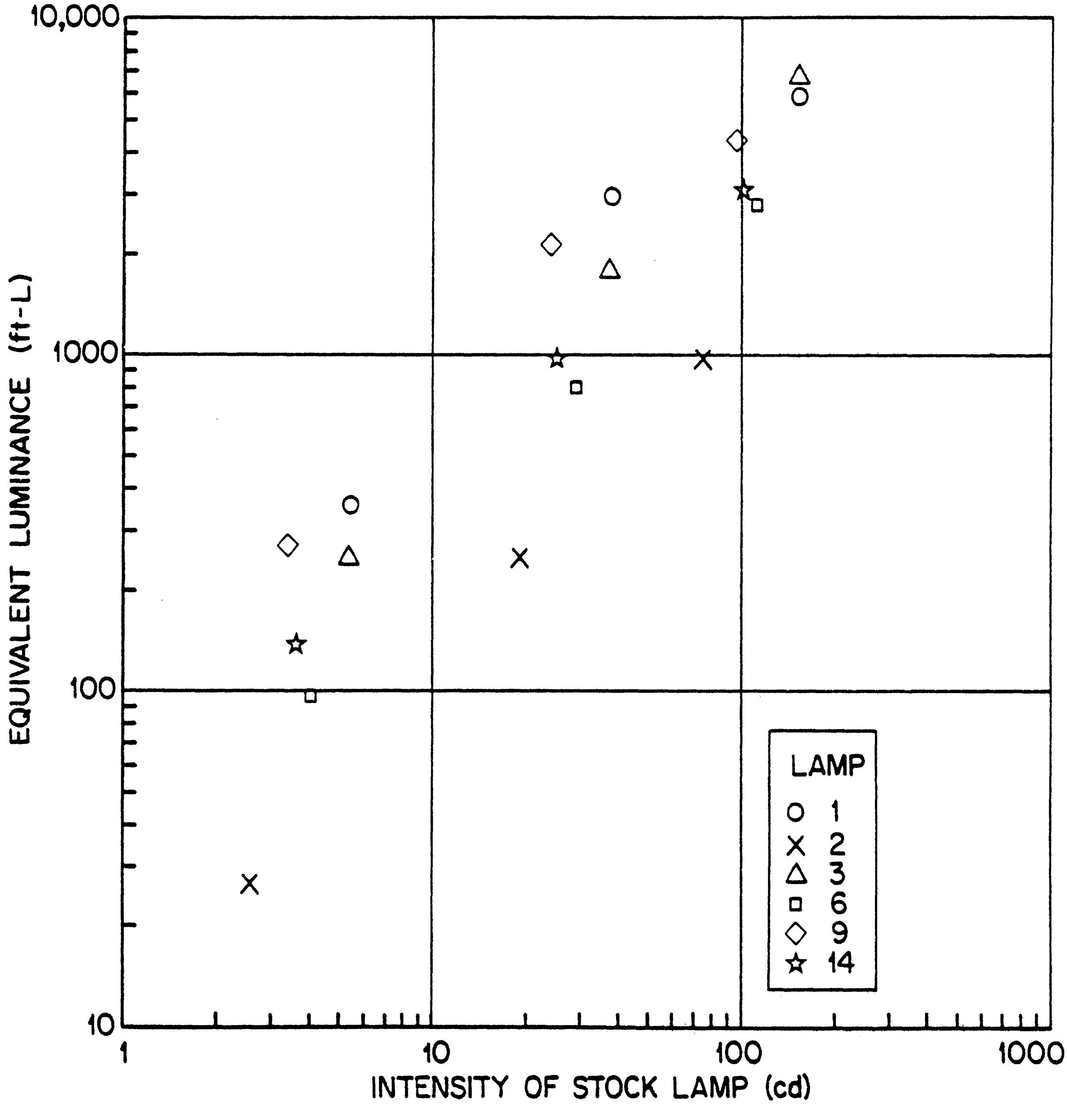

Figure 14. Relationship between the intensity of test lamps and the equivalent luminance. (50-ft viewing distance, "light" ambient illumination)

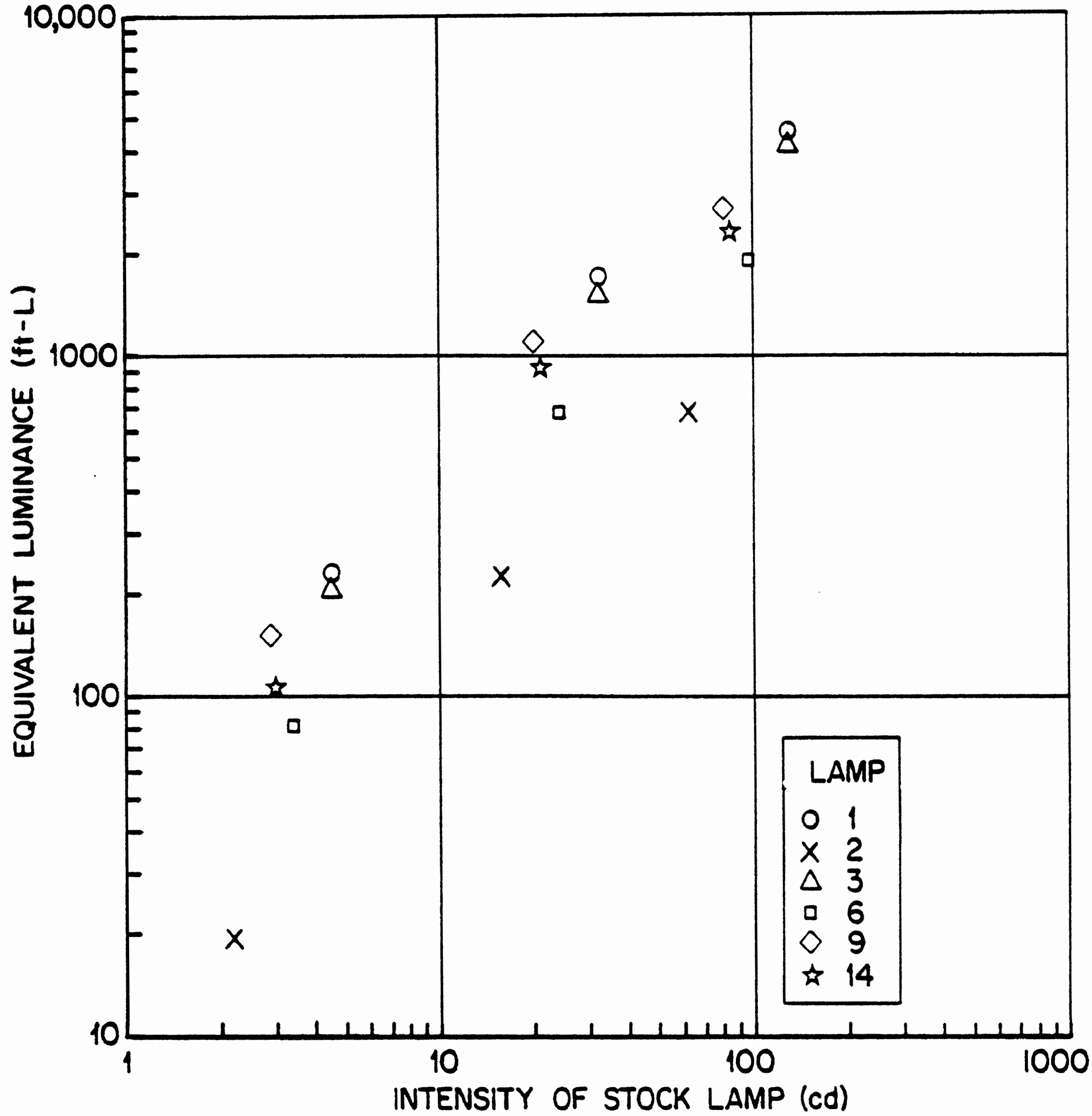

Figure 15. Relationship between the intensity of test lamps and the equivalent luminance. (145-ft viewing distance, "light" ambient illumination)

Discussion

One of the more interesting findings of this investigation is that the subjects tended to set the luminance of the uniform source higher than the average of the test unit. One explanation for this is that the subjects were influenced by "hot" spots in the test unit (or more precisely, the brightness of the hot spots).

It was anticipated that the subjects would be able to more accurately match the sources at the 145-foot viewing distance, where small details of the lens surface would be less easily noticed. This turned out to be the case primarily for the highest intensity level. It may be that, at the highest intensity level, irradiation effects blurred the image enough to provide a relatively uniform surface. At lower intensity levels it may still have been possible for the subjects to discern differences in the viewed surface.

Lamp 2 (a large, non-uniform lamp) shows the greatest differences associated with ambient conditions. This lamp had a small, high-brightness central area, with the surrounding area being of much lower luminance. Under high ambient conditions the surround area tended to be washed out. With only the high-intensity center area visible, the subjects set the uniform source at a higher level than they did when the surround was visible (i.e., under low-ambient conditions).

TASK 3A: MINIMUM BRAKE LAMP PHOTOMETRIC REQUIREMENTS FOR DAYTIME DETECTION: A LABORATORY STUDY

Introduction

This task had two objectives. The first was to determine the minimum lamp photometrics for signal detection under a reasonably worst case of viewing. Such a case involves having the lamp oriented toward the sun. Consequently, this experiment was performed under conditions simulating sun shining on the rear of the vehicle. The second objective was to assess the relative power of luminous intensity, equivalent luminance, and average luminance to predict performance in a signal-detection paradigm.

Method

Experimental setup. Subjects performed two simultaneous tasks. The primary task was detecting lamp signals in the near periphery of the visual field. The secondary, loading task, consisted of a compensatory tracking task, necessitating involvement of the foveal (central) visual field. Figure 16 is a schematic of the experimental setup for Task 3A. (The subject was not informed that the performance on only one task was of interest.)

Secondary task. The secondary tracking task consisted of a simulated road scene on a video display. The road scene was generated by a Commodore-64 computer. Deviations of the road's center were based upon repeated use of a 100-point sinusoidal sequence. The sequence repeated about every minute. However, since the subject was kept busy with two tasks, to the subject the road appeared to be curving in an unpredictable manner. Subject's task was to keep the road centered on the screen by use of a control knob.

Primary task: Independent variables

Test lamps. Three test lamps were used, Nos. 6, 9, and 14 (see Table 7, Task 2, for the description of these lamps).

Viewing distances/visual angles. Two viewing distances were used, 50 and 145 ft. These distances correspond to the distances used in Task 2. However, viewing distance was confounded with visual angle between the two lamps. Because of a constant separation of 8.5 ft between the centers of the two lamps, the inter-lamp separation was 9.6° in the 50-ft condition and 3.4° in the 145-ft condition.

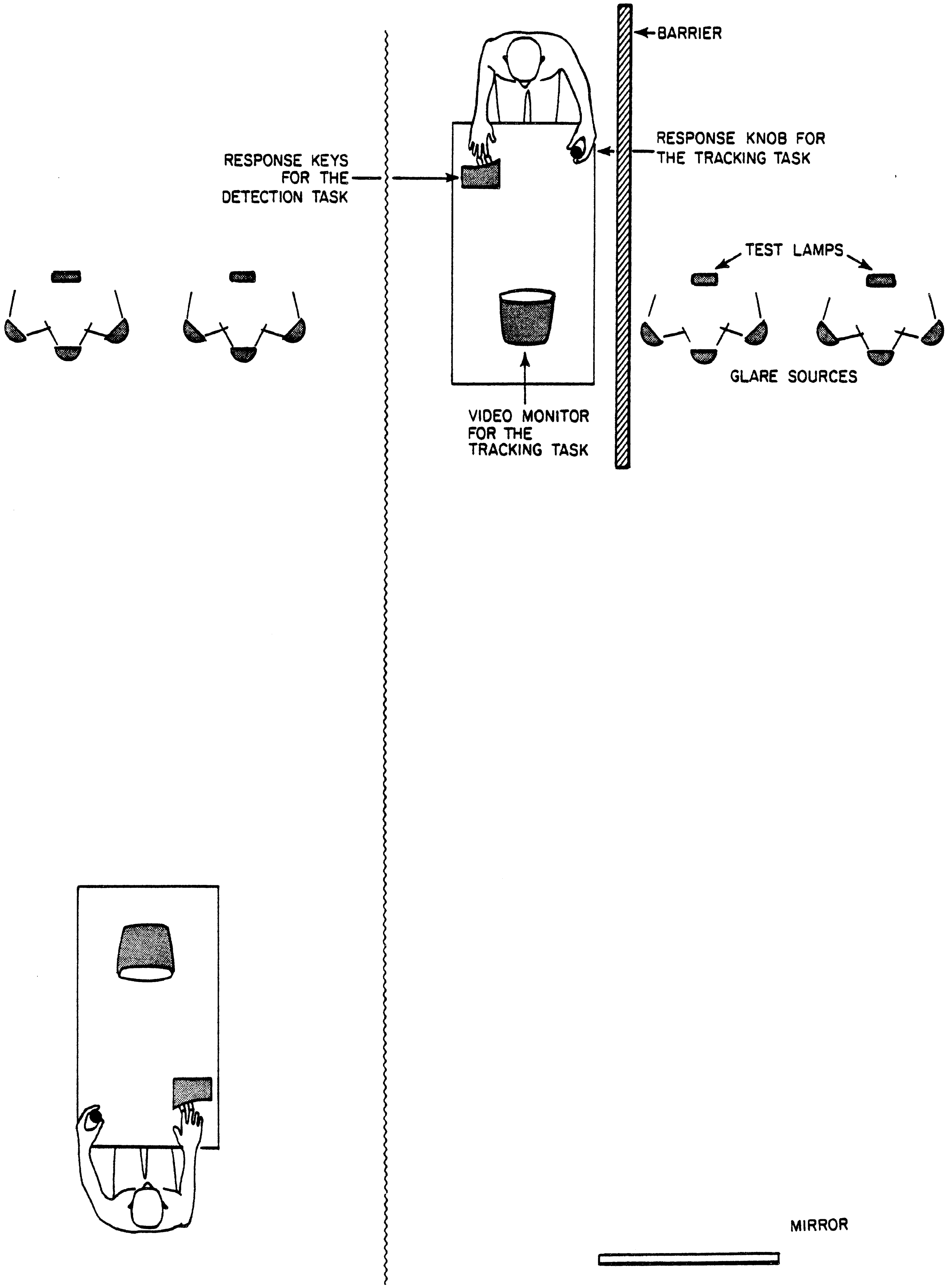

Figure 16. Schematic of the experimental setup in Task 3A. (The left panel illustrates the 50-ft viewing condition, the right panel the 145-ft condition.)

Intensity/luminance levels. Four intensity levels were used: 40, 60, 80, and 100 cd. These values were selected because of the following considerations concerning brake lamp photometrics: (1) 80 cd is the current U.S. minimum, (2) 40 cd is the current European minimum, (3) 60 cd is a frequently suggested compromise between the U.S. and European minima, and (4) 100 cd is a realistic value of actual U.S. brake lamps. The corresponding average luminance values (intensity divided by surface area) and equivalent luminance values (computed from the regression equations that were derived in Task 2) are listed in Table 9.

TABLE 9

PHOTOMETRIC PROPERTIES OF THE TEST LAMPS IN TASK 3A

LAMP	INTENSITY (cd)	AVERAGE LUMINANCE (cd/m^2)	EQUIVALENT LUMINANCE (cd/m^2)	
			50' VIEWING DISTANCE	145' VIEWING DISTANCE
6	40	2,540	3,365	2,991
	60	3,809	4,931	4,294
	80	5,079	6,496	5,597
	100	6,349	8,061	6,900
9	40	5,120	7,577	5,087
	60	7,680	10,415	7,222
	80	10,241	13,253	9,357
	100	12,801	16,091	11,492
14	40	4,840	4,461	4,098
	60	7,260	6485	5,838
	80	9,679	8,508	7,577
	100	12,099	10,532	9,317

Primary task: dependent variables. Tabulations were made of the proportions of correct responses, errors, and missed trials, as well as the reaction times of correct responses.

Ambient illumination. The ambient illumination was the same as in the "light" condition of Task 2, resulting in 6,000 foot-candles on the surface of the lamps, and 40 foot-candles at the subject's eyes.

Response-to-stimulus intervals. The time interval between a response and the onset of the subsequent stimulus was 6, 8, 10, 12, or 14 sec.

Subjects. Twenty-four paid subjects were tested. Twelve of them were younger (their ages were 18, 18, 18, 19, 20, 20, 20, 20, 20, 21, 21, and 27), and 12 were older (their ages were 52, 60, 68, 69, 69, 70, 71, 72, 74, 74, 75, and 80). Six males and six females were in each age group. Each subject had normal or corrected-to-normal visual acuity (20/40 or better).

Computer-control of the study. This study was under the control of an Apple II+ microcomputer. For each trial the computer selected a response-to-stimulus interval, left or right lamp, and the intensity, and stored subjects' responses and their delays. The computer controlled intensity levels by means of a two-channel digital-to-analog converter (DAC). Each channel corresponded to one of the two stimulus lamps. The outputs of the DAC were applied to the gates of two high-power high-current field-effect transistors (FET), each of which was in series between the positive terminal of the power supply and one of the brake filaments. The other ends of the filaments were connected to ground. In this configuration the voltage from the DAC to the gates of the FET's could be used to control the voltage across the brake filament (which was the DAC voltage minus the threshold voltage of the FET). Calibration measurements determined which filament voltages (and corresponding digital values for the DAC channels) produced the desired light intensity levels. By sending appropriate values to the DAC, the computer was able to turn on either stimulus lamp at any of the desired intensity levels. (Since we manipulated luminous intensity by changes in voltage [and filament temperature], some changes in the color of the emitted light should be expected. However, because of the relatively selective spectral transmissivity function of standard red taillight lenses, we would not expect any appreciable change in perceived color within the range of intensities that we used. Indeed, casual inspection did not reveal any noticeable color changes.)

Photometric calibrations. Prior to each subject's run a calibration check of the photometric output of the lamps was performed. These measurements proved all to be within ±4% of the nominal values, with 92% within ±2% of the nominal values.

Procedure

The subject was instructed to perform the compensatory tracking task continuously throughout the test session (except during breaks). The compensatory tracking task required the subject to use a knob with the non-dominant (i.e., usually the left) hand. The primary, detection task was responded to by pressing one of two response buttons with the dominant (i.e., usually the right) hand.

Each trial consisted of a 2-sec presentation of either the left or the right lamp. Subject's task was to press one of two response keys with the dominant hand, to indicate whether the left or right lamp was illuminated.

There were, nominally, 240 trials per subject (3 lamps x 2 distances x 4 intensities x 5 response-to-stimulus intervals x 2 positions [left or right]), with all variables counterbalanced. However, the trials on which the subject did not respond within three seconds, or responded with the incorrect response key, were repeated at the end of each block of five trials. (The originally missed and incorrectly responded trials were also tabulated.) The trials were presented in six blocks of forty (nominal) trials each. The first three blocks were for one viewing distance, while the second three blocks were for the other viewing distance. A practice session of forty trials was given to each subject at the beginning of the study; another practice session of twenty trials was given when the viewing distance was changed. With short breaks between blocks of trials, the study took about an hour and a half to two hours to complete.

Results

Frequency analyses. Table 10 presents the frequency of correctly responded trials, incorrectly responded (error) trials, and not-responded-to (missed) trials, collapsed over lamps and viewing distances. (Tables 10 through 12 are based only on the original 5760 trials [24 subjects x 240 trials]; the repeated trials are not included here.) Although there are trends for more errors at high intensity levels and more missed trials at low intensity levels, chi-square test proved to be non-significant ($F(6) = 8.8$, $p > 0.1$).

Table 11 lists the frequency of missed trials by lamp, intensity, and viewing distance. Table 12 is an analogous table for error responses.

TABLE 10
FREQUENCY OF CORRECT, ERROR, AND MISSED TRIALS IN TASK 3A

Trial	Intensity				
	100 cd	80 cd	60 cd	40 cd	All
Correct	1401	1408	1404	1397	5610
Error	17	13	9	9	48
Missed	22	19	27	34	102

TABLE 11
FREQUENCY OF MISSED TRIALS IN TASK 3A

Lamp No.	Intensity									
	100 cd		80 cd		60 cd		40 cd		All	
	50'	145'	50'	145'	50'	145'	50'	145'	50'	145'
6	3	5	1	5	2	6	6	7	12	23
9	1	2	2	2	3	7	2	6	8	17
14	3	8	4	5	5	4	8	5	20	22
All	7	15	7	12	10	17	16	18	40	62

TABLE 12
FREQUENCY OF ERROR TRIALS IN TASK 3A

Lamp No.	Intensity									
	100 cd		80 cd		60 cd		40 cd		All	
	50'	145'	50'	145'	50'	145'	50'	145'	50'	145'
6	2	3	4	3	0	2	0	2	6	10
9	4	5	2	1	2	1	0	2	8	9
14	2	1	1	2	2	2	2	3	7	8
All	8	9	7	6	4	5	2	7	21	27

Reaction-time analyses. Analysis of variance of the reaction time of correct responses revealed the following significant main effects:

Subject's age, F(1,30) = 8.94, p = 0.007 (younger subjects: 1.04 sec, older subjects: 1.22 sec).

Lamp intensity, F(3,60) = 11.95, p < 0.001 (40 cd = 1.17 sec, 60 cd: 1.14 sec, 80 cd: 1.12 sec, 100 cd: 1.10 sec). *Post hoc* pairwise comparisons using Newman-Keuls range test (Hicks, 1973) showed the following differences to be significant at the 0.05 level: 40 cd vs. 100 cd, 40 cd vs. 80 cd, 40 cd. vs. 60 cd, and 60 cd vs. 100 cd, while 60 cd vs. 80 cd was not significant at the 0.05 level, but would have been significant at the 0.1 level.

Viewing distance, F(1,20) = 18.24, p < 0.001 (50' distance: 1.08 sec, 145' distance: 1.17 sec).

Effects of the lamp and sex of the subject did not reach statistical significance at the 0.05 level.

Table 13 lists the mean reaction times by lamp, intensity, and viewing distance.

TABLE 13

REACTION TIME OF CORRECT RESPONSES IN TASK 3A (in seconds)

Lamp No.	Intensity							
	100 cd		80 cd		60 cd		40 cd	
	50'	145'	50'	145'	50'	145'	50'	145'
6	1.12	1.13	1.08	1.17	1.12	1.19	1.12	1.29
9	1.09	1.19	1.08	1.18	1.09	1.24	1.12	1.20
14	1.07	1.21	1.12	1.18	1.11	1.21	1.17	1.23
All	1.09	1.18	1.09	1.18	1.11	1.21	1.14	1.24

Intensity vs. equivalent luminance vs. average luminance. Tables 14 and 15 present the intercorrelations between the dependent variables (reaction time of correct responses, frequency of missed trials, and frequency of errors), and independent variables (intensity, equivalent luminance, and average luminance) for the two viewing distances. The data for each of these tables were the 12 combinations of three lamps and four intensities.

These analyses revealed the following main findings:

(1) The three independent variables (intensity, equivalent luminance, and average luminance) are significantly intercorrelated.

(2) From among the dependent variables, only reaction time of correct responses and missed trials are significantly correlated.

(3) Reaction time of correct responses is significantly related to intensity, equivalent luminance, and (for the 50' distance only) average luminance.

(4) Missed trials are significantly related to intensity, equivalent luminance, and (for the 145' distance only) average luminance.

(5) Errors are not significantly related to any independent variable.

(6) For the short-viewing condition, equivalent luminance accounts for more of the variance of the reaction-time data than does intensity, while the situation is reversed for the long-viewing condition. (Percent variance accounted for is derived by squaring the correlation coefficient.)

TABLE 14

INTERCORRELATIONS BETWEEN THE VARIABLES IN TASK 3A

(50' viewing distance; N = 12, r@ 0.05 = .58;
correlations in bold face are statistically significant)

	Reaction Time	Missed Trials	Error Trials	Luminous Intensity	Equivalent Luminance
Average Luminance	**−0.84**	−0.47	0.52	**0.74**	**0.89**
Equivalent Luminance	**−0.95**	**−0.64**	0.49	**0.67**	
Luminous Intensity	**−0.68**	**−0.67**	0.50		
Error Trials	−0.49	−0.49			
Missed Trials	**0.67**				

TABLE 15

INTERCORRELATIONS BETWEEN THE VARIABLES IN TASK 3A

(145' viewing distance; N = 12, r@ 0.05 = .58;
correlations in bold face are statistically significant)

	Reaction Time	Missed Trials	Error Trials	Luminous Intensity	Equivalent Luminance
Average Luminance	−0.56	**−0.67**	−0.09	**0.74**	**0.96**
Equivalent Luminance	**−0.61**	**−0.80**	0.08	**0.81**	
Luminous Intensity	**−0.84**	**−0.70**	0.15		
Error Trials	−0.24	−0.36			
Missed Trials	**0.67**				

Discussion

Intensity vs. equivalent luminance vs. average luminance. One of the objectives of this task was to evaluate the power of intensity, equivalent luminance, and average luminance to predict performance in a signal-detection paradigm. The present findings suggest that the currently used photometric parameter—luminous intensity—is a statistically significant predictor of both the reaction time to signals and frequency of missed signals. This pattern held true for both viewing distances. Equivalent luminance, derived in Task 2, was also significantly related to both performance measures. Average luminance was related only to reaction time at the shorter viewing distance, and to missed signals at the longer viewing distance.

Since both luminous intensity and equivalent luminance are significantly correlated with performance, one cannot differentiate between them based on correlation alone. At least part of the reason for this is that luminous intensity and equivalent luminance were significantly correlated.

Equivalent luminance accounted for more variance of the reaction time when considering the short-distance data, but the situation was reversed for the long-distance data. This pattern of findings was expected, because rear lamps at the shorter tested distance form more clearly an extended light source (where light per unit area should be the relevant variable), while at the longer tested distance the lamps approach point sources (where the total luminous flux should be the relevant variable).

An argument against equivalent luminance is that it would be a rather unwieldy parameter. It would not be possible to use an instrument to determine equivalent luminance. Instead, each new lamp would have to be subjected to a panel of standardized observers for equivalent-luminance determination. Furthermore, since there is some indication in the present data that equivalent luminance is distance dependent, it is unclear what standard distance would have to be used for such a determination.

Minimum brake-lamp intensity for daytime detection. Reaction time to lamp signals proved to be a decreasing function of lamp intensity. Small, but statistically significant differences, were present between 40 cd and 60, 80, or 100 cd, and between 60 cd and 100 cd (all at the 0.05 level of confidence), and between 60 cd and 80 cd (at the 0.1 level of confidence). These results argue against reducing the current minimum of 80 cd. On the other hand, these results provide no support for increasing the minimum. (The frequency of missed trials showed the same, albeit statistically non-significant, trends.)

Conclusions

In conclusion, the present findings support the status quo of luminous intensity as the relevant photometric parameter of brake lamps, and 80 cd as the minimum brake-lamp luminous intensity.

TASK 3B: MINIMUM BRAKE LAMP PHOTOMETRIC REQUIREMENTS FOR DAYTIME DETECTION: A FIELD VALIDATION

Introduction

The objective of this task was to provide a qualitative field validation of the findings in the laboratory Task 3A. Consequently, this experiment was performed under conditions analogous to those of Task 3A, but outdoors, and using only a limited number of conditions and subjects.

Method

Experimental setup. As in Task 3A, subjects performed two simultaneous tasks. The primary task was detecting signals in the near periphery of the visual field. The secondary, loading task consisted of a compensatory tracking task, necessitating involvement of the foveal (central) visual field.

The subject was seated in the right rear seat of a parked station wagon. The video display for the secondary task was positioned on a shelf constructed in the right front seat. To provide a realistic surround for the test lamps, a white van was parked sideways immediately behind the lamps.

Secondary task. The same as in Task 3A.

Primary task: Independent variables

Test lamps. Two lamps were used, Nos. 6 and 9 (see Table 7, Task 2, for the description of these lamps). These lamps were selected because they were the lamps with the highest luminance (lamp 9) and the lowest luminance (lamp 6) in Task 3A.

Viewing distance/visual angle. The viewing distance was 145 ft. This distance corresponds to the longer of the two viewing distances in Task 3A. At this distance, the center-to-center separation of 8.5 ft between the two lamps created a visual angle of 3.4°.

Intensity/luminance levels. Three intensity levels were used: 40, 60, and 80 cd. The corresponding average luminance values (intensity divided by surface area) and equivalent luminance (computed from the regression equations that were derived in Task 2) are listed in Table 16.

Primary task: dependent variables. Tabulations were made of the proportions of correct responses, errors, and missed trials, as well as the reaction times of correct responses.

TABLE 16

PHOTOMETRIC PROPERTIES OF THE TEST LAMPS IN TASK 3B

LAMP	INTENSITY (cd)	AVERAGE LUMINANCE (cd/m^2)	EQUIVALENT LUMINANCE (cd/m^2)
6	40	2,540	2,991
	60	3,809	4,294
	80	5,079	5,597
9	40	5,120	5,087
	60	7,680	7,222
	80	10,241	9,357

Ambient illumination. The study was performed on sunny spring days between 10:45 a.m. and 3:15 p.m. The illumination was measured on each test day at the beginning and end of the actual testing. These measurements showed that the illumination at the surface of the lamps averaged 5,500 foot-candles with a range of 4,500 to 6,000 foot-candles (in comparison to 6,000 foot-candles in Task 3A), and the illumination at the subject's eyes averaged 240 foot-candles with a range of 200 to 270 foot-candles (in comparison to 40 foot-candles in Task 3A).

Response-to-stimulus intervals. The same as in Task 3A (6, 8, 10, 12, and 14 sec).

Subjects. Eight paid subjects were tested. Four of them were younger (18, 21, 22, and 27 of age), and four were older (69, 71, 72, and 72 of age). Two males and two females were in each age group. Each subject had normal or corrected-to-normal visual acuity (20/40 or better).

Computer-control of the study. The same as in Task 3A.

Procedure

As in Task 3A, the subject was instructed to perform the compensatory tracking task continuously throughout the test session (except during breaks). The compensatory tracking task required the subject to use a knob with the non-dominant (i.e., usually the left) hand. The primary, detection task was responded to by pressing one of two response buttons with the dominant (i.e., usually the right) hand.

Each trial consisted of a 2-sec presentation of either the left or the right lamp. Subject's task was to press one of two response keys with the dominant hand, to indicate whether the left or right lamp was illuminated.

There were, nominally, 60 trials per subject (2 lamps x 3 intensities x 5 response-to-stimulus intervals x 2 positions [left or right]), with all variables counterbalanced. However, the trials on which the subject did not respond within three seconds, or responded with the incorrect response key, were repeated at the end of each block of six trials. (The originally missed and incorrectly responded trials were also tabulated.) The trials were presented in two blocks of thirty (nominal) trials each. A practice session of thirty trials was given to each subject at the beginning of the study. With short breaks between the blocks of trials, the study took about a half hour to complete.

Results

Frequency tabulations. Table 17 presents the frequency of correctly responded trials, incorrectly responded (error) trials, and not-responded-to (missed) trials (collapsed over lamps). (Tables 18 through 20 are based only on the original 480 trials [8 subjects x 60 trials]; the repeated trials are not included here.)

TABLE 17

FREQUENCY OF CORRECT, ERROR, AND MISSED TRIALS IN TASK 3B

Trial	Intensity			
	80 cd	60 cd	40 cd	All
Correct	147	145	149	441
Error	10	8	5	23
Missed	3	7	6	16

Table 18 lists the frequency of missed trials by lamp and intensity. Table 19 is an analogous table for error responses.

Reaction time. Table 20 lists the mean reaction times by lamp and intensity.

TABLE 18

FREQUENCY OF MISSED TRIALS IN TASK 3B

Lamp No.	Intensity			
	80 cd	60 cd	40 cd	All
6	0	2	5	7
9	3	5	1	9
Both	3	7	6	16

TABLE 19

FREQUENCY OF ERROR TRIALS IN TASK 3B

Lamp No.	Intensity			
	80 cd	60 cd	40 cd	All
6	4	2	2	8
9	6	6	3	15
Both	10	8	5	23

TABLE 20

REACTION TIME OF CORRECT RESPONSES IN TASK 3B (in seconds)

Lamp No.	Intensity			
	80 cd	60 cd	40 cd	All
6	1.18	1.25	1.30	1.24
9	1.09	1.27	1.23	1.20
Both	1.14	1.26	1.26	1.22

Discussion

The data from this field task are in good qualitative agreement with those from the laboratory Task 3A. This is the case both for the missed trials and for the reaction times.

Missed trials. Table 21 lists the percentages of missed trials for the comparable conditions of Tasks 3A and 3B. This comparison indicates that in both studies there is a tendency for the missed trials to increase if the lamp intensity is reduced from 80 cd to 60 cd. Furthermore, while the overall percentage of the missed trials is somewhat higher in Task 3B than in Task 3A, the two percentages are still comparable.

TABLE 21

PERCENTAGES OF MISSED TRIALS IN TASKS 3A AND 3B
(lamps 6 and 9, 145-ft viewing distance)

Task	Intensity			
	80 cd	60 cd	40 cd	All
3A	1.5	2.7	2.7	2.3
3B	1.9	4.4	3.8	3.3

Reaction time. Figures 17 and 18 present a graphic comparison of the reaction times in the comparable conditions of Tasks 3A and 3B. Again, the qualitative agreement between these two sets of data is good, since the curves for the two tasks tend to be parallel, with the reaction time in Task 3B being generally slower than in Task 3A.

Windshield transmissivity. The presence of a windshield between the lamps and the following driver reduces the amount of light from the lamps that eventually reaches the eyes of the following driver. Depending on the angle of the installation of the windshield, and the presence or absence of a tint in the windshield, the transmissivity ranges from about 68% to 90%. However, because of the relatively uniform spatial transmissivity, the windshield does not reduce the contrast between the lamp and its background (as long as the background brightness is non-zero). Furthermore, research indicates that target detection in the incremental-brightness paradigm is primarily influenced by the brightness contrast between the target and its background, and not by the brightness of the target (e.g., Cornsweet, 1970; Coren, Porac, and Ward, 1979). Consequently, it is not surprising

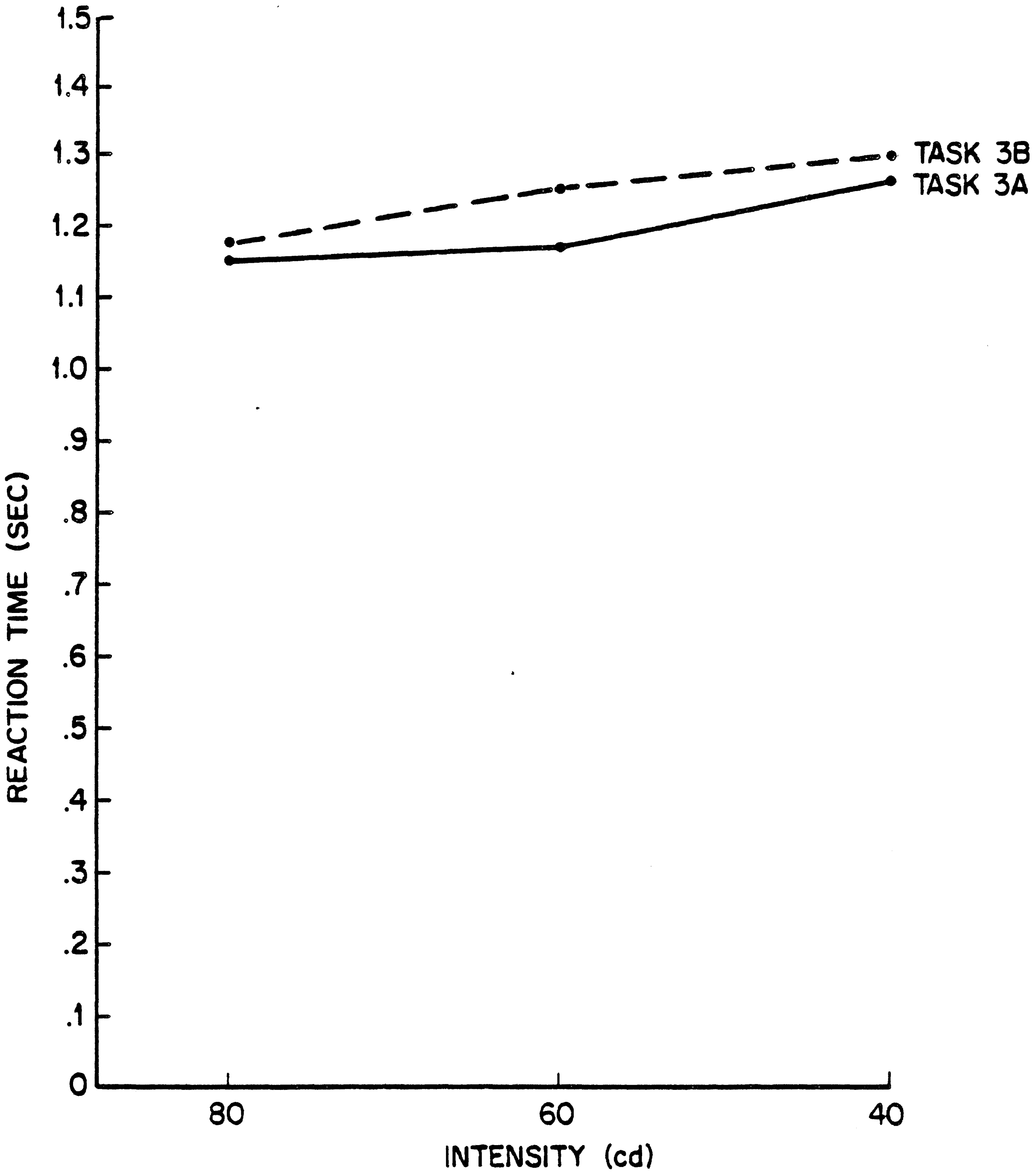

Figure 17. Comparison of reaction times in Tasks 3A and 3B. (Lamp 6, 145-ft viewing distance.)

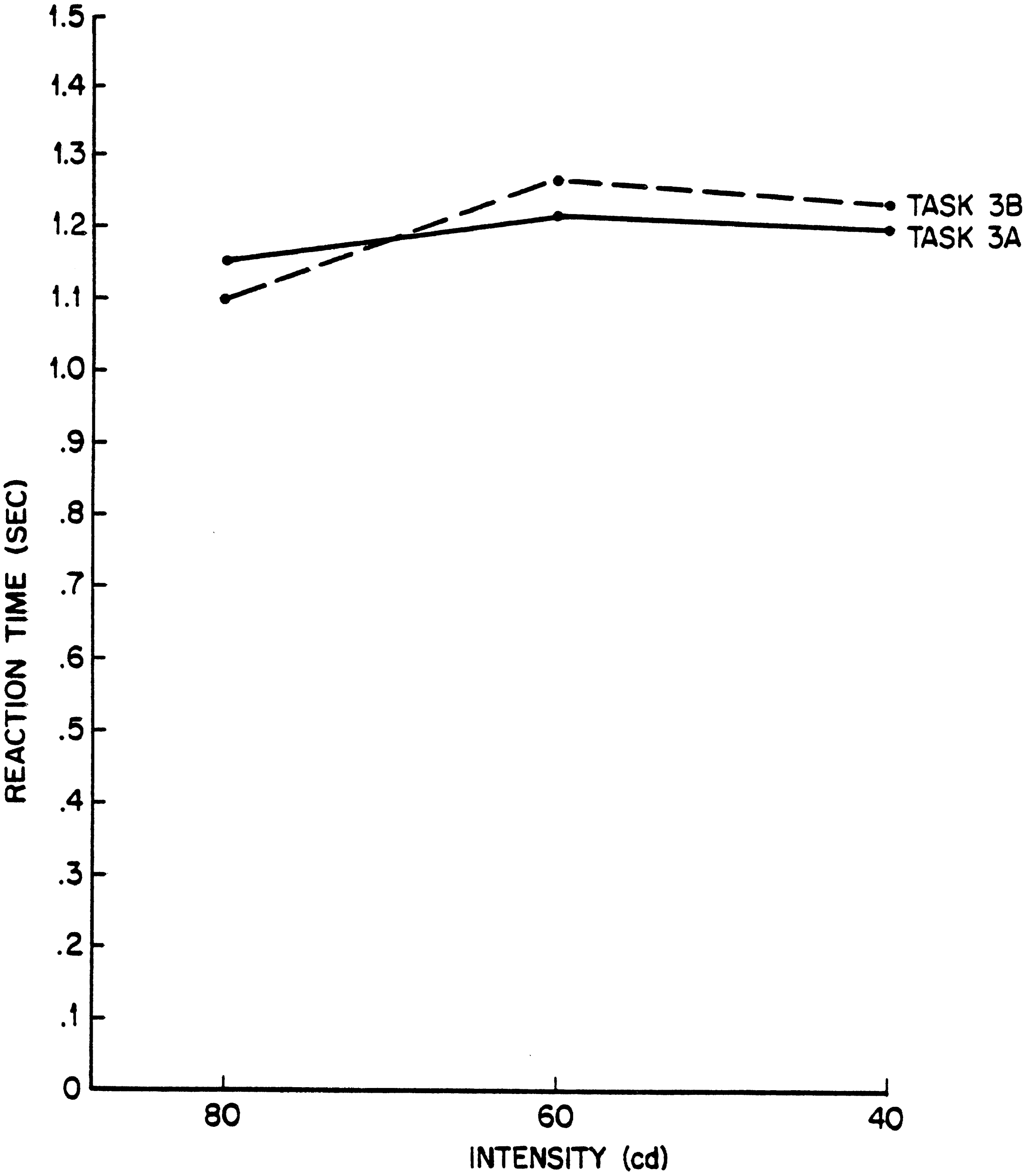

Figure 18. Comparison of reaction times in Tasks 3A and 3B. (Lamp 9, 145-ft viewing distance.)

that the results of Tasks 3A and 3B are in good qualitative agreement, despite the presence of windshield between the lamps and the subject in Task 3B.

Conclusion

In conclusion, the data from the field Task 3B are in good qualitative agreement with those from the laboratory Task 3A. Consequently, the data from the more extensive Task 3A (in terms of tested lamps, intensity levels, viewing distances, and subjects) can be relied upon in making recommendations.

TASK 4A: LAMP PHOTOMETRICS AND SIGNAL IDENTIFICATION

Introduction

This task had two objectives. The first was to determine the relationship between lamp photometrics and presence/brake signal differentiation. To assess this relationship, signal identification was evaluated as a function of lamp photometrics under simulated dusk/dawn conditions. The second objective was to assess the relative predictive power of luminous intensity, equivalent luminance, and average luminance to predict performance in a signal-identification paradigm.

Method

Experimental setup. Figure 19 is a schematic of the experimental setup for Task 4A. On each trial two identical lamps were simultaneously energized so that they simulated one of the following two dual-cavity lamp configurations:

(1) Non-separated functions, with both lamps red. Both lamps were presented at the same intensity, but the intensity was varied from trial to trial. This configuration was designed to simulate the typical U.S. rear-lighting system in which the *same* lamps are used to signal both presence and brake.

(2) Separated functions, with both lamps red. One lamp was set at 18 cd (corresponding to a presence light), while the intensity of the other lamp was varied from trial to trial. This configuration was designed to simulate the typical European rear-lighting system in which *different* lamps are used to signal presence and brake.

For the non-separated condition, the subjects were instructed as follows:

> ...It is dusk, and you are cresting a hill. As you crest the hill, you suddenly see a car in your lane, with two lamps illuminated. Your task is to decide whether the car in front of you is signaling "presence" (as would be the case when only the headlights are on), or whether it is signaling "brake" (as would be the case when the headlights are on and the brakes are being applied). All you have to go by in making the decision is the brightness of the lights: "Brake" is signaled by brighter lights than "presence."
>
> You should press the left key if you feel that "presence" is being indicated, and the right key if "brake" is being indicated. Please give us your best estimate of which condition is being shown. When you make up your mind, please respond as quickly as you can....

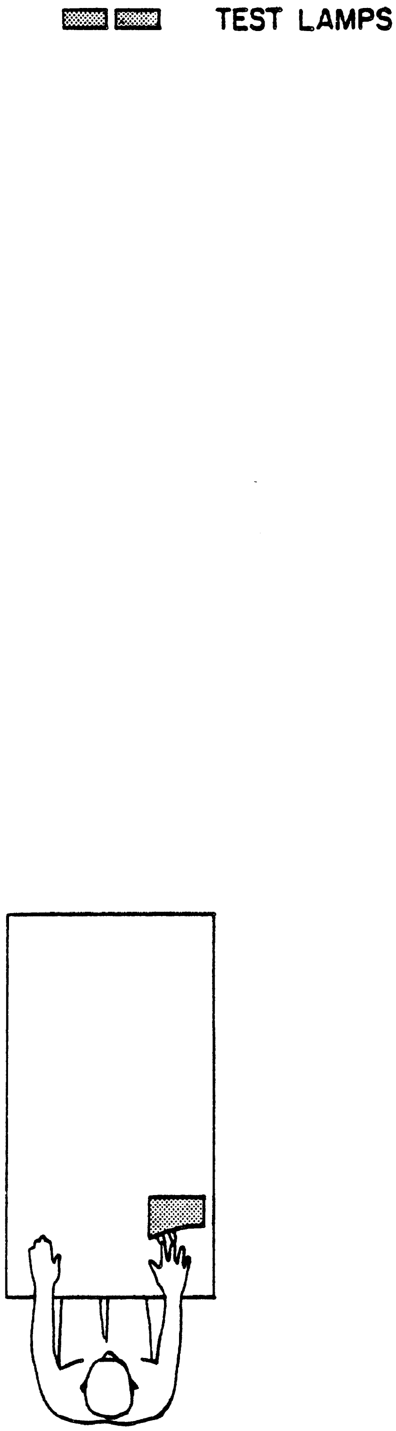

Figure 19. Schematic of the experimental setup in Task 4A.

The instructions for the separated conditions were analogous to those for the non-separated condition. Here subjects were told that "in this part of the study 'brake' will be signaled by a brightness difference between the two lights. If the two lights have the same brightness, they are indicating 'presence,' ...[and] if the two lights have different brightness, they are indicating 'brake.'"

In comparison with the Tasks 3A and 3B, there was no secondary (loading) task in this study. The rationale was that detection (under investigation in Tasks 3A and 3B) is frequently done peripherally. Consequently, to assure that the stimuli were presented in the periphery, a foveal loading task was employed. On the other hand, signal identification (under investigation in the present task) is assumed to be performed primarily while the signal is viewed foveally. Consequently, no loading task was deemed necessary in the present study.

Independent variables

Test lamps. Four test lamps were used, No. 2, 3, 6, and 14 (see Table 7, Task 2, for the description of these lamps).

Intensity levels. Five intensity levels were used: 18, 40, 60, 80, and 100 cd. These values were selected because of the following considerations: (1) 18 cd is the current U.S. maximum for presence lamps, (2) 80 cd is the current U.S. minimum for brake lamps, (3) 40 cd is the current European minimum for brake lamps, (4) 60 cd is a frequently suggested compromise between the U.S. and European minima for brake lamps, and (5) 100 cd is a realistic value of actual brake lamps. The corresponding average luminance values (intensity divided by surface area) and equivalent luminance values (computed from the regression equations that were derived in Task 2) are listed in Table 22.

Subject groups. The ability to discriminate presence from brake signals is potentially affected by prior experience of the observer. (In contrast, detectability [under investigation in Tasks 3A and 3B] is unlikely to be dependent on prior experience.) Consequently, one of the groups of subjects had only limited experience with U.S. rear-lighting systems. Specifically, three groups of subjects participated in this study: (1) Eight younger U.S. subjects (19, 19, 19, 20, 21, 21, 22, and 23 years of age), (2) eight older U.S. subjects (60, 68, 69, 71, 71, 72, 74, and 80 years of age), and (3) eight West-European subjects (20, 25, 26, 26, 28, 30, 31, and 37 years of age) who had arrived in the U.S. within six weeks of the test date. (There were four males and four females in each

TABLE 22

PHOTOMETRIC PROPERTIES OF THE TEST LAMPS IN TASK 4A

LAMP	INTENSITY (cd)	AVERAGE LUMINANCE (cd/m^2)	EQUIVALENT LUMINANCE (cd/m^2)
2	18	942	1,796
	40	2,094	3,991
	60	3,141	5,987
	80	4,188	7,983
	100	5,236	9,979
3	18	1,897	2,920
	40	4,215	6,489
	60	6,322	9,733
	80	8,430	12,977
	100	10,537	16,222
6	18	1,143	2,019
	40	2,540	4,487
	60	3,809	6,730
	80	5,079	8,974
	100	6,349	11,217
14	18	2,178	2,782
	40	4,840	6,183
	60	7,260	9,274
	80	9,679	12,365
	100	12,099	15,456

group of subjects.) Each subject had normal or corrected-to-normal visual acuity (20/40 or better).

Lamp configurations. Two lamp configurations, non-separated and separated (as described above) were used.

Dependent variables. The type of the response (presence/brake) and the corresponding reaction time were recorded.

Lamp separation. The center-to-center separation of all pairs of lamps was 11.25 in. (This was the minimum possible separation for one of the pairs.)

Viewing distance. The viewing distance was 50 ft. This distance corresponds to the shorter of the two distances used in Task 2.

Ambient illumination. The ambient illumination was the same as in the "dark" condition of Task 2, resulting in 0.2 foot-candles on the surface of the lamps, and 0.2 foot-candles at the subject's eyes.

Response-to-stimulus intervals. The delay between a response and the onset of the subsequent stimulus was 4, 5, 6, 7, or 8 sec.

Computer-control of the study. This study was under the control of an Apple II+ microcomputer. (The description of the computer control of Task 3A is applicable, in principle, to the present study as well.)

Photometric calibrations. Prior to each day's runs a calibration check of the photometric output of the lamps was performed. These measurements proved all to be within ±4% of the nominal values, with 72% within ±2% of the nominal values.

Procedure

Each trial consisted of a 2-sec presentation of two lamps. The subject's task was to press, with the dominant hand, one of two response keys to indicate whether the configuration signaled "presence" or "brake."

Two replications of each condition were given each subject. This resulted, nominally, in 400 trials per subject (4 lamps x 2 conditions x 5 intensities x 5 response-to-stimulus intervals x 2 replications), with all variables counterbalanced. However, the trials on which the subject did not respond within three seconds were repeated at the end of each block of five trials. The trials were presented in eight blocks of fifty (nominal) trials each. The first four blocks were for one condition (non-separated or separated), while the second four blocks were for the other condition. Practice sessions of fifty trials each were given to each subject at the beginning of the study and when the conditions were changed. With short breaks between blocks of trials, the study took about an hour and a half to complete.

Results

Likelihood of brake and presence responses. The percentages of brake responses (and the corresponding reaction times) by lamp configuration, intensity, and subject group are listed in Tables 23 through 25. Analysis of variance of the percent brake responses revealed the following significant main effects:

Lamp intensity, $F(4,84) = 423.28$, $p < 0.001$ (18 cd: 5%, 40 cd: 41%, 60 cd: 77%, 80 cd: 91%, 100 cd: 96%).

Lamps, $F(3,63) = 4.24$, $p = 0.008$ (No. 2: 64%, No. 3: 59%, No. 6: 62%, No. 14: 61%).

Effects of the configuration, subject group, and double interactions involving subject group did not reach statistical significance at the 0.05 level.

Reaction time. Analysis of variance of the reaction time revealed the following significant main effects:

Lamp intensity, $F(4,84) = 25.39$, $p < 0.001$ (18 cd: 0.95 sec, 40 cd: 1.15 sec, 60 cd: 1.06 sec, 80 cd: 0.94 sec, 100 cd: 0.86 sec).

Configuration, $F(1,21) = 43.73$, $p < 0.001$ (non-separated: 0.90 sec, separated: 1.09 sec).

Effects of the lamp, subject group, and double interactions involving subject group did not reach statistical significance at the 0.05 level. (However, the younger U.S. subjects were significantly faster [0.89 sec] than the older U.S. subjects [1.10 sec]. The European subjects turned out to be in between the two U.S. groups, both in terms of their ages and reaction time [1.00 sec].)

Relation of brake/presence responses to photometric parameters. The correlations between the photometric parameters and percent brake responses for the twenty lamp-by-intensity conditions are shown in Table 26.

Relation of brake/presence responses to reaction time. It was hypothesized, *a priori*, that reaction time would be an inverted function of the lamp intensity. This prediction was made because it was expected that reaction time would be longest in the conditions leading to greatest indecision concerning the brake/presence differentiation. Specifically, it was

TABLE 23

PROPORTIONS OF BRAKE RESPONSES AND REACTION TIMES FOR THE NON-SEPARATED LAMP CONFIGURATION IN TASK 4A

INTENSITY (cd)	SUBJECTS							
	YOUNGER		OLDER		EUROPEAN		ALL	
	% BRAKE	*RT (sec)*	% BRAKE	*RT (sec)*	% BRAKE	*RT (sec)*	% BRAKE	*RT (sec)*
18	8	*0.83*	3	*0.83*	6	*0.82*	6	*0.82*
40	52	*0.95*	23	*1.03*	40	*1.08*	39	*1.02*
60	80	*0.88*	58	*1.11*	82	*0.97*	74	*0.98*
80	92	*0.77*	86	*1.02*	92	*0.83*	90	*0.87*
100	98	*0.71*	93	*0.89*	99	*0.75*	97	*0.78*
$\bar{X}$	66	*0.83*	53	*0.98*	64	*0.89*	61	*0.90*

TABLE 24

PROPORTIONS OF BRAKE RESPONSES AND REACTION TIMES FOR THE SEPARATED LAMP CONFIGURATION IN TASK 4A

INTENSITY (cd)	SUBJECTS							
	YOUNGER		OLDER		EUROPEAN		ALL	
	% BRAKE	*RT (sec)*	% BRAKE	*RT (sec)*	% BRAKE	*RT (sec)*	% BRAKE	*RT (sec)*
18	3	*0.96*	5	*1.14*	5	*1.15*	4	*1.08*
40	42	*1.12*	39	*1.40*	48	*1.32*	43	*1.28*
60	86	*0.97*	78	*1.30*	79	*1.14*	81	*1.14*
80	94	*0.88*	90	*1.18*	90	*0.99*	91	*1.02*
100	95	*0.81*	95	*1.06*	93	*0.92*	95	*0.93*
$\bar{X}$	64	*0.95*	61	*1.21*	63	*1.10*	63	*1.09*

TABLE 25

PERCENTAGES OF BRAKE RESPONSES AND REACTION TIMES FOR BOTH LAMP CONFIGURATIONS IN TASK 4A

INTENSITY (cd)	SUBJECTS							
	YOUNGER		OLDER		EUROPEAN		ALL	
	% BRAKE	*RT (sec)*	% BRAKE	*RT (sec)*	% BRAKE	*RT (sec)*	% BRAKE	*RT (sec)*
18	5	*0.90*	4	*0.99*	6	*0.98*	5	*0.95*
40	47	*1.03*	31	*1.21*	44	*1.20*	41	*1.15*
60	83	*0.92*	68	*1.20*	81	*1.05*	77	*1.06*
80	93	*0.82*	88	*1.10*	91	*0.91*	91	*0.94*
100	96	*0.76*	94	*0.98*	96	*0.83*	96	*0.86*
$\bar{X}$	65	*0.89*	57	*1.10*	64	*1.00*	62	*0.99*

TABLE 26

INTERCORRELATIONS BETWEEN THE PHOTOMETRIC VARIABLES AND THE PERCENT OF BRAKE RESPONSES IN TASK 4A

(N = 20, r@0.05 = .43; all correlations are statistically significant)

	% BRAKE RESPONSES	LUMINOUS INTENSITY	EQUIVALENT LUMINANCE
AVERAGE LUMINANCE	**0.74**	**0.80**	**0.97**
EQUIVALENT LUMINANCE	**0.85**	**0.91**	
LUMINOUS INTENSITY	**0.96**		

predicted that reaction time would be longest in conditions leading to close to 50% brake responses, and that reaction time would decrease as the proportion of brake responses increases and decreases away from 50%. This specific prediction was tested by correlating the mean reaction time for each of the twenty lamp-by-intensity conditions with the smaller of the brake- and presence-response percentages for the corresponding conditions. This correlation proved to be statistically significant (r = 0.93, df = 18, p <0.001).

Discussion

Intensity vs. equivalent luminance vs. average luminance. One of the objectives of this task was to evaluate the power of intensity, equivalent luminance, and average luminance to predict performance in a signal-identification paradigm. The present findings indicate that the currently used photometric parameter—luminous intensity—is a statistically significant predictor of signal identification. While equivalent luminance (derived in Task 2) and average luminance were also significantly related to signal identification, luminous intensity accounted for more variance of signal identification than the other two predictors (92% vs. 72% and 55%).

Minimum brake-lamp intensity for signal identification. The likelihood of identifying a signal as a brake signal proved to be a monotonic function of lamp intensity. For the current U.S. minimum brake-lamp intensity of 80 cd, this likelihood was 91%. This likelihood decreased to 77% for 60 cd, and increased to 96% for 100 cd. These results argue against reducing the current minimum brake-lamp intensity.

Reaction time. Reaction time proved to be inversely related to the degree of subjects' uncertainty (as measured by the relative likelihood of brake and presence responses): Reaction time was slowest when the likelihood of both types of response was close to 50%, and it decreased as the likelihood of brake responses increased or decreased away from 50%. Specifically, the peak reaction time was for 40 cd (1.15 sec), and it decreased as the intensity either decreased to 18 cd (0.95 sec) or increased to 60 cd (1.06 sec), 80 cd (0.94 sec), and 100 cd (0.86 sec). (The greatest response indecision was for 40 cd [41% brake responses], and it decreased as the intensity either decreased to 18 cd [5% brake responses], or increased to 60, 80, and 100 cd [77%, 91%, and 96% brake responses, respectively].) The results of this analysis (in agreement with the results of the above-discussed identification analysis) argue against reducing the current minimum brake-lamp intensity.

Lamp configuration. The present study simulated both the typical U.S. (non-separated brake and presence lamps) and European (separated brake and presence lamps) rear-lighting systems. There was no significant effect of the lamp configuration on the likelihood of brake responses, but there was a statistically and practically significant effect on reaction time: The mean reaction time for the non-separated lamp configuration was 0.90 sec, while for the separated condition it was 1.09 sec. The obtained 0.19 sec disadvantage for the separated system is possibly the result of an increased duration of the decision process that requires comparison of two spatially separated areas (i.e., two lamps), in comparison to the decision process that *could* rely on only one of the two available spatial areas.

The advantage of the non-separated lamp configuration in this study contrasts with the reported advantage of separated rear-lighting systems in past studies (e.g., Mortimer, 1970; Campbell and Mortimer, 1972). However, these studies are not fully comparable with the present study because they measured reaction time to a *change* in the rear signal: In these studies the presence lamps was always illuminated between the trials, and the subject's tasks was to respond to the onset of brake or turn signals (or a change from turn to brake, and brake to turn signals). Consequently, these studies investigated reaction time in situations where the subject was observing the change from one signal to another. In contrast, the present study simulated the worst-case scenario, in which the following driver does not see the transition from one signal to another (e.g., seeing a car upon cresting of a hill). The present findings indicate that under these more demanding conditions, the reaction time to the non-separated configuration is significantly faster than the reaction time to the separated configuration.

Effects of prior experience. This study found no difference between the performance of U.S. and European subjects who arrived recently in the U.S: Both in terms of signal identification and reaction time, there were no significant main effects of subject group and no significant double interactions involving subject group. Consequently, the present findings suggest that prior experience does not significantly affect brake/presence differentiation and the corresponding reaction time.

Range effect. It is well known that subjective judgments are influenced by the range of stimuli presented. In the automotive context, for example, Olson and Sivak (1984) have shown that judgments concerning discomfort glare from vehicle headlights are affected by the range of illuminances used. Consequently, each study using a subjective scale is potentially susceptible to the range effect. In the present study, however, the influence of the range effect was minimized by selecting stimuli that reasonably represent the on-the-road photometric levels.

Conclusion

In conclusion, the results of this task provide support for retaining luminous intensity as the relevant parameter of brake-lighting specification. Furthermore, these results argue against reducing the current minimum of 80 cd for the brake-lamp luminous intensity.

TASK 4B: LAMP PHOTOMETRICS AND SIGNAL IDENTIFICATION FOR COLOR-CODED SYSTEMS

Introduction

The objective of this task was to evaluate for a color-coded rear-lighting system the potential effects of decreasing the intensity difference between presence and brake lamps from 18 vs. 100 cd to 18 vs. 40 cd. A signal-identification paradigm, analogous to the one in Task 4A, was used. This was an exploratory study, using a limited number of subjects.

Method

Experimental setup. The experimental setup was identical to the setup in Task 4A (see Figure 19, Task 4A), with the exception that one lamp was red and the other lamp green.

The subjects were instructed as follows:

> ...In this study we are testing a novel rear lighting system. This system indicates "presence" by a green light, and "brake" by an additional red light. Furthermore, the red brake light is brighter than the green presence light....
>
> You should press the left key if you feel that "presence" is being indicated, and the right key if "brake" is being indicated. Please respond as quickly as you can.

Independent variable. The intensity of the red lamp (0, 40, 60, 80, or 100 cd) was the independent variable. The green lamp was set always at 18 cd.

Test lamp. A pair of No. 2 lamps were used in this study. (See Table 7, Task 2, for the description of this lamp). The "green" lamp was obtained by replacing the red lens with a blueish green lens.

Subjects. Four younger subjects (18, 18, 21, and 24 years of age) and four older subjects (69, 73, 75, and 76 years of age) participated. There were two males and two females in each age group. Each subject had normal or corrected-to-normal visual acuity (20/40 or better).

Dependent variables. The error-response rate and reaction time were the dependent variables. (In comparison to Task 4A, the instructions in the present task specified the objectively correct response, thus allowing the tabulation of error rates. Specifically, "brake" responses to 18 cd green, 0 cd red condition, and "presence" responses to all other conditions were considered error responses.)

Viewing distance. The same as in Task 4A (50 ft).

Lamp separation. The same as in Task 4A (11.25 in, center-to-center).

Ambient illumination. The same as in Task 4A (0.2 foot-candles at the surface of the lamps, and 0.2 foot-candles at the subject's eyes).

Response-to-stimulus intervals. The same as in Task 4A (4, 5, 6, 7, and 8 sec).

Computer-control of the study. The same as in Task 4A.

Photometric calibrations. Prior to each day's run a calibration check of the photometric output of the lamps was performed. These measurements all proved to be within ±3% of the nominal values.

Procedure

Each trial consisted of a 2-sec presentation of the lamp(s). The subject's task was to press, with the dominant hand, one of two response keys to indicate whether the configuration signaled "presence" or "brake."

Fifty replications of each condition were presented to each subject, with the exception of the green-lamp-only condition, which was presented one hundred times (to increase the frequency of "presence" stimuli). This resulted, nominally, in 300 trials per subject. However, the trials on which the subject did not respond within three seconds were repeated at the end of each block of six trials. The trials were presented in five blocks of sixty (nominal) trials each. A practice session of thirty trials was given each subject at the beginning of the study. With short brakes between blocks of trials, the study took about an hour to complete.

Results

Errors. The percentages of error responses by conditions are shown in Table 27.

Reaction times. Reaction times by conditions are shown in Table 28. A test for linear trend was performed for the 32 combinations of 4 nominally "brake" conditions times 8 subjects. This test was statistically significant ($t = 2.84$, $df = 21$, $p < 0.01$). To estimate the effect of decreasing the brake lamp intensity from 100 cd to 40 cd (given a color-coded system with the presence lamp at 18 cd), a 95% confidence interval for the obtained reaction-time difference was computed as follows:

$$(RT_{18,40} - RT_{18,100}) \pm 1.96\sqrt{s^2} = 0.03 \text{ sec} \pm 0.02 \text{ sec}$$

TABLE 27

PERCENTAGES OF ERROR RESPONSES IN TASK 4B

CONDITION	% ERROR RESPONSES
18 cd green, 0 cd red	6
18 cd green, 40 cd red	1
18 cd green, 60 cd red	2
18 cd green, 80 cd red	1
18 cd green, 100 cd red	2
$\bar{X}$	3

TABLE 28

REACTION TIMES IN TASK 4B

CONDITION	REACTION TIMES (sec)
18 cd green, 0 cd red	0.66
18 cd green, 40 cd red	0.64
18 cd green, 60 cd red	0.63
18 cd green, 80 cd red	0.62
18 cd green, 100 cd red	0.61
$\bar{X}$	0.63

Discussion

The main finding of this study is that when rear lights are color-coded, decreasing the intensity difference between presence and brake lights from 18 vs. 100 cd to 18 vs. 40 cd does not increase the error rate of signal-identification responses, but it results in a small (0.03 sec) but statistically significant increase in reaction time.

This study was not designed to test the benefits of color-coding *per se*. Nevertheless, it is tempting to compare the results for the separated condition in Tasks 4A with the results for Task 4B to estimate the benefits of color-coding. Such a comparison reveals that the reaction time in Task 4B was (depending on the intensity level) 0.32 to 0.64 sec faster than in Task 4A. While the apparent advantage of the color-coded system is consistent with findings of past studies (e.g., Campbell and Mortimer 1972; Rockwell and Treitener, 1968), the obtained difference cannot be used to estimate the actual *magnitude* of the benefit of color-coding. The reason is that performance on a given task is affected by the overall difficulty of the task, which in turn is influenced by the particular stimulus levels that are used. For example, if Task 4A had used only two widely separated stimulus levels—say 18 red, 18 cd red; and 18 cd red, 100 cd red—one would expect better performance (i.e., better signal discrimination and faster reaction time) than was the case for the actual set of stimuli that included three additional intermediate stimuli (18 cd red, 40 cd red; 18 cd red, 60 cd red; and 18 cd red, and 80 cd red). (The inclusion of the intermediate levels makes the identification task more difficult.) In other words, performance for a given stimulus (e.g., 18 cd red, 100 cd red) is expected to be affected by the presence or absence of other stimuli. Consequently, a comparison of the performance on 18 cd red, 100 cd red from Task 4A with the performance on 18 cd green, 100 cd red from Task 4B is not necessarily a valid indicator of the benefit of color-coding.

Conclusion

In conclusion, the present findings indicate that when rear lights are color-coded, decreasing the intensity difference between presence and brake lights from 18 vs. 100 cd to 18 vs. 40 cd does not increase the error rate of signal-identification responses, but it results in a statistically significant (albeit small) increase in reaction time.

RECOMMENDATIONS

On the basis of these studies, it is recommended that

(1) luminous intensity be retained as the relevant photometric parameter of automobile brake lamps, and

(2) 80 cd be retained as the minimum brake-lamp luminous intensity.

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