



NRC Publications Archive Archives des publications du CNRC

Visual performance with realistic methods of changing contrast

Rea, M. S.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

Publisher's version / Version de l'éditeur:

Journal of the Illuminating Engineering Society, 10, 3, pp. 164-177, 1981-04

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=745b7f5a-dd97-49b8-b7af-048b23369611>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=745b7f5a-dd97-49b8-b7af-048b23369611>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.



Ser
TH1
N21d

no. 986
c. 2

National Research Council of Canada
Conseil national de recherches du Canada

8848

**VISUAL PERFORMANCE WITH REALISTIC
METHODS OF CHANGING CONTRAST**
by Mark S. Rea

ANALYZED

Reprinted from
Journal of the Illuminating Engineering Society
Vol. 10, No. 3, April 1981
p. 164-177

10265

BLDG. RES.
LIBRARY

81- 10- 16

BIBLIOTHEQUE
Rech. B

DRB Paper No. 986
Division of Building Research

Price \$1.25

OTTAWA

NRCC 19458

SOMMAIRE

On a enregistré la performance de jeunes adultes lorsqu'on variait le contraste photométrique d'une tâche selon des "méthodes réalistes". Une fonction de transfert qui lie le contraste de la tâche et la performance a été obtenue. A partir de cette fonction de transfert et de mesures photométriques supplémentaires, on présente des suggestions pour des projets d'éclairage pratiques.



Visual performance with realistic methods of changing contrast

Mark S. Rea

The performance of young adult subjects was recorded when the photometric contrast of a task was altered using "realistic" methods. A general transfer function was obtained relating task contrast to performance. Based upon the transfer function and additional photometric measurements, suggestions for practical lighting design were presented.

ANALYZED

Introduction

The performance of human observers at a task is determined by a wide variety of factors. These factors have varying degrees of influence; some are negligible in the outcome of an experiment while others are quite important. The light reflecting difference between the target and the background, i.e., contrast, is an important factor in determining performance at a visual task.¹ Very small changes in contrast can make the difference between seeing and not seeing. Contrast then, becomes one of the most important factors to be specified when studying visual performance.

In basic psychophysical experiments designed to measure human sensitivity to changes in contrast^{2,3,4} target and background luminances can be varied systematically without regard for methods of changing contrast in the real world. At realistic tasks, contrast can be altered by many methods^{5,6,7,8,9,10} including (a) position of the luminaire with respect to the task, (b) polarization of the light, (c) reflecting characteristics of the stimuli, and (d) viewing angle. Hopefully, photometric contrast data recorded in the field may be related to the basic psychophysical data. In this way evaluations of the effectiveness of realistic methods of changing contrast can be made using a human performance criterion.

This interfacing of contrast changes at realistic visual tasks with basic psychophysical data, however, tacitly assumes that performance at a job is like performance at a basic psychophysical task. If the laboratory experiments have included or excluded influential factors not found in realistic settings then the basic psychophysical functions will not accurately scale the effectiveness of the realistic methods for changing contrast. Because contrast is such a strong factor in determining performance, however, this

assumption may be appropriate. Nevertheless, a great deal of face validity would be gained if realistic methods of changing contrast were parametrically employed in an experiment where human subjects were engaged in a realistic task. In this way direct estimates of the importance of the various methods of changing contrast could be made.

This paper is about human performance at a realistic task, comparing two number lists for discrepancies, when the contrast of the task materials is changed. Four realistic methods were employed in this experiment to change task contrast; lighting geometry, ink pigment density, ink specularity, and polarization of illumination. The experiment was designed to measure directly the effectiveness of and the interactions among these methods in changing photometric contrast and in changing visual performance. Because contrast is such an important factor in determining subjects' behavior at a task, it should be possible to obtain a general transfer function relating photometric contrast to the performance measurement. This transfer function should provide an estimate of the expected changes in performance at the task when contrast is altered by any method(s). Performance at other tasks^{11,12,13} or with other methods of reducing visibility¹⁴ may not be accurately predicted by this transfer function.

Methods and procedures

Experimental room—Figures 1a and 1b are schematics of the experimental "black" room. Black felt curtains were hung from the ceiling to the floor. The ceiling panels were painted flat black. The floor was off-white linoleum.

Illumination of the task was provided by cool white fluorescent lamps (Sylvania XL, F40), enclosed in a luminaire mounted on a metal superstructure covered with black felt. The light emitting aperture of the luminaire was 95.5 × 95.5 cm.

Three luminaire lenses, alternately inserted behind the aperture, provided different degrees of vertically

AUTHOR: Research Officer, Energy and Services Section, Division of Building Research, National Research Council of Canada, Ottawa, Canada.

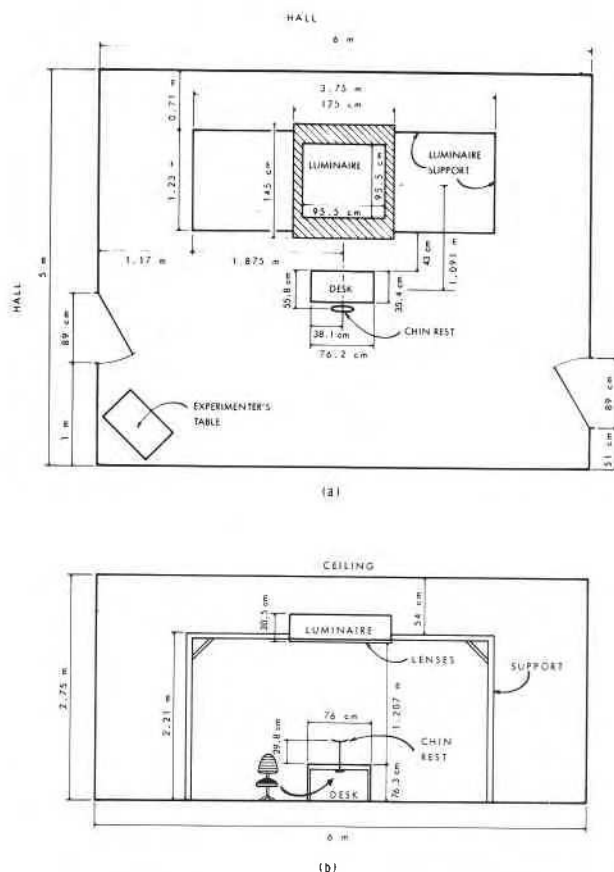


Figure 1. Schematic representations of the experimental laboratory.

polarized illumination on the task. One lens (LP) was a layer of linear dichroic polaroids (HN38 neutral-color, linear polarizers, from Polaroid Corporation) sandwiched below a sheet of polished white plexiglass and above a sheet of clear plexiglass. One lens (MP) was a layer of multilayer transmission polarizers (Type "W", diffuse-white prism back surface, from Polrized Corporation of America) below a sheet of clear plexiglass. The third lens (PM) was a sheet of polished white plexiglass above a layer of 13 mil mylar. Following Marks,¹⁵ the degree of polarization emitted from the three types of lenses at various angles was measured and computed by the formula:

$$\frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}} \times 100 = \text{degree of polarization (\%)}$$

The degree of polarization incident on the center of the task from the center of the luminaire (42.1° from normal) was measured and used to characterize the three types of lenses: LP, 99 percent; MP, 19 percent; and PM, 8 percent.

Task illumination from the three lenses on the center of the task was always constant (278 lux). Illumination was calibrated against the output of a photocell embedded in the top of the observer's work table. The experimenter monitored the output from the photocell by a digital voltmeter to keep the illumination level constant during the experiment.

Observers sat at a horizontal, white topped desk

69179	69179
27982	27982
15179	15179
39940	39940
60468	60468
18602	18602
71194	71124
94595	94595
57740	57740
38867	38867
56865	56865
18663	18663
36320	36320
67689	67689
47564	47562
60756	60756
55322	55322
18594	18594
83149	83149
76988	76988

Figure 2. Example of the stimulus sheets. A reference sheet is on the left; a response sheet is on the right.

equipped with a fixed chin rest. An adjustable chair enabled observers of different statures to be comfortably positioned at the chin rest. A matte black cardboard baffle below the chin rest minimized differential reflectances of light from subjects' clothing onto the task. The desk was located at one of two orientations with respect to the luminaire. At "0°" (shown in Fig. 1) the observer's line of sight to each number was at a mirror angle to a luminous point of the luminaire.⁶ At "90°" the desk was rotated clockwise about the center of the task so that the observer's lines of sight were perpendicular to those

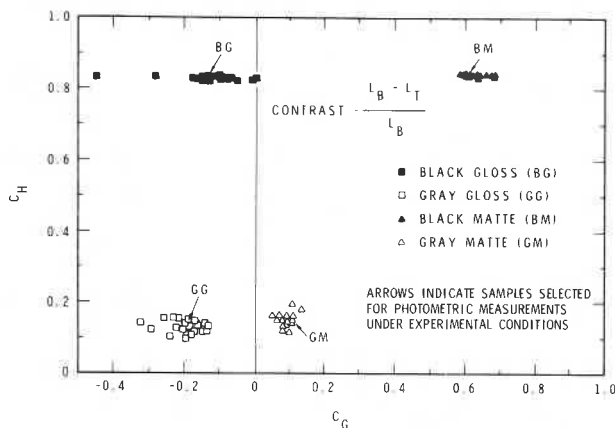


Figure 3. Gonio and (simulated) hemisphere contrast measurements for all reference sheets. Four sets of 32 reference sheets were used in the experiment (black gloss, black matte, gray gloss, and gray matte). An arrow points to the particular sample chosen for subsequent photometric measurements. The initials refer to the ink pigment density and the ink specularity, respectively, of the sample chosen.

at 0°. With an observer at the chin rest, viewing angles, from vertical, were between 46.8° for the top of the task to 36.8° for the bottom.

Stimulus sheets—Two sets of typed (IBM, Dual Gothic element, 12 characters/inch) number lists, a reference and a response set, Fig. 2, were employed in the experiment. Every sheet in both sets had a column of 20 five-digit numbers separated by horizontal lines, a small calibration square centered above the column of numbers, and a code number.

The reference lists were random numbers. The numbers in the response lists were the same as those in the reference lists except for interspersed discrepancies (errors). An error was a five-digit number in a response list with one digit different than the corresponding five-digit number on a reference list. The substituted digit and its location in the list were determined by modified randomization procedures.

There were three groups of 32 response list numbers corresponding to 32 different reference list numbers. The frequency of errors on a response list varied from 0 to 6. The mean frequency of errors in all three groups of response lists was 3.0. The standard deviations of list errors for the three groups were 1.19, 1.32 and 1.48.

During the experiment a reference sheet and a corresponding response sheet were placed side by side at the center of the desk. With the observer at the chin rest, the two columns of numbers were separated by approximately 7.5° at the center of the task.

Each of the 32 reference lists was reproduced in four special inks. Nominally the four inks were black matte, gray matte, black gloss, and gray gloss. Each ink was applied to the same type of matte white paper (Kashmere Text matte, 70 lb) by an offset printing process. This type of printing puts down a relatively uniform, microlayer of ink and minimizes embossing or intaglio effects.¹⁶

Contrast measurements of selected reference sheets were made under gonio and (simulated) hemisphere conditions.¹⁷ (The size of the reference sheets prohibited contrast measurements in the small standard hemisphere, so they were measured in a large white cubical (0.813 m × 1.02 m × 0.914 m) having a uniform illuminated ceiling. A small aperture in one wall of the cubical accommodated the objective lens of the photometer.) Both sets of measurements were done with the photometer at 25° from normal. A 4.8 mm aperture was attached to the front of the objective lens. With gonio measurements the light source was always at the mirror angle. (A linear dichroic polaroid was in front of the light source during the gonio measurements. Background and target luminances were taken as the sum of orthogonal polaroid readings.)

A homogeneous group of reference sheets according to the simulated hemisphere (C_H) and gonio (C_G) contrast values were selected for use in the experiment. C_H and C_G values for the reference sheets used in the experiment are presented in Fig. 3. Following IES recommendations,¹⁸ contrast (C) as used here follows the formula:

$$\frac{L_b - L_t}{L_b} = C$$

Where L_t and L_b are separately measured luminances from the calibration square, or target (t), and from the white page, or background (b).

Many copies of the 96 different kinds of response sheets were reproduced by an offset process at the National Research Council of Canada. Nominally these materials were all matte black on matte white paper. Gonio and hemisphere measurements were not made of these materials; sheets used in the experiment were selected visually for uniformity by the author.

Photometric measurements under experimental conditions—The polarizing lenses and the lighting geometries used in the experiment necessarily dictated changes in task contrast. Further, because the viewing angle, incident illumination angle and polarization of illumination were not uniform under the experimental conditions, the contrast will differ for each number position in the list. Five samples, one from each set of reference sheets (see Fig. 3) and one response sheet were selected for contrast measurements under the actual experimental conditions.

The photometer was placed above the chin rest in a position and at an angle to simulate an observer's eye during the experiment. A 4.8 mm aperture, as used in the C_H and C_G measurements, was attached to the front of the objective lens of the photometer to simulate the diameter of the human pupil.^{5,19} Measurements were made with the calibration square of each sample placed in many or all of the list positions. Estimates of the digit contrasts at those locations were made by separately measuring the luminances of the calibration square and of an adjacent area of the paper. Contrast was calculated as described above for C_H and C_G .

The data in Figs. 4a to c indicate the changes in

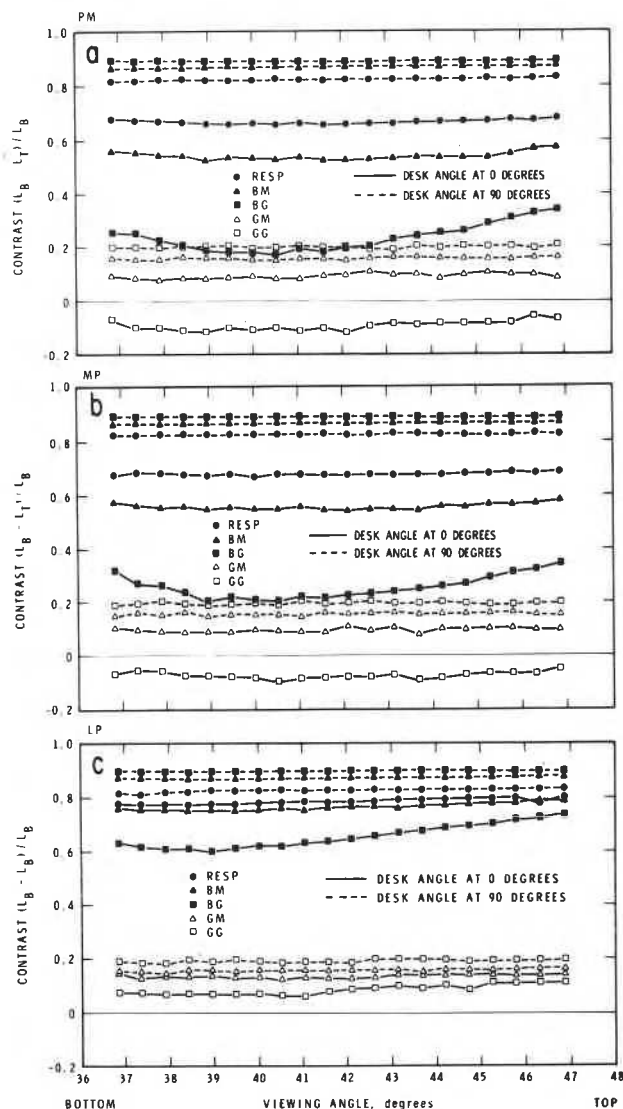


Figure 4. Contrast at different viewing angles (list positions). Each plot is for contrasts under a different type of luminaire lens, plexiglass and mylar (PM), multilayer polaroid (MP), and linear polaroid (LP). The connected points are for a given sheet at one of the two desk orientations. As in Fig. 3, the reference sheets measured are designated by four pairs of initials, (BG, BM, GG, and GM), and the response sheet measured is designated by RESP; the two desk orientations are designated 0° and 90°.

reference and response sheets contrasts through the lists for the three types of luminaire lenses. Figure 5 illustrates how the average contrast of the four reference sheets changed as a function of the degree of polarization incident at the center of the task at the two desk orientations.

Observers—Three males and three females between the ages of 18 and 24 years participated in the experiment. All observers had excellent, uncorrected vision. A battery of vision screening tests was administered to every subject with a Keystone Ophthalmic Telebinocular.

Protocol—Before collecting the data to be analyzed, subjects read instructions and were given practice trials (N = 24). During practice, observers

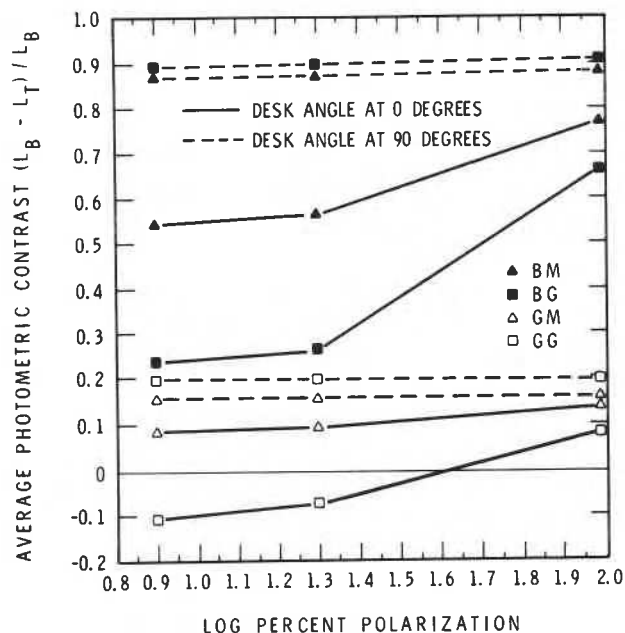


Figure 5. The effects of vertically polarized illumination on average contrast for four types of reference sheets at two orientations. As in Fig. 3, the reference sheets measured are designated by four pairs of initials (BG, BM, GG, and GM); the two desk orientations are designated 0° and 90°.

saw all of the conditions they would see in the subsequent experiment.

On each trial subjects were instructed to “quickly and accurately” compare a reference sheet (on the left) and a response sheet (on the right) and mark discrepant numbers on the response sheet. Time to complete the list comparison was recorded by the experimenter for each trial. No performance feedback was provided to subjects during the experiment. Subjects were also instructed to avoid looking from the (white) task area to the black room before trials. Following these instructions minimized effects from transient adaptation.

Every subject completed four sessions (96 trials/session), one in the morning and one in the afternoon on two consecutive days. Sessions were comprised of three blocks (32 trials/block); changes in blocks corresponded to changes in the luminaire lenses. Each block was comprised of two half-blocks (16 trials/half-block); changes in half-blocks corresponded to changes in desk orientation. Within half-blocks subjects saw four, randomly distributed examples of each type of reference sheet (matte black, matte gray, gloss black and gloss gray).

Results

Three “direct” performance measures were obtained in the experiment; time to complete a list comparison (time), the frequency of list discrepancies unmarked (misses), and the frequency of matching numbers marked wrong (false positives). Overall performance is usually conceived of as a composite of both speed (time/list) and errors (misses and false positives). Also, overall performance is assumed to increase with better visibility; time, misses and false

Table 1. Significant terms from the analysis of variance for score as the dependent variable.

Term	(a)	Prob [†]	Term	(b)	Prob [†]
Polarizing Lens	(L)	.0001	Subject	(P)	.0001
Orientation	(O)	.0001	Half-block	(H)	.0001
Ink pigment density	(D)	.0001	Meridian	(M)	NS [‡]
Ink specularity	(S)	.0001	Day	(Y)	.0001
	LXO	.0001		HXM	.0003
	LXD	.0009		PXY	.0001
	OXD	.0001		MXY	.0001
	OXS	.0001		PXMXY	.0001
	DXS	.0001		PXO*	.0001
	LXOXD	.0001		PXS*	.0007
	LXDXS	.0001		YXL*	.0007
	OXDXS	.0001			
	LXOXDXS	.0004			

[†] Estimated maximum probability that the term is significant by chance alone. Only terms with probabilities less than or equal to .01 are included.

* Significant interactions between terms in Tables 1a and b.

[‡] Not significant.

positives decrease with improved visibility. An index of performance, called score, was devised that incorporated speed and errors and increased with visibility. A trial score, as used in this experiment and earlier by Smith and Rea,²⁰ was calculated following the formula:

$$\text{Score} = \frac{(T - E) 100}{S + 5}$$

where T = total number of comparisons per trial (always 20)

E = number of errors, both misses and false positives, committed per trial

S = time to complete the comparisons per trial (in seconds).

This index is similar to Weston's.¹¹

Score will be used in subsequent discussions of the results. However, the Analyses of Variance (ANOVAs) and transfer functions (to be discussed later) for the direct performance measures are presented in Appendices I and II, respectively.

An ANOVA was employed to analyze the score data obtained in the Latin squares experimental design. Only the significant terms from the ANOVA are presented in Tables 1a and 1b. In this paper only the results characterized in Table 1a will be discussed (polarizing lens, PM, MP, and LP; desk orientation, 0° and 90°; ink pigment density, gray and black; ink specularity, gloss and matte). The terms presented in Table 1b were not of direct interest in this study, but were employed to more efficiently conduct the experiment (meridian, morning and afternoon; day, first and second; half-block, first and second; subjects, 1-6). Because the factors producing these effects in Table 1b were strictly counterbalanced and/or randomized and because they were separated in the ANOVA, the results presented in Table 1a are relatively "pure" and would be expected to occur again if the same factors were repeated in an experiment, even in one of a different design. (The performance predictions obtained from this experiment and those obtained by Smith and Rea²⁰ were nearly

identical under comparable conditions despite differences in experimental design, factors, observers, and viewing angles. A comparison between the two sets of data can be found in Appendix III.)

Although all of the main effects and many of the large interactions in Table 1a were significantly different, interpretation of these findings should be done with caution. The magnitude of the main effects and interactions (i.e., whether they are significant or not and by how much) depends in part on the particular factor levels chosen for the experiment. Therefore, many generalizations about these factors cannot be made from these data alone; other supplementary analyses and inferences must be employed before a complete understanding of these results can be made. In order to limit misinterpretations of the results by averaging across fixed parameter levels only the four way interaction between polarizing lenses (L), orientation (O), reference sheet ink pigment density (D), and reference sheet ink specularity (S) is presented (Figs. 6a to f). These figures show the large interdependence of the experimental factors characterized by the significant LxOxDxS interaction.

The Tukey method of multiple comparisons²¹ was performed on the mean scores from the 24 LxOxDxS cells. The results of this analysis are presented in Table 2. The ordinal ranking of the mean scores are presented with bars showing cells which are *not* significantly different (95% confidence interval). The experimental results from the performance study may be summarized by the Tukey analysis (Table 2):

1. At 90° there was no difference between matte and glossy inks of the same pigment density. Scores for both matte blacks and glossy blacks were within the bounds of bar #1, and scores for both matte grays and glossy grays were within the bounds of bar #4.

2. At 0° polarization of illumination made no difference in performance for glossy grays (bar #7), glossy blacks (bar #2), or matte blacks (bar #1); polarization made a large difference for matte grays (no bar includes all scores for matte grays at 0°).

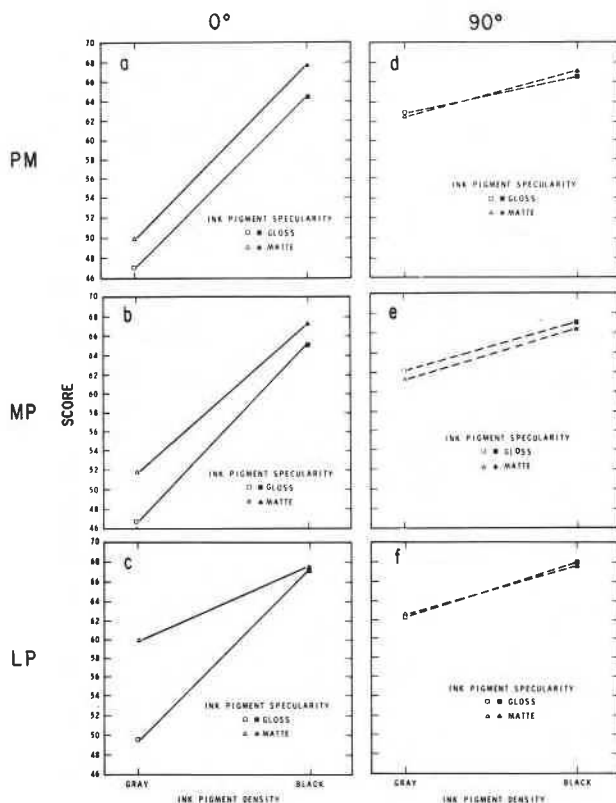


Figure 6. The combined effects of polarization, desk orientation, ink pigment density, and ink specularity on performance score. The three rows of plots are for polarization produced by the plexiglass and mylar (PM), multilayer polaroid (MP) and linear polaroid (LP) luminaire lenses; the two columns of figures are for 0° and 90° desk orientations.

3. At 90° polarization made no difference in performance for a given pigment density; scores for all polarizing lenses at 90° with black materials were within the bounds of bar #1, and scores for all polarizing lenses at 90° with gray materials were within the bounds of bar #4.

4. Black inks produced a consistently high score for both specularities, both orientations, and almost any degree of polarization. All scores for black inks were within the bounds of bar #1, except for gloss black at 0° for PM which was just outside.

Discussion of results

Figure 5 depicts the reference sheet contrasts under the experimental conditions. Before discussion of the psychophysical results, there are several points to make strictly from the physical changes in relative reflectances (i.e., contrast) shown in this figure.

First, with all four reference sheets, contrasts were higher at the 90° desk orientation than at 0° for any degree of polarization. This indicates that contrast can be improved more by changing orientation than by increasing the degree of vertical polarization, even to 99 percent. Certainly in many cases the latitude for changing desk orientation is limited or impossible. Nonetheless, polarization would be beneficial with these materials only in circumstances where people could not move their desk. (It also seems reasonable

to expect that changes in the orientation of the luminaire relative to the desk would produce the same results.) Second, all of the curves at 90° are virtually flat. This indicates that polarization makes very little or no difference perpendicular to the mirror angle. Third, matte materials change contrast less than glossy materials of the same hemisphere contrast with polarization at 0° although, clearly, matte black materials do react to polarization.^{10,22} At 0°, polarization had to be very high with gloss black materials to surpass the contrast obtained for matte black materials even under the worst conditions (i.e., 0° with the PM panel). At 0°, the contrast of the glossy gray materials was never as high as matte gray under any conditions. Fourth, gloss gray materials passed from negative to positive contrast with increased polarization of illumination. This indicates that at intermediate degrees of polarization these materials will have zero contrast. Therefore, it is misleading to say^{15,23} that increasing polarization always increases contrast. One needs to know the *absolute* contrast (i.e., ignoring the sign) produced. It is true, however, that increasing the degree of incident vertically polarized light reduces the amount of horizontally polarized light reflected from the task, but differential reductions in the amount of reflected light from target and background can reduce the *absolute* contrast, as was shown for the gloss gray materials.

The performance data are presented in Figs. 6a to f, and they depict the relative change in performance (score) with the different degrees of polarization, lighting geometry, ink pigment density and ink pigment specularity used in the experiment.

Perhaps the most noted feature of these figures is the similarity between curves in Figs. 6d to f, the 90° data. These results indicate that, by a performance criterion, there is a consistent, absolute difference between grays and blacks at this orientation independent of their specularity or the amount of polarized light incident upon them. These results are fairly consistent with the photometric data obtained with materials at this orientation.

Looking at the 0° data, Figs. 6a to c, one can see that the black materials remain high in score for all degrees of polarization, at or near the levels obtained for the black materials at 90°. Only gloss black is slightly reduced with decreased degrees of polarization. This slight shift in performance for gloss black and no shift for matte black is markedly different than their relatively large changes in photometric contrast with different degrees of polarization (see Fig. 5).

The gloss gray materials at 0° show very little change in performance. This can be understood best perhaps by looking at the *absolute* contrast of the gloss gray materials produced by the different degrees of polarization in Fig. 5. There is very little difference in the absolute contrast for the specific degrees of polarization employed in the experiment.

The performance data obtained with matte gray materials at 0° is perhaps the most interesting. They produced the largest change in score with changes in polarization (Figs. 6a to c), but it will be recalled from

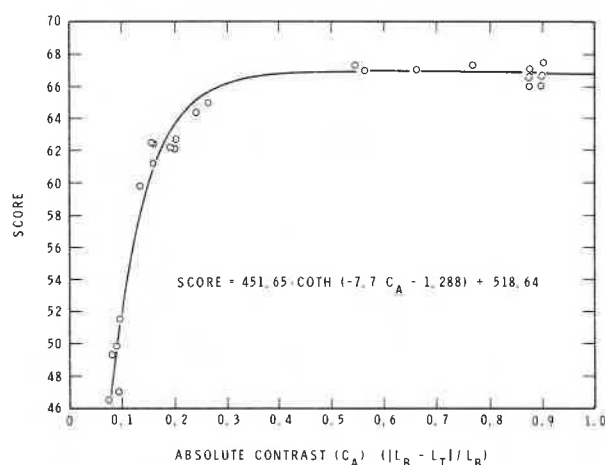
Table 2. The results of the Tukey method of multiple comparisons on the rank ordered performance scores. The bars indicate mean scores that are not significantly different (95% confidence).

Rank Order	Ink Specularity	Ink Pigment Density	Orientation	Polarization Panel	Average Score	Tukey Grouping of means (95% confidence)
1	Gloss	Black	90°	LP	67.59	1
2	Matte	Black	0°	PM	67.43	
3	Matte	Black	0°	LP	67.35	
4	Matte	Black	90°	LP	67.22	
5	Gloss	Black	0°	LP	67.10	
6	Matte	Black	0°	MP	66.95	
7	Gloss	Black	90°	MP	66.76	
8	Matte	Black	90°	PM	66.74	
9	Gloss	Black	90°	PM	66.17	
10	Matte	Black	90°	MP	66.10	
11	Gloss	Black	0°	MP	65.01	2
12	Gloss	Black	0°	PM	64.42	
13	Gloss	Gray	90°	PM	62.72	3
14	Matte	Gray	90°	LP	62.47	
15	Matte	Gray	90°	PM	62.35	4
16	Gloss	Gray	90°	LP	62.24	
17	Gloss	Gray	90°	MP	62.14	5
18	Matte	Gray	90°	MP	61.24	
19	Matte	Gray	0°	LP	59.80	6
20	Matte	Gray	0°	MP	51.54	
21	Matte	Gray	0°	PM	49.78	7
22	Gloss	Gray	0°	LP	49.25	
23	Gloss	Gray	0°	PM	46.96	
24	Gloss	Gray	0°	MP	46.50	

Fig. 5 that there was very little change in contrast for these materials with increased polarization. Thus, these small changes in contrast produced the largest changes in performance.

In total, these findings indicate that the magnitude of changes in contrast are not necessarily indicative of the magnitude of changes in performance; small changes in the contrast of matte gray produced large changes in performance, while large changes in contrast for matte black produced no change in performance. This point can perhaps be best understood by a general function relating contrast to score, a transfer function relating the input to the observer to his output at the task. To obtain the transfer function for these experimental conditions, the photometric contrasts in Fig. 5 were matched with the performance scores from Fig. 6a to f to produce the points in Fig. 7. This figure approaches a step function; visual performance was only affected slightly for changes from moderate to high contrasts

Figure 7. Transfer function relating absolute contrast to performance score. The performance data from Fig. 6 were combined with the absolute contrast values from Fig. 5.



(greater than 0.3) but was strongly reduced for changes from moderate to low contrasts (less than 0.2). This conclusion has also been reached by others.^{24,25} For example, black matte materials changed a great deal in contrast for the conditions in the experiment, but because the data points remained on the flat part of the function, there was no effect on performance. Conversely, the data points for the matte gray materials shifted on the steepest part of the curve with increased polarization and, thus, were the most sensitive to the small changes in contrast. In other words, although the matte gray contrast was only slightly affected by polarization, these small changes had a large effect on performance. When performance is important, therefore, the benefits of any strategy for changing task contrast must be judged in relation to the psychophysical transfer function not just in terms of the effects on contrast.

Supplementary photometry

The performance data were related to photometric contrast measurements in Fig. 7. Through this transfer function realistic methods of improving visibility could be evaluated by a performance criterion, not simply by a contrast criterion. However, not all realistic conditions that affect contrast were systematically explored in the study just described. In order to make the data more general, additional photometric measurements of the stimulus materials were obtained. These measurements were made like the photometric measurements described in the Methods and Procedures section of this paper. Through Fig. 7, these photometric data should provide a more complete picture of some realistic method of improving visual performance.

Polarization and desk orientation—The contrast of the stimulus sheets will be affected by changes in the desk orientation and/or in the degree of polarization from the luminaire. Only two orientations of the desk and only three polarizing lenses were employed in the experiment. To augment the contrast data already obtained in the visual performance experiment, additional polarizing lenses and orientations of the desk were employed. Using the transfer function in Fig. 7 these new stimulus contrast values may be related to visual performance at the task.

Three additional polarizing luminaire lenses were constructed. One lens (D) was a 3 mm thick sheet of translucent white plexiglass, sanded on the underside. The other two luminaires (TPa and TPb) were constructed like the LP lens except for a thin covering of white toothpaste on the underside of the clear plexiglass sheet. Each thin layer of toothpaste acted as a partial diffuser and reduced the polarization produced by the dichroic layer. The degree of polarization incident on the center of the task from the center of the luminaire was used to characterize these three new types of lenses: D, 2 percent; TPa, 84 percent; TPb, 62 percent.

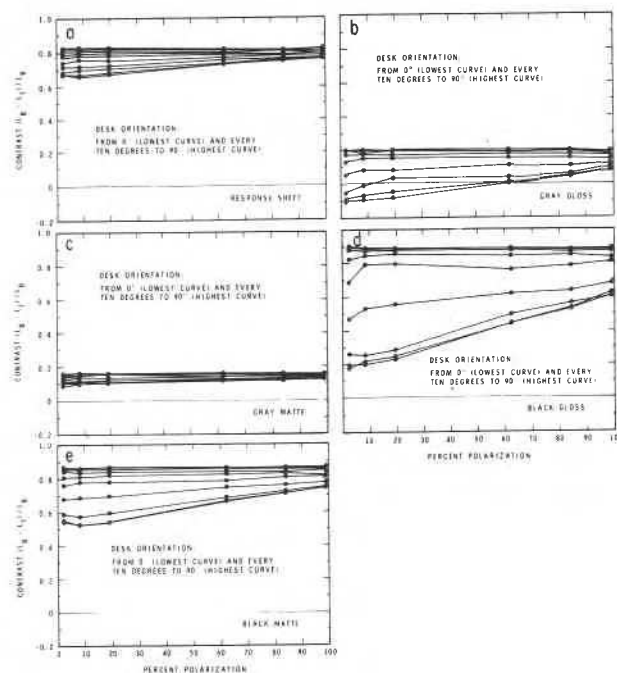
Contrast measurements of the task materials were made at 10° rotations of the desk about the center of the task (0° to 90°) under each of the six luminaires (LP, TPa, TPb, MP, PM, and D). As with the mea-

surements of photometric contrast previously described, the calibration square and an adjacent area of the paper were measured. The calibration square was placed in position #10, 42.1° from normal at the center of the luminaire. The photometer, with a 4.8 mm aperture, was placed at the mirror angle to the center of the luminaire (i.e., 42.1°). There was a correlation of .9996 between the average contrasts for every position on a page and the contrasts at position #10. The single readings at position #10, therefore, should closely characterize the average contrast for each sheet.

The changes in stimulus sheet contrasts produced by the 10 different orientations and the different degrees of polarization from the six luminaires are presented in Figs. 8a to e. After establishing a criterion contrast, these curves permit one to trade-off polarized illumination with desk orientation for these stimulus materials. In every case, the highest contrasts are achieved near desk orientations perpendicular to the mirror angle. Polarization can never improve contrast at these perpendicular orientations; the contrast curves are virtually flat. In addition, more contrast can be gained by rotation of the desk away from the angles near the mirror angle than by polarizing the light at those angles. It should be noted that gloss gray contrasts pass through zero; movement away from the mirror angle will initially decrease *absolute* contrast before increasing it if polarization is below about 50 percent. Similarly, increasing polarization at desk orientation less than about 25° will initially decrease *absolute* contrast for gloss grays before increasing it.

The contrasts due to the combined effects from desk orientation and degree of polarization can be used to predict performance at the task using Fig. 7.

Figure 8. Contrasts for different degrees of vertically polarized illumination incident on the task materials at different desk orientations.



Viewing and illumination angles—Changes in desk orientation and degree of polarization will interact with changes in illumination angle and/or viewing angle to further alter contrast.^{9,26} Only one small range of viewing angles and illumination angles was employed in the performance of this experiment (centered about 42°). To further extend the contrast data, the position of the measuring photometer (simulating viewing angle) and the illumination angles were systematically changed in conjunction with desk orientation and polarization changes. Again, the transfer function (Fig. 7) should allow predictions of visual performance from the contrast data.

Three simulated viewing angles, 25°, 35° and 45°, and four illumination angles, designated 22°, 30°, 40° and 50°, were employed. The viewing angles refer to the photometer's recording position relative to normal. The illumination angles refer to the angle a single ray from the center of the luminaire would strike the center of the task relative to normal. (At 22° the center of the task was directly below the front edge of the luminaire aperture.) Contrast measurements of the sample reference and response sheets were done at the two desk orientations used in the experiment, 0° and 90°. The three polarizing luminaires used in the performance experiment, LP, MP

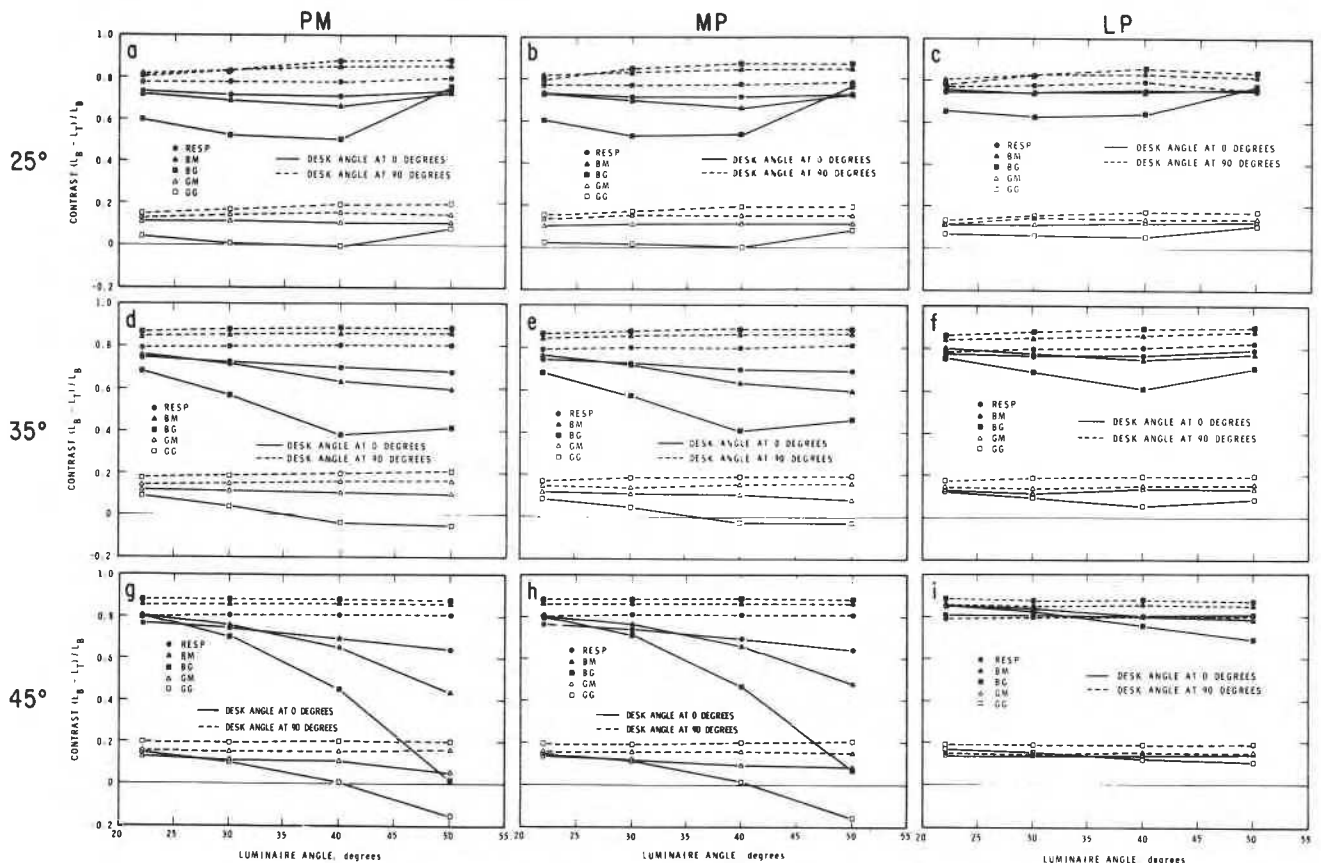
and PM, were used to provide different degrees of polarized light on the task.

Figures 9a to i show strong interactions between the factors manipulated for these supplementary measurements. Although many points can be made from these figures, there are five points that should be stressed:

1. It will be recalled that the transfer function indicated that very small changes in contrast below about 0.2 made a large difference in performance, whereas changes in contrast between 0.4 and 1.0 had little effect on performance. Therefore, under most "black ink" conditions shown in Figs. 9a to i there would be no effect on performance from changes in specularity, polarization, desk orientation, illumination angles, or viewing angle. Only at extreme illumination angles, extreme viewing angles, at desk orientations near 0°, and with a low degree of vertical polarization, would performance be affected when the ink was black.

On the other hand, with gray ink the effects of specularity, polarization, illumination angle, desk orientation and viewing angle become critical when contrast is translated into performance. Because the transfer function is very steep in this region, tiny improvements in contrast can make very large

Figure 9. Contrasts for different viewing angles and illumination angles with the conditions used in the performance experiment. As in Fig. 3, the reference sheets measured are designated by four pairs of initials (BG, BM, GG, and GM), and the response sheet measured is designated by RESP; the two desk orientations are designated 0° and 90°. The three columns of figures are for the plexiglass and mylar (PM), multilayer polaroid (MP), and linear polaroid (LP) luminaire lenses; the three rows are for 25°, 35° and 45° simulated viewing angles.



changes in performance. Consequently, *any* method of improving contrast becomes important if the ink pigment density is relatively low.

In an early IES publication,¹⁶ it was stated that polarization had little effect for viewing angles less than 25°, whereas it had appreciable effects at 40° and 60°. The data just presented point out the over-simplification of this statement. One can see that with black materials, polarization has little or no effect on performance at any viewing angle except when simultaneously coupled with glossy materials and directional lighting at the mirror angle. Conversely, with gray materials small contrast changes can lead to significant changes in performance even at 25°. The most important point to stress here is that when the difference between target and background pigment densities is small *every* parameter must be considered to improve performance; when the difference is large nearly every parameter can be ignored.

2. Hemisphere contrast is not necessarily the best lighting arrangement. Hemisphere contrast for the matte gray and gloss gray samples was equal to .1382 and .1471 respectively (at all measuring angles less than about 45°). At the 90° desk orientation, contrast for these materials exceeded hemisphere contrast. Black materials made similar gains, but because of their location on the transfer function, these changes are irrelevant to performance. Directional lighting can be very important, therefore, when one wants to improve the visibility of materials with relatively low pigment density.

3. As was pointed out previously, contrast can be driven through zero with specular materials and directional lighting. If it is driven far enough through zero then the absolute contrast can be high enough to make materials more visible than they would be under more conventional lighting designs. Figures 9g and h show that at a 45° viewing angle and 50° illumination angle, gloss gray *absolute* contrast approaches 0.2, the best contrast obtained for these materials in any situation and higher absolute contrast than would occur under hemisphere contrast (point #2). Therefore, so called "veiling reflections," usually described with negative connotation,^{26,1} can actually improve performance for certain materials by reversing contrast. (This would be true only for a fixed adaptation level. Pages which are not flat, like bound, glossy magazines, could produce bright highlights on certain areas of the task. As the eyes scanned such a page the effects of transient adaptation from luminance transitions could negate any contrast improvements.)

4. The factors that improve visibility the most at 90° desk orientation are those that reduce contrast the most at 0° (except where contrast is driven below zero). Thus, steep viewing and illumination angles with highly specular inks are usually the best conditions for improving contrast at the 90° orientation. This is shown in Figs. 9g and h. The highest contrast for the black materials was obtained with gloss black at 45° viewing angle, 50° illumination angle, low degree of vertically polarized illumination (MP and PM), and when the desk was at 90°. The lowest was

obtained under the same conditions with the desk orientation at 0°. As mentioned previously, even small improvements in contrast can be very important when the relative ink pigment density is low, because small changes in this region of the transfer function can make large improvements in visual performance. For example, the gloss gray materials at 90° desk orientation, 45° viewing angle and 50° illumination angle produced contrasts near .2 where performance would be close to that for black materials (see Fig. 7).

5. Contrast reduction for luminaires in the "offending zone"¹ is angle dependent. That is, the greater the mirror angle (over the range measured), the greater is the contrast reduction (Fig. 9). Judd and Wyszecki²⁷ present some fundamental curves that show the reflecting properties of highly specular glass under three levels of polarized light. At 25°, the "typical" viewing angle^{28,29} (veiling) reflection would be small, even for something as specular as glass. With less specular materials like those measured here the effect would be even less. Therefore, the "offending zone" will not be a problem in many cases if the ink pigment density is relatively high and the observer's viewing angle is small relative to normal. This may be seen by comparing the photometric data recorded at 25°, 35°, and 45° and relating them to the transfer function (Fig. 7).

These points amplify the difficulty in unequivocally saying a particular method of lighting to improve contrast is a panacea for lighting design. In some cases one set of conditions is optimum for performance, whereas in others, just the opposite would be true (point #4). Therefore "hard wired" general recommendations for lighting design seem inappropriate. Others^{8,10} have made similar points. Nevertheless, relatively simple solutions for lighting design do suggest themselves from these data.

Practical guidelines for lighting design

Performance in the experiment was measured as a function of the photometric contrast of the five digit numerals. The data indicated that digit contrast, no matter how it was produced realistically, was a strong determinant of performance. The general transfer function relating digit contrast to task performance approached a step function (Fig. 7); performance was not affected for moderate to high contrasts but was strongly affected from moderate to low contrasts.

From the photometric data collected here, moderate to high contrasts were ensured under most conditions if the ink pigment density was high relative to the background. Using the transfer function, one would conclude that performance with these black digit sheets was lowered only if several factors like specularity, steep viewing angle, and mirror angle to the luminaire were simultaneously combined (Figs. 8 and 9). Except for this rather narrow set of conditions, contrast remained at levels where performance was maximum. These data indicate that the most important parameter to ensure is relatively high ink pigment density because variations in nearly every other parameter will not affect performance but may alter contrast.

Sometimes it is impossible to ensure that black digits on white paper will be presented to people. Relatively low pigment density materials such as those produced by poor photoduplication or magazines with half-tone illustrations are common. From these data, they would be highly susceptible to performance decrements from small contrast reductions after alterations in the lighting conditions. Therefore, small changes in contrast occurring from alterations in, say, the desk location in an office, the daylighting, or the location of lamps could produce substantial reductions in performance with materials having relatively low pigment density. Due to the potential variability of workers in moving desks, adjusting window blinds, and switching lights it seems unlikely that a particular "hard wired" lighting design could ensure high performance levels all of the time at all locations with materials having relatively low pigment density. Also, it will be recalled that optimum lighting for performance may be very different depending upon the light reflecting characteristics of reading materials (i.e., specularly). For example placing the light source at the mirror angle (the so called "offending zone"¹) can be both the worst and the best conditions for producing the highest absolute contrast (Figs. 8 and 9). Again, a particular "hard wired" lighting design could reduce performance for some kinds of materials.

When the relative pigment density was not high, illumination geometry (desk orientation, illumination angle, and viewing angle) affected performance most strongly (e.g., see Figs. 8 and 9). Because each worker would have different lighting conditions depending upon his physical stature and his location in the office, and because different reading materials may require different lighting arrangements, it seems reasonable to incorporate *versatility* into the illumination geometry.

Practically speaking, then, this study offers two suggestions. First, and perhaps more important, if ink pigment density could always be high relative to the background then lighting design for performance becomes simpler under many circumstances. Except for a rather specific combination of conditions, if ink pigment density is relatively high then performance will be at a maximum. Therefore, if task materials were produced with new typewriter ribbons, clear photoduplication, or black felt pens, the designer might be able to supply illumination in the cheapest most efficient way without worrying about decrements in performance. Consequently, the designer would be freer to install lighting on the bases of energy conservation or aesthetics.

Second, when relatively high ink pigment density cannot be ensured and it is important to keep performance as high as possible, these data suggest that versatility in the illumination geometry may be very important in lighting design. Although many versatile methods may be possible, it may be worthwhile considering the incorporation of a simple movable desk lamp. With such a lamp the worker may be able to easily "solve" his own lighting problems. Providing the worker with some versatility in the illumination geometry could free the designer from considerations

about such important interacting parameters as task specularly, desk location, and viewing angle because the worker can adjust the lighting to fit the requirements of the task. Again, the designer is freer to attend to important considerations like cost, aesthetics and energy conservation.

As pointed out above, performance is not the only criterion for lighting design. For a variety of reasons it may be impractical to incorporate the suggestion above. For example, wiring costs and/or increased air conditioning costs for desk lamps may make their use prohibitive; for that matter workers might not use movable desk lamps properly if they were provided. These considerations must also be studied before a set of satisfactory, practical solutions is obtained. Nevertheless, these laboratory data offer some specific directions for further studies of practical lighting design.

Summary

Performance at a complex visual task was measured under a set of realistic conditions. These conditions, including variations in the reflective properties of the task and in the lighting geometry, strongly influenced the photometric contrast of the visual task. The data supported the hypothesis that the amount of task contrast, no matter how it was achieved under the set of realistic conditions, determined the level of performance because a single, general transfer function was obtained relating photometric contrast to performance at the task.

The general transfer function allowed quantitative predictions of performance under various combinations of (1) ink pigment density, (2) ink specularly, (3) angle of illumination on the task, (4) degree of vertical polarization of the illumination, (5) orientation of the work station relative to the illumination, and (6) viewing angle. Despite the large and complicated interactions that occurred between these factors to change contrast, and thus performance, the latitude for lighting designers and consultants concerned with visual performance may be greater than previously believed.

Acknowledgments

The author would like to thank Mr. B. Guzzo for running subjects and performing many computations, Prof. H. R. Blackwell for the use of his laboratory and photometric equipment and for discussion of the experimental results, Dr. A. R. Robertson for calibration of the reflectance standard, Mr. W. Budde for calibration of the photometer, Dr. A. Hsu for computer assistance, Dr. A. W. Levy for the ongoing discussions from the inception of the experiment, and Professors G. A. Fry and S. W. Smith for discussion of the experimental results.

This project was funded jointly by the Illuminating Engineering Research Institute of North America and by the National Research Council of Canada, Division of Building Research.

References

1. IES Technical Department, "Progress in solving veiling reflections," LIGHTING DESIGN AND APPLICATION, Vol. 3, No. 5, pp. 31-34, May 1973.

2. P. Moon and D. E. Spencer, "Visual data applied to lighting design," *Journal of Optical Society of America*, Vol. 34, No. 10, October 1944.
3. H. R. Blackwell, "Contrast thresholds of the human eye," *Journal of the Optical Society of America*, Vol. 36, pp. 624-643, 1946.
4. D. H. Kelly, "Visual contrast sensitivity," *Optical Acta*, Vol. 24, No. 2, pp. 107-129, 1977.
5. D. M. Finch, "The effect of specular reflection on visibility: Part I—Physical measurements for the determination of brightness and contrast," *ILLUMINATING ENGINEERING*, Vol. 54, No. 8, pp. 474-481, August 1959.
6. J. M. Chorlton and H. F. Davidson, "The effect of specular reflection on visibility: Part II—Field measurements of loss of contrast," *ILLUMINATING ENGINEERING*, Vol. 54, No. 8, pp. 482-488, August 1959.
7. I. Goodbar, "The effect of specular reflection on visibility: Part III—New charts for brightness contrast calculations," *ILLUMINATING ENGINEERING*, Vol. 54, No. 8, pp. 489-499, August 1959.
8. I. Goodbar, "Point-by-point prediction of contrast losses," *ILLUMINATING ENGINEERING*, Vol. 58, No. 4, pp. 262-276, April 1963.
9. A. A. Eastman and W. B. DeLaney, "Visibility of office-type tasks under various lighting materials—Part I," *ILLUMINATING ENGINEERING*, Vol. 61, No. 5, pp. 366-378, May 1966.
10. R. R. Boyce, "Variability of contrast rendering factor in lighting installations," *Lighting Research & Technology*, Vol. 10, No. 2, pp. 94-105, 1978.
11. H. C. Weston, "The relation between illumination and visual efficiency: The effect of brightness contrast," Industrial Health Research Board Report No. 87, London: Great Britain Medical Research Council, pp. 1-35, 1945.
12. R. M. Boynton and D. E. Boss, "The effect of background luminance and contrast upon visual search performance," *ILLUMINATING ENGINEERING*, Vol. 66, No. 4, pp. 173-186, April 1971.
13. P. R. Boyce, "Age, illuminance, visual performance and preference," *Lighting Research and Technology*, Vol. 5, No. 3, pp. 125-144, 1973.
14. S. W. Smith, and M. S. Rea, "Proofreading under different levels of illumination," *JOURNAL OF THE ILLUMINATING ENGINEERING SOCIETY*, Vol. 8, No. 1, pp. 47-52, October 1978.
15. A. M. Marks, "Multilayer polarizers and their application to general polarized lighting," *ILLUMINATING ENGINEERING*, Vol. 54, No. 2, pp. 123-135, 1959.
16. M. J. Langford, *Advanced Photography*, Focal Press, London, England, 1974.
17. H. R. Blackwell and R. N. Helms, "Application procedures for evaluation of veiling reflections in terms of ESI: I. General principles," *JOURNAL OF THE ILLUMINATING ENGINEERING SOCIETY*, Vol. 2, No. 3, pp. 230-253, April 1973.
18. J. E. Kaufman and J. F. Christensen, eds., *IES Lighting Handbook*, 5th Edition, Illuminating Engineering Society, New York, New York, 1972.
19. A. A. Eastman, "Contrast determination with Pritchard telephotometer," *ILLUMINATING ENGINEERING*, Vol. 60, No. 4, pp. 179-186, April 1965.
20. S. W. Smith and M. S. Rea, "Performance of complex tasks under different levels of illumination—Numerical verification task," in preparation.
21. J. Neter and W. Wasserman, *Applied linear statistical models*, Irwin, Homewood, 1974.
22. J. B. de Boer and D. Fischer, *Interior lighting*, Deventer: Kluwer Technische Boeken, 1978.
23. H. R. Blackwell, "Visual benefits of polarized light," *Journal of the American Institute of Architecture*, Vol. 40, pp. 87-92, 1963.
24. H. Spencer, L. Reynolds, and B. Coe, "The effects of image background contrast and polarity on the legibility of printed materials," The British Library, London, Report, No. BLRD-5425, November 1977.
25. E. C. Poulton, "Skimming lists of food ingredients printed in different brightness contrasts," *Journal of Applied Psychology*, Vol. 53, No. 6, pp. 498-500, 1969.
26. "An interim statement on reflected glare," *ILLUMINATING ENGINEERING*, Vol. 57, No. 8, pp. 561-562, August 1962.
27. D. B. Judd and G. Wyszecki, *Color in business, science and industry*, John Wiley and Sons, New York, 1963, Second Edition.
28. C. L. Crouch and J. E. Kaufman, "Practical application of polarization and light control for reduction of reflected glare," *ILLUMINATING ENGINEERING*, Vol. 58, No. 2, pp. 277-283, April 1963.
29. C. L. Crouch and L. J. Buttolph, "Visual relationships in office tasks," *LIGHTING DESIGN AND APPLICATION*, Vol. 3, No. 5, p. 23, May 1973.

Appendix I

Table A. Significant terms from the analyses of variance for the "direct" measures.

(1) Time as the dependent variable					
Term	(a)	Prob [†]	Term	(b)	Prob [†]
Polarizing Lens	(L)	.0001	Subject	(P)	.0001
Orientation	(O)	.0001	Half-block	(H)	.0001
Ink Pigment Density	(D)	.0001	Meridian	(M)	NS [‡]
Ink Specularity	(S)	.0001	Day	(Y)	.0001
	LXO	.0001		HXM	.0019
	LXD	.0001		PXY	.0001
	OXD	.0001		MXY	.0001
	LXS	.0018		PXMX	.0001
	OXS	.0001		PXD*	.0001
	DXS	.0001		PXS*	.0004
	LXOXD	.0001		YXL*	.0001
	LXDXS	.0001		YXOXD*	.0005
	OXDXS	.0001		PXMXDXD*	.0066
	LXOXDXS	.0001			

Appendix I (continued)

(2) Misses as the dependent variable

Term	(a)	Prob [†]	Term	(b)	Prob [†]
Polarizing Lens	(L)	NS [‡]	Subject	(P)	.0001
Orientation	(O)	.0001	Half-block	(H)	NS [‡]
Ink Pigment Density	(D)	.0001	Meridian	(M)	NS [‡]
Ink Specularity	(S)	.0001	Day	(Y)	.0049
	LXO	.0004		HXM	.0001
	OXD	.0001		PXY	.0001
	OXS	.0001			
	DXS	.0001			
	LXOXD	.0004			
	OXDXS	.0001			

(3) False positives as the dependent variable

Term	(a)	Prob [†]	Term	(b)	Prob [†]
Polarizing Lens	(L)	.0020	Subject	(P)	.0005
Orientation	(Q)	.0001			
Ink Pigment Density	(D)	.0001			
Ink Specularity	(S)	NS [‡]			
	LXD	.0040			
	OXD	.0001			
	LXOXD	.0003			
	OXDXS	.0058			

[†] Estimated maximum probability that the term is significant by change alone. Only terms with probability less than or equal to .01 are included.

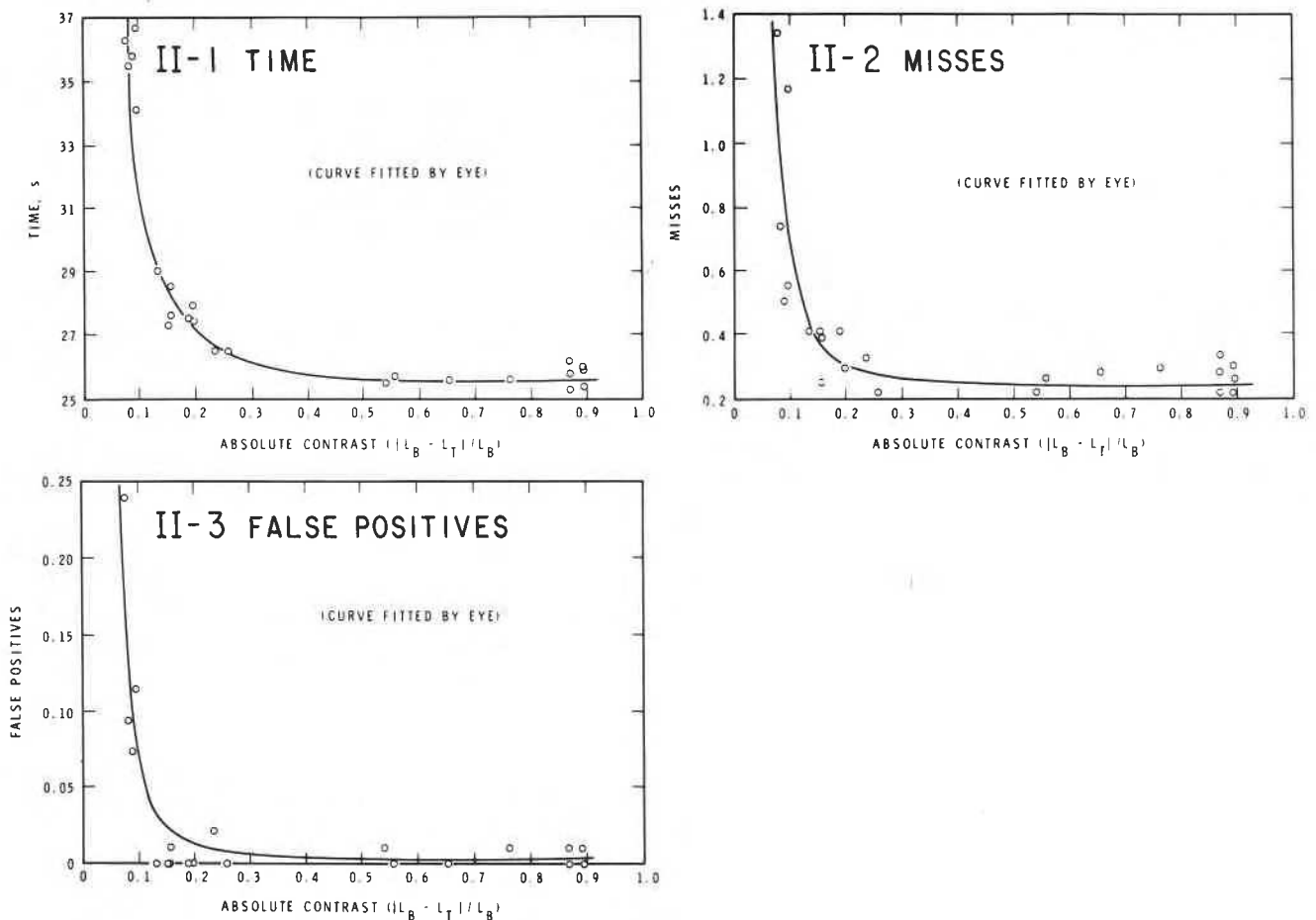
* Significant interactions between terms in Appendix 2 ANOVA Tables (a) and (b).

[‡] Not significant.

Appendix II

Figure II. Transfer functions relating absolute contrast to the three "direct" performance measures. These plots combine the absolute contrast values in Fig. 5 with the average time,

the average misses and the average false positives obtained under the experimental conditions producing those contrasts.



Appendix III

Smith and Rea²⁰ collected performance data at the same task as was employed in this experiment. Reference sheets were presented at two contrast levels (estimated to be 0.8 and 0.3) under various illumination levels. The Smith-Rea data for young adults are presented in Figure III. Predicted scores from the transfer function in Fig. 7 at contrasts of 0.8 and 0.3 are also included in the figure. The average luminance of the reference sheets in this experiment was 67cd m^{-2} .

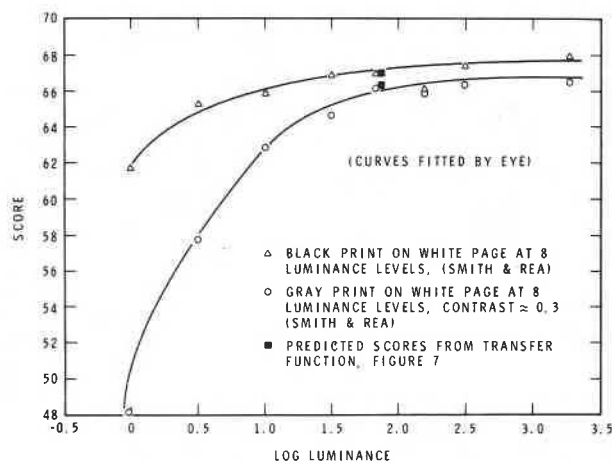


Figure III. Smith-Rea data for young adults.

This publication is being distributed by the Division of Building Research of the National Research Council of Canada. It should not be reproduced in whole or in part without permission of the original publisher. The Division would be glad to be of assistance in obtaining such permission.

Publications of the Division may be obtained by mailing the appropriate remittance (a Bank, Express, or Post Office Money Order, or a cheque, made payable to the Receiver General of Canada, credit NRC) to the National Research Council of Canada, Ottawa. K1A 0R6. Stamps are not acceptable.

A list of all publications of the Division is available and may be obtained from the Publications Section, Division of Building Research, National Research Council of Canada, Ottawa. K1A 0R6.