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by M.S. Rea

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RÉSUMÉ

Les mesures photométriques classiques ne tiennent pas compte du degré ni de l'angle de polarisation de la lumière réfléchie par des surfaces, ni de la nature dichroïque-biréfringente de l'oeil humain. Des analyses préliminaires indiquent que les variations associées à une fonction de transfert de la performance visuelle peuvent être réduites si l'on tient compte de ces effets de polarisation. Toutefois, cette réduction est extrêmement faible, ce qui signifie qu'il ne serait peut-être pas réaliste de considérer les effets de polarisation dans ces types d'expériences. Les analyses fournissent aussi des preuves indirectes de stratégies de mouvement des yeux.

Effects of Haidinger's brushes on visual performance

M. S. Rea

Conventional photometric measurements account for neither the degree and orientation of polarization reflected from surfaces nor the dichroic-birefringent nature of the human eye. Preliminary analyses indicate that the variability associated with visual performance data can be reduced by accounting for these polarization effects. Reduction in variability is extremely small, however, indicating that it might not be practical to account for these polarization effects in such experiments. Indirect evidence for eye movements is also provided by the analyses.

Introduction

A wide variety of data support the notion that a discrepancy can exist between photoelectrically determined contrast and what people actually perceive, i.e., subjective contrast.[1–3] Photometry does not account for the relative polarization of the target and its background nor for the dichroic-birefringent nature of the human eye.[4] This "polarization effect" of the eye can produce the well-known entoptic phenomenon called Haidinger's brushes. The appearance of Haidinger's brushes is dependent upon many factors, including the orientation of polarization incident on the cornea, individual differences in the polarization mechanisms of the eye, the fixation location of the individual with respect to the target, and the spectral distribution of the stimuli. For example, with targets spectrally distributed as cool white fluorescent (CWF), subjects have on average a 2 percent difference in sensitivity to polarized test fields relative to unpolarized test fields under controlled eye fixations.[5]

It is the purpose of this paper to discover whether it is possible to reduce the uncertainty associated with a function relating contrast to performance by taking into account the spectral distribution and polarization of the light reflected from a task as well as the magnitude of the dichroic-birefringent analyser in the human eye. Data from a previous visual performance experiment[6] have been re-examined to see whether these polarization effects are important. Because the polarization effect is dependent on fixation location, it should also be possible to gain information about eye position during the experiment, assuming that the polarization effect reduces uncertainty in the contrast-visual performance function.

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Background

The earlier visual performance experiment[6] gives procedural details. Briefly, the subjects' task is to compare two number lists and note discrepancies as quickly and accurately as possible (Fig. 1). The adaption level is kept constant while the contrast is changed by "realistic" techniques (i.e., contrast is altered by such typical methods as ink pigment density, ink specularity, polarization of illumination, and lighting geometry). The spectral distribution of the target and the background are nearly identical to CWF. Performance score, a combination of speed and accuracy, is plotted against reference sheet photoelectric contrast (Fig. 2) where contrast (C) is defined as:

$$C = |(L_B - L_T)|/L_B \qquad (1)$$

where

L_B = background luminance (paper)

L_T = target luminance (ink).

As different lighting arrangements were used in the experiment, different degrees and orientations of polarization were reflected from the task. If polarization induces discrepancies between subjective contrast and photoelectric contrast, then the data plotted in Fig. 2 should demonstrate some "noise," because target and background polarization were not taken into account.

Measurement of the task stimuli

For the analyses in this paper the stimulus materials that produced the abscissa values in Fig. 2 were re-examined and measured for polarization characteristics. Measurements were taken of the degree and orientation of polarization reflected from the ink calibration squares on the five types of stimulus sheets (including four reference sheets and a black

31935	31935
66321	66321
72958	72958
83944	83944
39117	39117
51111	51111
06694	06694
85922	85922
42416	42416
46583	46583
99254	99254
92431	92436
07408	07408
24010	24010
89303	89303
05418	35418
03574	03574
47539	47539
61337	21337
60627	60627

Figure 1. Stimulus configuration. Subjects were required to search such lists for discrepancies. The reference list is on the left and the response list on the right.

matte response sheet) as well as the stimulus sheet backgrounds (see Fig. 1). The response sheet was printed with black matte ink, and the reference sheets with black matte, black gloss, gray matte or gray gloss inks. To do this, a variable dichroic analyser (Polaroid, HN38) was used in front of the objective lens of a Pritchard photometer (Model 1980A). Maximum and minimum analyser transmissions produced at each target and at each adjacent background location in the lists were recorded at each list position. These maximum and minimum transmission values were either parallel (horizontal) or perpendicular (vertical) to the plane of the task, depending upon experimental conditions.

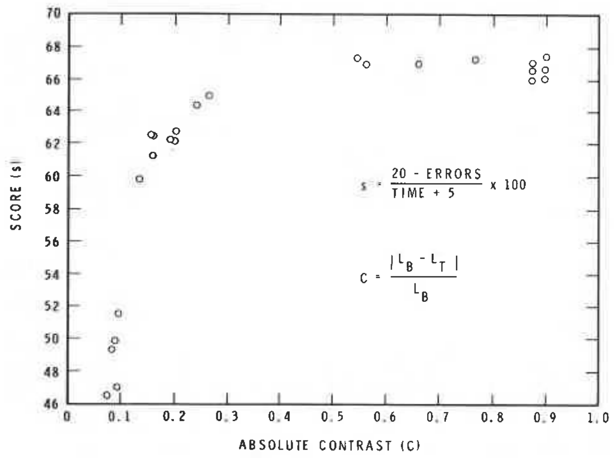


Figure 2. Visual performance score plotted against absolute photometric contrast.[6] Adaption level was held constant while contrast was changed by combinations of ink pigment density, ink specularity, polarization of illumination and incident angle of illumination. Score is a combination of time and errors.

Following Marks,[7] the degree of polarization (D) was computed by the formula:

$$\frac{\max - \min}{\max + \min} \times 100 = \text{D (in percent)} \qquad (2)$$

These data are plotted in Fig. 3 (A-F). As the curves are fairly flat, the connected points were averaged (arithmetic mean). The averaged degrees of polarization reflected from the calibration squares and backgrounds were used in the subsequent calculations.

Relating performance to contrast

The distance of the data points from the function selected to represent them depends to a large extent upon the suitability of the model used in deriving the curve; a good model accounts for more variability than a poor one. Recently, the visual system's response to increments of light has been modelled by a variety of researchers recording electrophysiological responses from various sites in the eye.[8,9] This model has been likened to self-shunting electrical circuits.[10–12] Hood and his co-workers[13,14] also used the same response function to model certain psychophysical responses. (No one has attempted to model visual performance data having dependent measures like speed and accuracy). In the present experiment, an attempt was made to model visual performance using a function similar to those used in modelling both electrophysiological and psychophysical responses:

$$R/R_{max} = L^n/(L^n + k^n) \qquad (3)$$

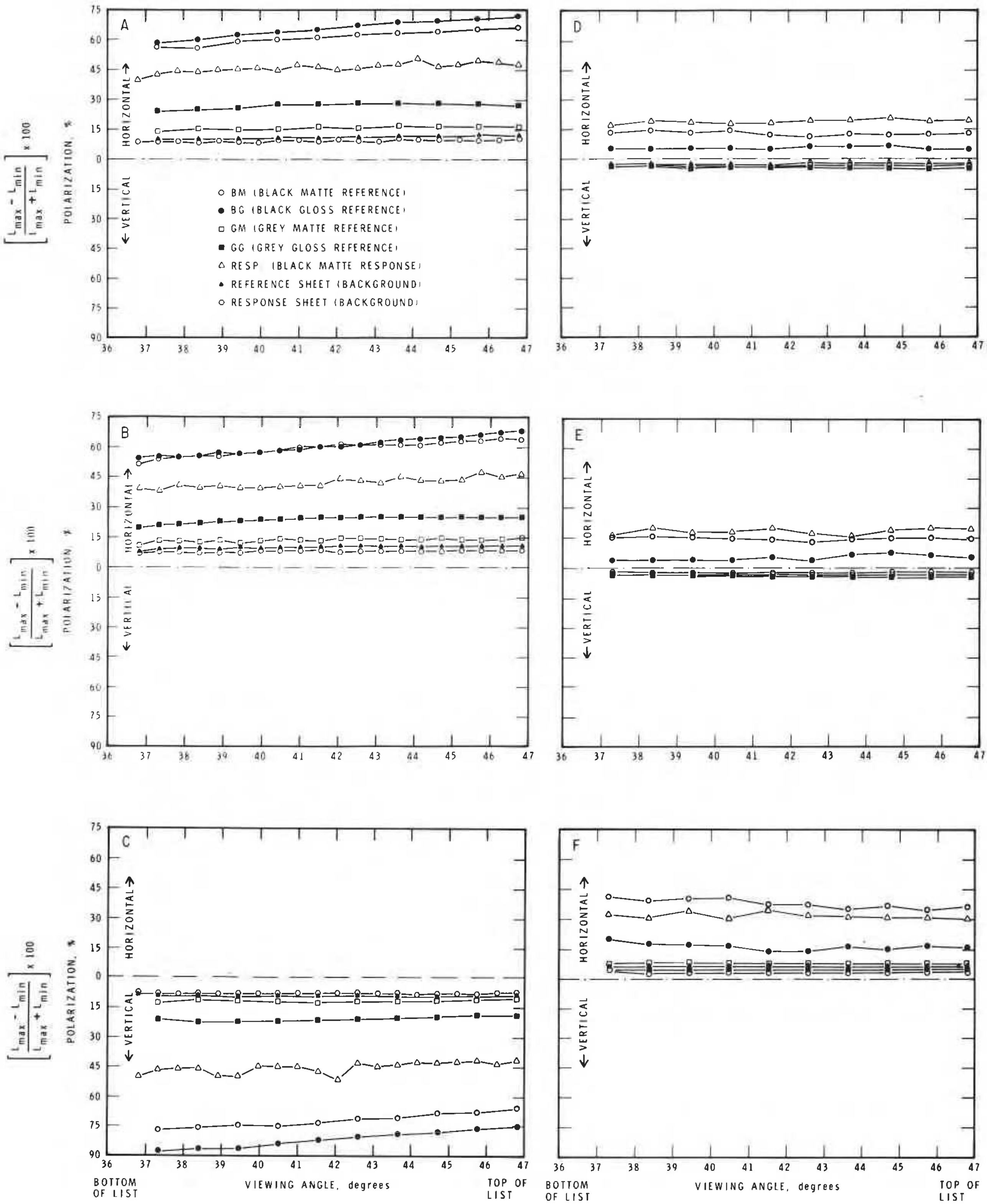
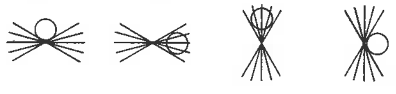


Figure 3. Degree of polarization reflected from the calibration squares on stimulus sheets at different list positions under experimental conditions. Three degrees of illumination polarization were produced by different types of luminaire panels: Plexiglas and Mylar (PM), multilayer polarizer (MP) and linear dichroic polarization (LP). Two incident angles of illumination were used: illumination from the mirror angle to a subject's eyes (0°), and illumination from a subject's left (90°). Four types of reference lists were employed: black gloss (BG), black matte (BM), gray gloss (GG), and gray matte (GM). One type of response list was used throughout the experiment: black matte (RESP).

A: 0°, PM
B: 0°, MP
C: 0°, LP
D: 90°, PM
E: 90°, MP
F: 90°, LP

Table 1. Hypothetical effects of Haidinger's brushes.

	A	B	C	D
Orientation of polarization	V	V	H	H
Illustration of target and brush				
Fixation location (clock position)	6	9	6	9
Appearance to subject	brighter target	darker target	darker target	brighter target
Terms in equation	$X_L < 1$, $X_M = 1$	$X_M < 1$, $X_L = 1$	$X_L < 1$, $X_M = 1$	$X_M < 1$, $X_L = 1$

where

R_{max} = maximum response, or score, obtained at a given adaptation luminance

R = response for a given target luminance change

L = target luminance increment above, or decrement below, threshold luminance*

n = free parameter

k = half-saturation constant and another free parameter.

The contrast data used in Fig. 2 (abscissa values based on Eq. (1)) were transformed following Eqs. (4) and (5) so as to put the target values in units suitable for Eq. (3).

$$L_T^t = L_B(1 - C^t) \quad (4)$$

where

L_T^t is derived threshold target luminance

C^t is threshold contrast; psychophysical data,[15] magnitude estimations, and settings of a Visual Task Evaluator[16] were used to estimate threshold contrast for these targets to be 0.055

L_B is as in Eq. (1) and equal to 67 cd/m^2 in the performance experiment

and

$$L = |L_T^t - L_T| \quad (5)$$

where

L is as in Eq. (3)

L_T^t is as in Eq. (4)

L_T is as in Eq. (1).

* Any change below threshold produces no response.

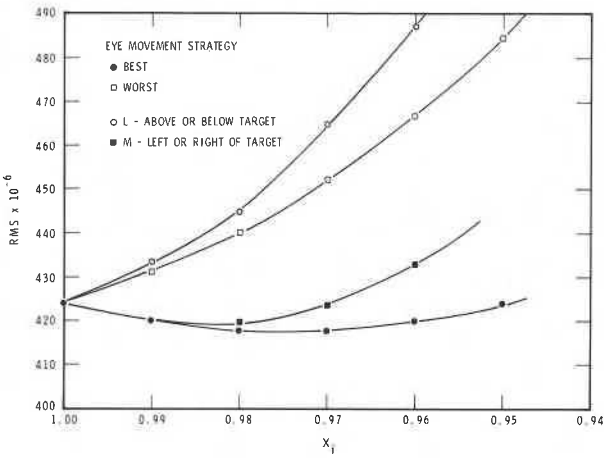


Figure 4. Results of residual mean square (RMS) analysis; RMS is plotted as a function of X_i, the magnitude of the dichroic-birefringent mechanisms producing Haidinger's brushes. The four curves correspond to hypothetical eye movement strategies employed by subjects in the experiment. The "best" strategy corresponds to eye positions that always maximize contrast. The "worst" strategy corresponds to eyes position exactly opposite that for "best." The "L strategy" corresponds to eye positions either below or above targets (numerals). The "M strategy" corresponds to eye positions consistently to the left or right of targets.

For this analysis, light increments and decrements were assumed to have identical effects on the visual system. Allowing only n and k to vary, a series of iterations was performed on the data in order to obtain the best values of the two parameters, i.e., the values that gave the lowest residual mean square (RMS).† The value of 1.02 was obtained for n; this is very close to the values obtained electrophysiologically[12] and the assumed value of n = 1.0 used in psychophysical analyses.[13,14] This agreement indicates that the vision model (Eq. (3)) can be used to predict visual performance satisfactorily in this type of experiment.

Rationale for analysis

To see whether the dichroic-birefringent analyser influences subjective contrast in the performance experiment, transformations of Eq. (1) were performed following Eq. (6):

$$|[L_B(X_Lp + X_Mq) - L_T(X_Lr + X_Ms)]| / L_B(X_Lp + X_Mq) = C \quad (6)$$

where

p = proportion of horizontally polarized light reflected from the background

q = proportion of vertically polarized light reflected from the background

† $RMS = \frac{\Sigma(Yi - Yf)^2}{N - p}$

Yi – observed score

Yf – predicted score

N – number of cases

p – number of independent parameters estimated.

$p + q = 1$

r = proportion of horizontally polarized light reflected from the target

s = proportion of vertically polarized light reflected from the target

$r + s = 1$

L_B, L_T and C are as in Eq. (1)

X_i = attenuation of polarized light by the dichroic-birefringent analyser in the eye for a given spectral distribution

i = M or L.

Thus

$X_i = X_M$ when fixation location is to the left or right of the target

$X_i = X_L$ when fixation location is below or above the target.

X_i can be applied in Eq. (6) *either* X_L or X_M since both are intended to have behavioral significance. Specifically, they are terms corresponding to the subjects' eye position relative to target location during performance of the task. X_L corresponds to an eye position below or above the target; X_M corresponds to an eye position to the left or to the right of the target.‡ The rationale behind the X_i values in Eq. (6) can best be shown by Table 1 and its illustrations.

With regard to Table 1, four points should be noted:

1. The target (in this experiment, a numeral) can be schematized as a small circle reflecting elliptically polarized light, with energy primarily on the horizontal (H) or vertical (V) axis relative to the plane of the task.

2. The dichroic-birefringent analyser in the eye can be schematized by a prototype characterization of Haidinger's brushes, namely a darkened hourglass.[17] The hourglass is oriented vertically or horizontally, depending upon the primary axis of polarization reflected from the task. The orientation of the hourglass is perpendicular to the primary plane of polarization because less light is transmitted when the dichroic fibers are crossed with the primary axis of the light coming from the stimulus. Thus, when horizontally polarized light is reflected from the target the hourglass is vertical, and when vertically polarized light is reflected from the target the hourglass is horizontal.§

3. The isthmus of the hourglass corresponds to the fixation point. Although the fixation point can be anywhere with respect to the target, only positions at 12, 3, 6, and 9 o'clock are of interest. These are the points of maximum effect, and thus are the points to which fixation must be biased if the Haidinger's brush effect is to be discovered.

For the sake of illustration, only 9 o'clock and 6 o'clock fixation positions were drawn. These points would be equivalent to 3 o'clock and 12 o'clock, respectively, if the macular dichroism were symmetric about the fixation point. There is no evidence to suppose otherwise.

4. Because the stimulus paper is matte, the target ink was always more polarized than the background paper (Fig. 3, A-F). For the sake of the illustration (but not analysis), therefore, the background should be assumed to be unpolarized.

Hypotheses

By varying X_L and X_M in Eq. (6) and comparing the RMS values, several hypotheses can be tested. First, it is possible that subjects might attempt to maximize subjective contrast. Thus if a target reflects relatively more horizontally-polarized light (the background being relatively unpolarized), then to increase the contrast of a target reflecting less total light than the background, subjects should look immediately below (or above) the target. In this way, the subject can take advantage of the cross-polarization produced by the analyser in the eye (column C in Table 1). Under these conditions X_L would apply in the equation. Conversely, if the target reflects vertically polarized light, the optimum strategy would be to look to the left or right of the target (column B in Table 1). Thus X_M would apply in the equation for these conditions. If the target is brighter than the background, then the opposite strategies are best (columns D and A, respectively).

To see whether subjects' data were consistent with such a strategy to improve contrast, X_L and X_M values were appropriately substituted in Eq. (6) and the contrast recomputed. To see whether the transformation reduced the variability of the data associated with the function (Eq. (3)) the new RMS values were obtained with X_i values between 1.0 and 0.95 to bracket possible magnitudes of Haidinger's brushes. If the transformation characterizes the performance strategy, i.e., the eye movements of the subjects, then the RMS should go down with smaller values of X_i until it reaches a minimum at 0.98 (the estimated magnitude of Haidinger's brushes under a CWF spectral distribution[5]) and then begin to increase.

To gauge these new RMS values, opposite substitutions were employed (X_L for X_M and X_M for X_L), in essence providing a control condition. This would characterize the worst eye movement strategy one could use to improve contrast. If there is no difference in the absolute RMS values obtained for the two hypothetical eye movement strategies, then it would appear that subjects have not used these strategies or that the RMS analysis was inappropriate.

A second hypothesis requires X_M to apply irrespective of the contrast changes induced by the analyser in the eye. Eye movement data[18,19] indicate that people use stereotyped saccadic eye movements

‡ X_L and X_M are terms less than 1.0 and are the hypothetical magnitudes of Haidinger's brushes. The X_L term is always with the horizontal components (p and r); X_M is always associated with the vertical components (q and s). If the eye is to the left or right of the target during the experiment, the dichroic fibers cross the target in such a way as to decrease the brightness of the target when it is vertically polarized ($s > r$) and to increase the brightness of the target when it is horizontally polarized ($r > s$). (The background is relatively unpolarized.) As X_M accomplishes this function in Eq. 6, it corresponds to an eye position to the left or to the right of the target whether it is vertically or horizontally polarized. X_L accomplishes the same effect in Eq. 6 if the eye is above or below the target during the experiment. As X_L and X_M are mutually exclusive, when one term is not equal to 1.0 the other term must be equal to 1.0.

§ The complete brushes would not be observed when only the target is polarized. The illustration shows the "potential" brushes for an entire field emitting polarized light.

when looking at printed text. When reading a paragraph, for example, subjects move their eyes left to right along a row of printed characters. (This strategy would be schematized in columns B and D, Table 1.) In this experiment the configuration of the stimulus materials is much like the stimuli in the eye movement studies. If subjects behaved in this way, the lowest RMS values would therefore occur when X_M was used in Eq. (6); X_M is used to characterize eye movements to the left and right along the row of numerals. (It should be emphasized that even if the contrast and thus the scores were lowered, the RMS would be lower because, according to the hypothesis, the transformation would better characterize the eye movements employed by the subjects in the experiment.) Conversely, if subjects always looked below or above the target, then the RMS would be lower when X_L was employed in Eq. (6). There is no evidence for this supposition, but it is a testable hypothesis and one that can gauge the X_M hypothesis. As with the first hypothesis, one would expect the RMS values to be minimal at 0.98 for the more suitable hypothesis (X_M or X_L) if the analyser in the eye influenced subjective contrast in the performance experiment.

A third hypothesis (included in the previous two) centers round the magnitude of X_i. Because the ink and the background paper were spectrally distributed like CWF, one should obtain a minimum RMS at or near values of $X_i = 0.98$, the estimated magnitude of the dichroic-birefringent mechanisms in the eye for a CWF spectral distribution.[5] It should be stressed that this third hypothesis depends upon the aptness of an eye movement hypothesis. If an experimental hypothesis does not properly characterize the subjects' behavior, then the RMS values will not change, worsen, or minimize at some other value. Thus, the third hypothesis is not independent of the other two.

Results of the RMS Analysis

Figure 4 presents the results of the RMS analysis. Moving one's eyes to the position that leads to the lowest contrast (worst) and always looking below or above the target (L) are less appropriate in accounting for the data than applying no coefficient (i.e., X_i equal to 1.0). On the other hand, moving one's eyes to the best position for improved contrast (best) and looking to the left and right of the target (M) are more appropriate. Importantly, the two functions (the RMS functions for the so-called "best" strategy and the "left-right" strategy) were minimum near 0.98, indicating that the magnitude of the dichroic-birefringent polarization in the eye is in the neighborhood of 2 percent under a CWF spectral distribution. This estimate agrees with the 2 percent estimate obtained in the experiment in which fixation was controlled.[5]

The similarity between the "left-right" and the "best" eye movement strategies implies that performance can be improved simply by moving the eyes left to right when reading these materials. If one computes the potential score improvement after the data are transformed according to the "best" strategy and according to the "left-right" strategy, there is very little difference. When $X_i = 0.98$, the "best" strategy provides an over-all score improvement of 0.55 units while the "left-right" strategy increases the score by 0.33 units, both in relation to $X_i = 1.0$. The fact that the "best" strategy had a slightly lower RMS than the "left-right" strategy indicates that subjects may have deviated from the "left-right" strategy to improve contrast.

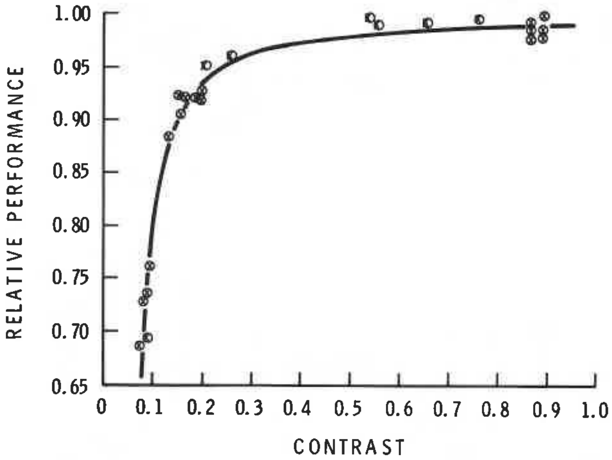


Figure 5. Relative performance as a function of photometric contrast and contrast transformed to account for Haidinger's brushes. Curve fit based upon Eq. (3) and "best" eye movement strategy where n = 1.07 and k = 0.833.

Minimization of RMS for the "left-right" and "best" strategies at $X_i = 0.98$ supports the hypothesis that the magnitude of dichroic-birefringent attenuation under a CWF spectral distribution was 2 percent. This indicates that polarization needs to be accounted for in order to reduce the variability in visual performance data.

Nevertheless, two points should be made. First, these are preliminary data and move evidence should be obtained (e.g., with an eye marker) about whether it is worth making extensive measurements to determine the polarization of the light reflected from the task (e.g., Fig. 3, A-F). Second, the RMS reduction is very small. The circles in Fig. 5 are data from Fig. 2 using a relative performance ordinate. The "X" points in Fig. 5 were obtained from the transformed contrasts (Eq. 6), assuming the "best" eye movement strategy and $X_i = 0.98$. It is apparent that the transformed data are only marginally different from the circles, based upon conventional photometry. Thus, if the polarization reflected from the task materials is ignored, the scatter about the curve is increased only slightly.

In summary, the analyses indicate that variability in the visual performance data can be reduced by accounting for the polarization of the light reflected from the task and for the dichroic-birefringent analyser in the human eye. The data are only preliminary, however, and should be viewed with caution. Further, even if the data and the analysis were completely substantiated by more measurements, accounting for the polarization effect in the eye would only marginally improve predictions of performance in this type of experiment. Lastly, the data indicate that subjects employed eye movements similar to those documented for other printed material. They may also have deviated from this strategy somewhat to improve contrast.

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