NRC Publications Archive Archives des publications du CNRC

Photometry and visual assessment of polarized light under realistic conditions

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, 11, 3, pp. 135-139, 1982-04

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

<https://nrc-publications.canada.ca/eng/view/object/?id=84f36342-bf2b-4c7d-a753-bc31ed07daae>
<https://publications-cnrc.canada.ca/fra/voir/objet/?id=84f36342-bf2b-4c7d-a753-bc31ed07daae>

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.

National Research
Council Canada

Conseil national de
recherches Canada

Canada

Ser
THL
N21d
no. 1037
c. 2
BLDG

National Research Council of Canada
Conseil national de recherches du Canada

10431

PHOTOMETRY AND VISUAL ASSESSMENT OF POLARIZED
LIGHT UNDER REALISTIC CONDITIONS
by M. Rea

ANALYZED

Reprinted from
Journal of the Illuminating Engineering Society
Vol. 11, No. 3, April 1982
p. 135-139

DBR Paper No. 1037
Division of Building Research

Price \$1.00

OTTAWA

NRCC 20272

3729729

SOMMAIRE

Le mécanisme qui produit les franges de polarisation de Haidinger introduit une discordance entre l'évaluation photoélastique et subjective de la luminance. Bien que ces effets soient mesurables, ils sont probablement si faibles qu'ils ne présentent aucun intérêt dans la majorité des cas pour l'ingénieur en éclairage.

Photometry and visual assessment of polarized light under realistic conditions

M. Rea

The mechanisms that produce Haidinger's polarization brushes introduce a discrepancy between photoelectric and subjective assessments of luminance. Although these effects are measurable they are probably too small to be of concern to the illuminating engineer under most circumstances.

Photometry is used extensively to specify the light-reflecting characteristics of materials. Photometry, unlike radiometry, is based upon the wavelength-by-wavelength spectral sensitivity of "normal" human subjects under a certain set of conditions.¹ As such, photometry is intended to characterize the human visual sensitivity to these light-reflecting materials. There are anomalies associated with particular individuals that place photometry and subjective sensitivity, or visibility, for these people in disagreement. For example, certain color-blind individuals are less sensitive than normal people to certain wavelengths of the spectrum.² These discrepancies between subjective brightness for a small part of the population and photometry might be tolerated under many circumstances where only "averages" are important. However, there are other incongruities between photometry and subjective visibility for normal people under certain circumstances. Photometry incorporates a wavelength-by-wavelength linear integration without taking into account interactions between wavelengths in the visual system. Because the visual system is nonadditive in wavelength sensitivity,³ two fields with the same photometric luminance but different spectral compositions may have different brightness to normal individuals. Therefore, photometry does not characterize human sensitivity for certain spectral distributions.

A similar limitation of photometry, and the one discussed in this paper, is its failure to account for the polarization of the light reaching the eye. Recently

there has been a revival of interest in this area, although nearly a century ago Helmholtz identified dichroism of the macular pigment as the major determinant of polarization sensitivity in the human eye.⁴ The macular pigment is a yellow screening pigment in the foveal region of the retina. Although some controversy has existed in the literature,⁵ the hypothesis proposed by Helmholtz has been substantiated by several psychophysical studies.^{6,7} More recently Helmholtz's model has been extended and attention has been given to another site where polarization of light reaching the eye is important.

Birefringence of the cornea has been documented quite clearly,⁸ and very recently quantitative estimates of this birefringence have been provided.⁹ This documentation⁴⁻⁹ has provided a fairly complete model of the polarization effects produced by the human eye.

The model for polarization sensitivity in the eye may be described briefly as follows: The cornea is composed of preferentially aligned birefringent collagen fibers. If plane polarized light is transmitted through the cornea at angles oblique to the alignment of the fibers, it is changed to elliptically polarized light (one component of the transmitted light is out of phase with the other). At angles parallel or perpendicular to the preferential alignment of the collagen fibers no reduction in the degree of polarization will occur.^{10,11} The light is relatively unaffected as it passes through the subsequent optical media until it reaches the macular screening pigment. Fibers in the macular pigment are aligned much like wagon-wheel spokes, the hub of the wheel at the point of fixation. These fibers are dichroic and as such preferentially absorb incident light that is polarized perpendicular to the orientation of the fiber. Maximum absorption of, say, vertically polarized light

A paper presented at the Annual IES Conference, August 9 through 13, 1981, Toronto, Ontario, Canada. AUTHOR: National Research Council of Canada, Ottawa, Ontario, Canada.

Figure 1. Variations of the density of macular pigment with wavelength. (After Wyszecki and Stiles¹⁹).

occurs along the horizontal spoke of the macular fibers. The absorption naturally produces a luminance reduction that falls off as the angle from the perpendicular is reduced.⁹ It also produces a color change in this area because the screening pigment is not spectrally flat (Fig. 1). In total these polarization sites in the eye produce the well documented entopic image called Haidinger's brushes.

The luminance differences produced by Haidinger's brushes for spectral distributions like those encountered in offices and industrial settings were measured in order to estimate potential "errors" associated with photometric measurements.¹² In other words, the discrepancy between observers' sensitivity to polarized and unpolarized test fields of equal photometric luminance was estimated.

To obtain these estimates the absolute thresholds were measured for small (39 ft) polarized test fields in areas near those that would be maximally and minimally attenuated by Haidinger's brushes; these thresholds were compared to those for unpolarized test fields at the same locations. Two spectral distributions were used for the test fields; one was distributed as cool white fluorescent (CWF) (Fig. 2), while the other was produced by violet, monochromatic 462 nm light. The results of the experiment showed a luminance difference of 9 percent for the vertically polarized violet light relative to the same light when unpolarized. This estimate agrees closely with other estimates.^{7,9} The luminance difference for the CWF distribution was 2 percent. To test the hypothesis that the spectral absorption of the macular pigment produced this effect for the CWF test fields, the spectral absorption of the macular pigment (Fig. 1) was normalized to 9 percent at 462 nm. A predicted luminance difference of 2 percent was obtained using these normalized values and the spectral distribution of CWF. (A detailed description of this experiment may be found elsewhere.¹²) Figure 2 shows the 2 percent luminance reduction of polarized light spectrally distributed as CWF.

These results show that the difference in apparent luminance for polarized light relative to unpolarized

light can be predicted using the dichroic macular pigment hypothesis. Using the same procedure as for CWF a correction for other "realistic" light sources was applied (Table 1).

It is extremely important to point out, however, that the values in Table 1 should not necessarily be taken as luminance corrections for materials illuminated by these sources. These estimates would not apply in particular situations for the following reasons:

1. The spectral power distribution of these lamps will vary according to actual operation and installation characteristics.

2. The spectral distribution of these lamps is rarely seen directly by the eye, rather it is their spectral distribution coupled with the spectral reflectance of the material being illuminated that determines the spectral distribution reaching the eye.

3. The light reflected from a task is rarely completely polarized or unpolarized.

4. There is some question as to the true spectral absorption of the macular pigment. Recently Pease and Adams¹³ presented evidence that the macular pigment absorbs significantly longer wavelengths than those obtained by others (e.g., Brown and Wald¹⁴). (Whether the agreement between the predicted and the empirical attenuation by Haidinger's brushes for a CWF spectral distribution presented here was fortuitous or not may have to be carefully re-examined. For example, one might test the results from Pease and Adams¹³ by measuring the polarization effect with a very long monochromatic wavelength.)

5. The retinal location of the target must be taken into account. In the experiment described here the small target was placed to the right of and below the fixation spot. Any other location or different target size could produce different results.

6. The birefringence of the cornea will produce different magnitudes of the effect depending upon

Figure 2. Luminance attenuation by Haidinger's brushes (solid area) of a polarized cool white fluorescent spectral distribution.

Table 1. Potential luminance differences (in percent) for completely polarized vs unpolarized light.

Fluorescent ¹	
Standard Coal White	2.04
Standard Warm White	1.25
White	1.85
Daylight	2.77
Warm White Deluxe	1.14
Soft White	1.95
Cool White Deluxe	1.79
HID ²	
Mercury Arc	2.25
High Pressure Xenon	2.40
High Pressure Sodium	0.60
Clear Mercury	2.19
Mercury Deluxe White	1.87

¹ From Wyszecki and Stiles,¹⁹ Table 1.12.

² From National Research Council of Canada, Division of Physics, Optics Section.

incident plane of polarization. As was described previously, different incident planes of polarization will produce different degrees of elliptically polarized light as it passes through the cornea to the macular pigment.⁷ Thus, the effect will be larger or smaller depending upon the alignment of the cornea fibers relative to the incident plane of polarization.

Further, large individual differences can be found in the alignment of the corneal fibers. Bone, for example, found the orientation to vary between 0 and 77 deg in his subjects.⁹ Thus, physically specifying the orientation of polarization will not enable one to predict accurately the maximum magnitude of the effect for a particular individual without also knowing the preferential orientation of his corneal fibers.

7. There are also individual differences in the density of macular pigment.^{15,16} Similarly it appears that individuals having, say, the same density of macular pigment, may have different proportions of fiber alignment in the macular pigment.⁹ Therefore, the attenuation could be larger or smaller depending upon the population being considered.

All of these effects will produce discrepancies between the values in Table 1 and those that might be found under a particular set of conditions. Nevertheless, these values give "ball park" estimates for the discrepancies between photometric measurements and the visibility of polarized and unpolarized stimuli, and at least give relative estimates of error that might be expected for various light sources.

One must also be aware of the effects of polarized light in inducing discrepancies between photometry and subjective appearance when considering the relationship between contrast and visual performance.* Because of the analyzer in the eye, photoelectrically

* Ideally one should also account for polarization-induced errors associated with the relationship between adaptation level and visual performance, but because the transfer function relating adaptation level to performance is nearly flat at levels commonly experienced in offices (say, above 50 cd/m²) a 2 or 3 percent error (Table 1) in the adaptation level will make little difference in predicting performance.

equated contrasts can produce different subjective contrasts depending upon their spectral composition and degree and orientation of polarization. Thus, "noise" will be associated with a transfer function relating contrast and visual performance unless the polarization induced changes in *subjective* contrast are also taken into account.

If, say, the background of a task (e.g., a sheet of paper) reflected light that was unpolarized but the target (e.g., a printed numeral) was reflecting completely polarized light and both areas were spectrally distributed as CWF, a 2 percent error could exist between photometric contrast and subjective contrast (subject to the qualifications given earlier).

It has been pointed out previously¹⁷ that there is a nonlinear relationship between contrast and performance at a given adaptation level (Fig. 3). It was found from this study that performance did not vary for contrasts between about 0.4 and 1.0 for young adults adapted to 67 cd m⁻² of CWF distributed luminance. Thus, discrepancies between photoelectric and subjective contrasts of the order of 2 percent will not be important in this region. However, a 2 percent discrepancy below contrasts of about 0.2 could produce a substantial amount of "noise" if polarization of target and background were not taken into account, because the transfer function is very steep in this region.

After obtaining measurements of the degree and orientation of polarization reflected from the target and from the background in the direction of an observer's eye, a series of "corrections" were applied to the photometric contrasts. The variability of the data around the idealized transfer function was reduced by adjusting photometric contrasts to be consistent with the polarization analyzer model outlined earlier for the human eye. Specifically, a correction of 2 percent was the best in reducing the variability of the data. This is the same magnitude estimated by direct measurement.¹² Therefore, failure to account for the degree and orientation of polarization reflected from

Figure 3. Relative performance as a function of photometric contrast (O) and contrast transformed to account for Haidinger's brushes (X).

task materials can lead to "noise" or systematic errors in predicting visual performance.

It should be stressed, however, that the reduction in variability was, although measurable, extremely small (Fig. 3). This was partly true because the transformations produced no reduction in variability for contrasts greater than 0.4. Further, eye movements were not controlled in the experiment and subjects may have been performing the task so rapidly that they did not completely utilize the polarization effects. Variability from other sources (e.g., motivation, fatigue) that were unaccounted for in the transformation probably contributed to the "noise" as well. Thus, the analysis indicated that while photoelectric contrast accounts for the greatest amount of variability in predicting visual performance, "fine tuning" of the photoelectric contrast by taking into account the polarization characteristics of the target and background can place photoelectric contrast in closer agreement with subjective contrast. (For more detail of the analysis see Rea.¹⁸)

Summary

Recent advances in the determination of polarization sensitivity of the human eye have clearly elucidated the underlying mechanisms, namely the dichroic absorption by the macular pigment and the birefringence of the cornea. The measurements of the Haidinger's brushes effect under ideal conditions described here agree well with those already obtained. Further, the model could be used to predict direct estimates of the attenuation by Haidinger's brushes for a realistic light source, cool white fluorescent, under ideal conditions. Estimates of potential photometric errors were also given for other kinds of light sources. It was pointed out, however, that the estimated errors for the various light sources could be substantially different under different sets of conditions because of variations in both the physical characteristics of the stimuli and the observer's polarization mechanisms. Finally, an analysis of some performance data was described that indicated that one could reduce the variability in the data by taking into account the Haidinger's brushes effect, but that the reduction was very small.

Acknowledgment

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

References

1. *CIE Proceedings*, 1924, Cambridge Univ. Press, 1926.
2. Y. Hsia, and C. H. Graham, "Colour blindness," Chapter 14, *Vision and Visual Perception*, C. H. Graham (ed.), John Wiley, New York, 1965.
3. S. L. Guth, N. J. Donley, and R. T. Marrocco, "On luminance additivity and reflected topics," *Vision Research*, Vol. 9, 1969, p. 537.
4. H. Helmholtz, *Handbook of Physiological Optics*, Banta, Menasha, Wisconsin, 1924.
5. B. F. Hochheimer, "Polarized light retinal photography of a monkey eye," *Vision Research*, Vol. 18, 1978, p. 19.

6. H. L. DeVries, A. Spoor, and R. Jielof, "Properties of the eye with respect to polarized light," *Physica*, Vol. 19, 1953, p. 419.
7. W. W. Somers, and G. A. Fry, "The role of macular pigment in heterochromatic photometry," in preparation.
8. C. Shute, "Haidinger's brushes and predominant orientation of collagen in corneal stroma," *Nature*, Vol. 250, July 12, 1974, p. 163.
9. R. A. Bone, "The role of the macular pigment in the detection of polarized light," *Vision Research*, Vol. 20, 1980, p. 213.
10. J. Walker, "Studying polarized light with quarter-wave and half-wave plates of one's own making," *Scientific American*, December 1977, p. 172.
11. F. A. Jenkins, and H. E. White, *Fundamentals of Optics*, Third Edition, McGraw-Hill, New York, 1957.
12. M. S. Rea, "Quantitative estimates of Haidinger's brushes with realistic spectral distributions," National Research Council of Canada, Division of Building Research, Building Research Note No. 173, July 1981.
13. P. L. Pease, and A. J. Adams, "'Green' cone sensitivity and the difference spectrum of the macular pigment," Paper presented to the Topical Meeting on Recent Advances in Vision, Optical Society of America, 1980, Sarasota, Florida.
14. P. K. Brown, and G. Wald, "Visual pigments in human and monkey retinas," *Nature*, Vol. 200, 1963, p. 37.
15. R. A. Bone, and J. Sparrock, "Comparison of macular pigment densities in human eyes," *Vision Research*, Vol. 11, 1971, p. 1057.
16. J. A. Spencer, "An investigation of Maxwell's spot," *British Journal of Physiological Optics*, Vol. 24, 1967, p. 103.
17. M. S. Rea, "Visual performance with realistic methods of changing contrast," *JOURNAL OF THE ILLUMINATING ENGINEERING SOCIETY*, Vol. 10, No. 3, April 1981, p. 164.
18. M. S. Rea, "An analysis of the effects of Haidinger's brushes on the visual transfer function," in preparation.
19. G. Wyszecki and W. S. Stiles, *Color Science*, John Wiley, New York, 1967.

DISCUSSION

H. R. BLACKWELL:* Dr. Rea is to be commended highly for the present paper and for the closely related recently published paper entitled "Visual performance with realistic methods for changing contrast" appearing in *JIES*, Vol. 10, No. 3, p. 164-177 (April 1981). In both contributions to our ever-increasing knowledge of applied visual science as it relates to illuminating engineering, Dr. Rea has demonstrated good knowledge of both visual science and illuminating engineering, and solid experimental technique. In the published paper, Dr. Rea has shown solid and convincing evidence that "point contrast" photometry of the luminance contrast of task details predicts visual performance for task details varying in luminance contrast due to the plane and proportional amount of linear polarization of illumination, as well as other realistic methods of altering luminance contrast such as differences in task detail contrast under standardized spherical illuminance and differences in task "specularity" relative to differences in task illumination geometry which result in different values of the contrast rendering factor, CRF. This work supports the general validity of photometric measurements of CRF by the point contrast method with or without selectively plane polarized light.

The present paper provides, once again, solid and convincing evidence for an even more subtle aspect of the problem of understanding the effects of light polarization upon task detail visibility and visual performance. In this paper Dr. Rea shows that the well-known response of the human eye to the plane of polarization of illumination affects "apparent luminance contrast" and visual performance. The particular ocular response to light polarization with which Dr. Rea is primarily concerned is the antisotropic

* Institute for Research in Vision, Ohio State University, Columbus, Ohio.

spectral response to light polarization which leads to the perception of Haidinger's brushes as a darkened "sheaf of wheat" oriented at right angles to the plane of light polarization, a phenomenon well explained by the known orientation of pigment granules of macular xanthophyl in a "wagon-wheel spoke" arrangement with respect to the ocular line of sight. Dr. Rea has shown by direct measurements of the visibility threshold in a darkened field that a disc located to the right of ocular fixation will require more luminance contrast to be visible than an identical disc located below fixation, the effect being greatest when light of 462 nm is used. The difference between the two planes of polarization equals 18 percent, the disc requiring more luminance when located to the right when illumination is vertically plane-polarized. The effect is identical in direction with other illuminants but considerably smaller than 18 percent for an illuminant with less shortwave power, the difference being 4 percent when cool white fluorescent lamps are used. Dr. Rea concludes, correctly in my opinion, that these data signify that the apparent luminance contrast of a disc will be reduced when illumination is plane polarized vertically and the disc is located to the right of fixation, the opposite being the case when the disc is located an equal distance below fixation. Dr. Rea then goes on to show that the visual performance data presented in the published paper show clear evidence that the differences in visibility found when the discs located to the right of fixation appear as corresponding differences in visual performance when vertically plane polarized illumination was used in the realistic performance experiments. This implies both that point contrast photometry of task details illuminated by polarized light must include the effects of the eye's own response to light polarization, and that in the numerical verification task details were viewed to the right (or left) of fixation rather than below (or above) fixation, a conclusion completely in agreement of the expected patterns of eye positions to be expected in this task.

Dr. Rea correctly notes that small differences in apparent contrast produced by polarization or other means will have measurable and significant effects upon visual performance only when task detail contrast and/or lighting levels result in low visibility levels, the effects being insignificant whenever task visibility is high in any case. Of course, now that CIE Report No. 19/2 is published and available from Paris, this point no longer needs emphasizing. In fact, Dr. Rea can now presumably take advantage of the rational transfer functions relating visual performance to task contrast and hence task visibility described in such detail in Report No. 19/2 and will not need his own empirical transfer function in place of the rational one fitted to his earlier data in the internationally-accepted report. Nor will he need to make the point that differences in CRF are of much greater significance when task contrast or task visibility is low than when these quantities are high.

My principal conclusion from this truly challenging paper is that we must at once realize that luminance photometry of task details involving polarized light must be complicated into the following form:

$$\text{Luminance Contrast, } C' = \frac{L'b - L'd}{L'b}$$

where $L'd = \epsilon_h L_{bh} + \epsilon_v L_{bv}$; and $L'b = \epsilon_h L_{dh} + \epsilon_v L_{dv}$, values of L_{bh} and L_{bv} and values of L_{dh} and L_{dv} being measurements of task background and task detail in vertically plane polarized and horizontally plane polarized illumination, and values of ϵ_h and ϵ_v being proportional measures of the attenuation of the light of either plane by the macular pigment granules in a given retinal location.

The practical consequences of such a redefinition of luminance contrast photometry should be appreciated in advance. If task

details are seen to the right (or left) of fixation, then vertically polarized illuminance and the resulting vertically polarized task luminance will increase task contrast, visibility and visual performance whenever task details are darker than the task background. The reverse will be the case when either the task detail location is below (or above) fixation or when the task details are brighter than the task background. Since it is commonly considered that task details will most often be viewed right or left of fixation and will most often be darker than task backgrounds, it is to be expected that vertically polarized illumination will most often increase task luminance contrast with respect to horizontally polarized illumination of otherwise identical properties, the effect to be greatest the more the shortwave power to be found in the illuminant. The magnitude of the effect will of course depend upon the quantitative extent to which polarized illuminance results in polarized luminance, which will depend no doubt upon both the specularly of each component of task details and upon the illumination geometry.

REBUTTAL

AUTHOR: I wish to thank Professor Blackwell for his extensive comments to my presentation. Professor Blackwell had the advantage of reading and then commenting upon two other manuscripts related to measurements of Haidinger's brushes. Specifically, References 12 and 18 support many of the points made in this summary paper.

Returning to Professor Blackwell's comments, I was pleased to read his accurate and short paraphrase of the work. He was given a somewhat limited amount of time to read, digest and then comment on this paper and the supporting documents. His comments should assist others in reading the various manuscripts.

I must take issue with his proposition for taking into account the reflected polarization components of stimuli. Firstly, the formulation proposed by Professor Blackwell is incomplete. His attenuation terms, ϵ_h and ϵ_v , are not specific enough to be accurate descriptions of the luminance reduction or increase produced by the polarization mechanisms in the eye. As noted in the paper, these attenuation terms can vary significantly, depending upon the characteristics of the task and the observer. To be accurate, the ϵ_h and ϵ_v terms must be specific about such factors as the spectral distributions of the target and the background, the eye position of the observer, and the pigment density and the corneal birefringence orientation of the observers. All of these factors will alter the magnitude of the attenuation terms, but each requires very special equipment or experiments to estimate.

Luckily, the magnitude of Haidinger's brushes is very small, even under ideal conditions; Haidinger's brushes will do little to change the visibility of realistic material. Looking at the visual performance data in Fig. 3, for example, one can see that the transformed points accounting for Haidinger's brushes (crosses) are not very different from the data based upon traditional photometric contrast measurements (circles). Although it is true that the effect of Haidinger's brushes on visibility is measurable, both directly (Fig. 2) and indirectly (Fig. 3), very special conditions must be invoked to detect it. In most situations of interest to illuminating engineers, therefore, measurement of the polarization characteristics of tasks and precise evaluation of the attenuation terms would do little to change the visual performance functions. Practically speaking, the tedious polarization measurements and computations can be ignored.

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.