Title
CAN POLARIZED LIGHTING PANELS REDUCE ENERGY CONSUPTION AND IMPROVE VISIBILITY IN BUILDING INTERIORS?

Author
Berman, S.

Publication Date
1979-08-01

LBL-8671 c.2
UC-95d
EEB-L-79-05
L-25

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

CAN POLARIZED LIGHTING PANELS REDUCE ENERGY CONSUMPTION AND IMPROVE VISIBILITY IN BUILDING INTERIORS?

S. Berman and R. Clear

August 1979

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

rinted in the
[illegible]
itional Tech [illegible]
S. Departm
85 Port Ro
ringfield, V
ce Code: A

LBL-8671
EEB-L-79-05
L-25

CAN POLARIZED LIGHTING PANELS REDUCE ENERGY CONSUMPTION AND IMPROVE VISIBILITY IN BUILDING INTERIORS?

S. Berman and R. Clear

Windows and Lighting Section
Energy and Environment Division
Lawrence Berkeley Laboratory

The work described in this report was funded by the Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Applications of the U. S. Department of Energy under contract No. W-7405-ENG-48.

Table of Contents

I. INTRODUCTION

It has been claimed that artificial lighting systems utilizing polarizing panels have the potential for major energy savings when compared to the more conventional acrylic panels.

This report on polarizing panels is based on a survey of published materials and subsequent original analysis of this literature. We have reviewed the lighting and vision literature as well as briefly examined materials on management science and on the reflectivity of surfaces. Our analysis has, for the most part, been concerned with the connection between lighting design and productivity.

We have concluded that polarizing panels should be included among the alternatives normally considered by the lighting designer to utilize energy more efficiently than normal general lighting systems using standard prismatic or diffusing panels. A lighting design using polarizing panels might use 1/4 to 1/3 less energy than a reference system using standard prismatic panels without compromising function. The cost effectiveness of conversion or new design with polarizing panels depends upon the costs of the alternatives (including high efficiency, as distinct from standard, prismatic or diffusing panels). Current information of this type is available at the design stage. We unfortunately have only spotty data on how the use of polarizing panels compares to other potential lighting conservation designs in terms of potential energy savings.

Our estimate of the potential energy savings available with polarizing panels is based on our estimate of their efficiency at producing Equivalent Spherical Illumination, or "ESI". ESI combines the effects of luminance and contrast into a single figure of merit for visibility. Section II of this report provides a short history and some background for ESI. It then describes how polarizing panels affect ESI levels and how they compare to standard panels.

ESI is not universally accepted as a measure of visibility. In particular a theoretical model for contrast of diffuse-specular surfaces published by Marks in 1959 has been used to support very general claims for the superiority of polarizing panels. Section III reviews first Marks' model and then a statistical model for reflectivity. This review shows that the theoretical models are not that precise and do not support a general claim for the superiority of polarizing panels. Section III continues with a discussion of the measured reflectivities of paper and pencil on paper. These data are used in ESI calculations. We discuss briefly why these data may be inadequate for determining visibility for polarizing panels. The error (if it exists) would tend to make ESI underestimate the visibility produced by polarizing panels.

Section III closes with a discussion on absorption and multilayer reflecting-type polarizers. For the standard linear absorption polarizer, such as is found in sunglasses, the axis of polarization on a surface, and hence the effect on contrast, will depend upon the orientation of the surface with respect to the polarizer. Present polarizing panels use instead a multilayer reflecting principle. These panels produce what Marks described as "radial" polarization. The axis of polarization with respect to a horizontal surface is independent of the orientation of the surface with respect to a "radial" polarizer.

The problems and limitations of evaluating lighting systems strictly in terms of ESI per watt (or dollar) are discussed in Section IV. The relationship between visibility and productivity that determines the cost effectiveness of a lighting system is neither straightforward nor well understood. A short exposition on some of the factors affecting productivity - with emphasis on lighting - provides a perspective on the importance of differences in ESI levels. It also gives a rationale for judging a lighting system by its footcandle level, its comfort level, its "interest" level, or even general aesthetics, instead of ESI.

The discussion of cost effectiveness raises the important subsidiary point that the lighting system is not the only factor in visibility. There is a brief discussion of the possibility of using alternative investments, i.e., remodeling or the purchase of new office equipment, to improve visibility, and how this affects investment decisions about lighting systems.

Section IV closes with a discussion of task-ambient lighting systems versus general lighting systems. Our evaluation of polarizing panels versus standard panels consisted of a comparison of ESI values for general lighting systems and is not predictive of the merit of polarizing panels used with task-ambient systems. The discussion in Section IV shows that a task-ambient system may often be far more efficient than a general lighting system.

Section V attempts to evaluate polarizing panels in terms of the factors discussed in Section IV. Several specific situations where polarizing panels should be useful are mentioned. Potential benefit of task-ambient lighting with polarizing panels is evaluated qualitatively using the material in Section III.

Section V completes the body of this report. There are, however, four appendices which cover material in more detail than was felt necessary in the general text.

Appendix A provides a historical background on the viewing angle controversy. Appendix B tabulates comparative ESI data calculated by Bill Jones of the Lighting Research Laboratory. Appendix C provides very specific definitions of vertical and horizontal polarization and demonstrates how "linear" and "radial" polarization differ. Finally, Appendix D discusses modeling of visibility and productivity.

II. BACKGROUND - ESI AND POLARIZATION

Since Equivalent Spherical Illumination (ESI) is an important metric for evaluating any lighting system and in particular the effect of polarizing systems, a short history of vision research related to the concept of ESI is useful.

Early work by Cobb and Moss in 1928[1,2] and Holladay in 1926 and 1927[3,4] are excellent examples of publications that identified important visual parameters and discussed measurements of their effects on "visibility". The parameters studied were the light level (actually the luminance of the task or light level times reflectivity), the "contrast" of the task, the size (visual angle) of the target, the time available to see the target, and the presence of glare. Contrast is the difference of the luminances of the background and the target normalized by dividing by the adaptive luminance[5,6] (which is usually just the background luminance). Glare was considered to be the presence of light sources in the field of view. Finally, visibility was defined by measuring a "detection threshold" of the task.

Although detection thresholds can lead to reproducible measurements, it was not obvious how they related to visual performance in real work situations. In 1959 Blackwell[7] measured a static and a dynamic threshold and determined the relationship between them. In the static threshold measurement the subject knew where and when the target would appear (for 1/5 second). Threshold is defined as the condition under which the subject correctly detects the presence of the target 50% of the time. In the dynamic threshold experiment the subject did not know when and where the target would appear. Furthermore, the accuracy criterion for "threshold" detection was increased to 99%. These latter conditions were claimed to be reasonably representative of real conditions when the subjects are working at their maximum potential. The lighting recommendations adopted by the Illuminating Engineering Society have essentially been based on this study.

Blackwell's experimental procedure used a "standard" target and a "standard" lighting environment. The lighting environment consisted of uniform diffuse illumination such as would be found in a sphere. When the standard target is used, the visibility for an average observer can be calculated from the specification of the viewing angle and light level alone. Therefore, the visibility of the standard target in a lighting environment can be specified by the light level in a sphere that would give the same visibility-hence "Equivalent Spherical Illumination."

In his subsequent 1963 papers, Blackwell[8,9] utilized the 1959 results to compare different lighting systems (including polarizing systems). To simulate realistic viewing conditions, Blackwell calculated a weighted average of visibilities over viewing angles. An alternative procedure suggested by Crouch and Kaufman[10] was to use a 25° viewing angle for the calculations as this was thought to be the most common viewing angle. This latter procedure was the one chosen by the IES when it presented the ESI concept in its 1969 RQQ #4 report.[11] Appendix A discusses the viewing angle problem in more detail.

The physical measurements needed for an accurate ESI computation involve knowing the bidirectional reflection coefficients of various materials and are difficult and time consuming. In 1973 Blackwell, Helms and DiLaura[12] published reflection data for a standard pencil task. The IES RQQ #5 report[13,14] shows how this data can be used along with a model of a room and its lighting system to estimate ESI values in place of the more difficult and tedious measurements. This method was validated by comparison of computer estimates with computations from physical measurements in a test room.

Computer programs, such as the "Lumen II" program developed by DiLaura,[15] calculates ESI for a grid of points, with up to four viewing orientations at each point, in the room of interest. Because the relationship between ESI and visibility is non-linear, the average value of ESI over the grid of points is generally not a good measure of the average visibility in the room. In 1977 the IES published an interim recommendation[16] on ESI specifications for the "speculative" building market which consists of specifying a target ESI value which must be exceeded by a target percentage of the locations in the room. This procedure allows the user to weight the ESI values to insure adequate visibility almost everywhere. It does not determine the average visibility and it does not claim to provide the most cost-effective lighting.

In practice, most lighting designers[17] only use ESI if the client asks for specifications in ESI. Instead of ESI, designers usually specify light level (e.g., horizontal footcandles). The client will directly perceive the light level. It can be easily measured, and it is simple to calculate the number and spacing of lighting fixtures needed to deliver a given footcandle level rather than ESI levels.

The relationship between ESI and footcandles at any point depends significantly upon the difference in contrast that a target has at that location compared to what it would have in uniform sphere lighting. The contrast is affected by the distribution and polarization of the light and of course the type of target used. However, differences in contrast are not normally as noticeable as differences in light level. Hence, if the designer has some qualitative feel for what makes good lighting, the resulting lighting designs will usually be acceptable to the client.

The most recent IES Lighting Handbook[18] was published in 1972, at a time slightly before there was a practical method of determining ESI values. Many of its lighting recommendations are given in terms of ESI even though a quantitative procedure for its determination is not specified, and only the general issues of lighting quality are discussed. It provides guidelines as to the placement of lighting fixtures, and the type of fixtures used, so that the lighting designer can produce a design which has a relatively high ratio of ESI to footcandles. There is no mention of the effects of polarization or polarizing panels, and it appears that few lighting designers are knowledgeable about polarizing panels. In the remainder of this section, polarization and ESI are briefly discussed in order to help fill this information gap.

At a lighting level of about 50 footcandles, relative changes in contrast are about 10 times more important than relative changes in light level in terms of their effect on ESI.[18] In 1959 Marks[19] pointed out that the gloss, or surface reflectivity, of an item is polarization dependent. When gloss is present contrast is decreased. For the "multilayer reflection polarizer" gloss will be reduced for all surfaces that lie in a horizontal plane relative to the polarizing panel. The theory behind this is discussed in Section III.

What is important to our discussion now is that polarizing panels also affect the light distribution, which affects contrast. Further, as shown below, they do not transmit as much light as clear lenses. Also, as we show in Section III, incident polarized light affects the entire luminance distribution of the task, not just the surface gloss of a material. Since all these factors interact, the simplest procedure to determine the overall effect is to measure it.

Blackwell's 1963 paper[8,9] measured "visibility" for several lighting systems. The polarizing panels did very well in this comparison. However, as stated earlier, Blackwell's weighting procedure for the viewing angle is not the procedure currently used.

The 1973 reports by Blackwell, Helms and DiLaura[12] list values for ESI obtained by comparing a diffusing panel, a high efficiency prismatic panel, a batwing panel, and a polarizing panel. Only one lighting installation was studied. Furthermore, ESI was calculated at only a few points and these points were not randomly distributed through the room. The results should therefore only be considered illustrative.

The diffusing panels appeared to be uniformly poorer than the other three panels in this installation. Of the remaining three panels the high efficiency prismatic has the highest average ESI over the points in the grid (both calculated and measured) followed by the polarizing panel and then the batwing panel. The order is reversed for uniformity of ESI. Visual performance and ESI are related in a non-linear fashion with the low values of ESI affecting the average visual performance more than the high values of ESI. This means that uniformity must be considered along with the average ESI in evaluating average visual performance. It appears that for this installation the three high visibility panels are roughly comparable.

A number of case studies of standard prismatic panels versus polarizing panels have been performed by Bill Jones[20] at the Lighting Research Laboratory. In general, the polarizing panels did well in these studies, giving both better uniformity and a higher average ESI than the standard panels with which they were compared. The estimate in Section I of the energy savings attainable with polarizing panels was derived from one of the case studies[21] which had a sufficient number of computed ESI values to provide reasonable statistics for the ESI values over the room. These results are discussed in more detail in Appendix B.

It is important to note that the replacement of a standard prismatic panel with a polarizing panel does not increase light levels.[20] The key consideration is that ESI values are higher for polarizing panels in the case studies above because improved contrast more than compensated for reduced light levels. If a building is built or lit to a footcandle specification rather than an ESI specification, then polarizing panels, or for that matter any lighting design which sacrifices footcandles for contrast, will result in an increased use of power.

To save energy without loss of visibility the lighting specification must either be in terms of ESI or it must provide a correction factor for reducing the lighting level for lighting designs which provide better than average contrast. From the example above, we estimate that this correction factor would be 0.6 to 0.7 for the polarizing panels as compared to standard prismatic lenses in a general lighting system. This factor is also consistent with the less detailed data for other lighting systems studied.[20]

III. REFLECTIVITY, POLARIZATION AND CONTRAST

The effect of polarized light on contrast is central to the argument that any polarizing system can improve visibility. A short review of the reflectivity of flat surfaces is given below as it presents the needed vocabulary and provides in addition a useful prelude to the discussion of the effect of polarization on contrast.

The theory[22] of specular reflection from plane surfaces predicts that the reflectivity is a function of the angle of incidence of the light, its polarization, and finally the "admittance", or for transparent materials, the index of refraction of the material. The reflection from a smooth plane is mirrorlike or "specular" with the angle of incidence equal to the angle of reflection. Light which has its polarization vector perpendicular to the plane defined by the incident and reflected light rays is called horizontally polarized light and is more strongly reflected than light which has its polarization vector in the plane defined by the incident and reflected rays (vertical polarization).

When the angle of incidence of the light ray is perpendicular to the reflecting surface the incident and reflected rays are in opposite directions and no longer define a unique plane. For this case, reflectivity is independent of polarization. For horizontally polarized light the percentage reflectivity increases steadily as the angle between the incident light ray and the normal to the surface increases, reaching 100% at the grazing angle (90^o). Conversely the reflectance of vertical polarized light first drops to a minimum and possibly to zero at the "Brewsters Angle" (which depends upon the material) before also rising to 100% at the grazing angle.[23]

Flat pieces of metals, transparent plastics, or glasses, act like these theoretical planar surfaces in terms of their reflectivity. However, in general, the reflectivity of most materials is not adequately described in this fashion. Instead, most of the materials we commonly deal with, and hence constitute most of our important visual tasks (e.g., paper, cloth, and most building materials), are not perfectly smooth and exhibit a combination diffuse specular reflectance.

Diffuse reflectance is random reflection in any direction and thus is proportional to the projected area of the reflector in the light beam direction. This is Lambert's law, the reflectance as a function of θ, the angle between the reflected ray and the normal to the surface, is a constant times $\cos\theta$.

A material such as paper which exhibits diffuse specular reflectance will have a broad peak centered around the specular angle superimposed on a background reflectance that is roughly Lambertian. For example, for matte finish paper[13] the peak is approximately 25% above the average reflectance when the specular angle is 25°. Thus, any theory which purports to predict the effect of polarization on contrast for a material like paper must examine both the diffuse and specular portions of the reflectance. An early attempt to perform this type of analysis was made by Marks in 1959.[19]

Marks analyzed the reflectance of polarized lighting on these materials by assuming that they could be modeled as diffusely reflecting pigments suspended in a transparent medium with the diffuse reflectance assumed to be independent of polarization. The importance of both the specular and diffuse components in contrast is shown in the following example.

Contrast is defined[5,6] in terms of the reflectivities of the task ζ_t, (e.g., a pencil stroke) and the background, ζ_b,

$$C = |(\zeta_b - \zeta_t| / \zeta_b \tag{1}$$

First consider a case where there is no specular reflection (i.e., viewing at Brewster's angle with incident vertical polarized light). If, for example, the reflectivities of the diffuse background and task are 0.9 and 0.6 respectively, then the contrast is

$$C = (.9 - .6) / .9 = \overline{.333} \tag{2}$$

Now consider the case where some of the light is specularly reflected from the surface of the transparent medium instead of all the light being reflected by the pigment layer underneath. If the illumination is uniform then the specular component (or veiling reflection) will be independent of orientation of the surface in the room and will vary in magnitude with respect to viewing angle only. Since the surface reflectance is independent of the reflectance of the pigmented area it will reduce the contrast. When this is applied to the example above and at a viewing angle where the specular reflection is 10% it gives

$$C = \frac{(.9 \times .9) + .1 \quad - \quad (.9 \times .6) + .1}{(.9 \times .9) + .1} = 0.297 \qquad (3)$$

Thus, the larger the specular component the lower the contrast. Since incident horizontally polarized light is more strongly reflected than vertically polarized light at all angles (except the trivial cases 0^{o} and 90^{o}) this model predicts that vertical polarized will give higher contrast than horizontally polarized, or unpolarized light at all angles and orientations.

There are several serious objections to accepting the Marks model described above as an adequate description of real materials. One objection is that the physical model may not be appropriate for many materials. The most serious objection,however, is the failure of the model to consider the possibility that real diffuse reflectance will depend upon polarization.

Some insight into this possibility is achieved by examining the extension of the theory of specular reflection from planar surfaces to some simple non-planar surfaces. In particular, randomly rough surfaces can be analyzed so long as there is local planarity with respect to the wavelength of the light. For instance, Beckmann[24] discusses reflection from a surface with a Gaussian distribution of heights. The correlation between the height at one point of the surface to another point was assumed to decay as e^{-d^2/L^2}, where L is a correlation length and d is the horizontal distance between the points. This model gives an increasingly diffuse reflection as the surface roughness increases.

Two features of this model for diffuse reflection are particularly worth noting. First, since local planarity is assumed,the relative differences in reflectivity between vertical and horizontal polarization still hold. Second, the diffuse scattering is generated from specular reflection from randomly orientated local surfaces. Therefore, vertical and horizontal polarization has to be defined in terms of each of these local surface orientations.

Light that is vertically polarized relative to the flat plane is still vertically polarized relative to any local plane which reflects the light either back or along the original orientation ($\phi = 0^0$, or $\phi = 180^o$, where ϕ is the azimuthal angle, see Appendix A). However, it is horizontally polarized relative to the local planes which reflect it perpendicularly from the original orientation ($\phi = 90^o$) and of mixed polarization for other orientations.

This diffusely reflecting rough surface does not have the same behavior as Mark's composite model of perfect diffusers embedded in a plane reflector. Consider as an example the set of incident and reflected light rays associated with local planes of one orientation.

To distinguish the local planes from the surface plane we let + and − refer to vertical and horizontal polarization respectively relative to the local plane, and let v and h refer to the surface plane. The contrasts are:

$$C^{+} = (\zeta_b^{+} - \zeta_t^{+})/\zeta_b^{+} = 1 - \alpha^{+}; \ \alpha^{+} = \zeta_t^{+} / \zeta_b^{+} \tag{3a}$$

$$C^{-} = (\zeta_b^{-} - \zeta_t^{-})/\zeta t^{-} = 1-\alpha^{-}; \ \alpha^{-} = \zeta_t^{-}/\zeta_b^{-} \tag{3b}$$

The ratio of the contrasts for the two local polarizations is then

$$C^{+}/C^{-} = (1-\alpha^{+})/(1-\alpha^{-}) \tag{4}$$

Let 2θ be the scattering angle between the incident and reflected rays. In general, reflectivity is more sensitive to polarization when $\zeta(\theta = 0)$ is low. Since ζ^{+} declines until it reaches the Brewsters angle, α^{+} will be smaller than α^{-} for most reasonable viewing angles. This implies that $C^{+} > C^{-}$. Relating the local plane to the surface plane gives $Cv > C_h$ near the forward and back scattered directions. At $\phi \to 90^{o}$ $V \to -$; and $C_h > C_v$. Intermediate angles will give $C_v \sim C_h$. Thus, for the diffusely reflecting rough surface, vertical polarization should improve contrast for light along the line of sight. For light which is reflected to the viewer from the side, vertical polarization should give less contrast than unpolarized or horizontally polarized light.

It is necessary to emphasize that these results are model dependent. For example, consider replacement of the perfect diffusing pigments in Marks' composite model with rough surfaced diffusing pigments. The angular distribution of the contrasts would be composed of contributions from both models. This result is more realistic than Marks' original model and might describe materials such as glossy paper.

Other models might be more appropriate. The statistical model can be modified by using different distributions of the heights or a different correlation function. Very rough surfaces (i.e., L less than the wavelength of light) can be modeled for a limited number of special surfaces.[24] Finally, one could attempt to model embossing, color absorption and possibly other absorption and radiation effects.

Available theoretical models such as the example here do not support the contention that vertically polarized light will give better contrast for all viewing angles and all materials. In fact, these models suggest that horizontal polarization might be superior in some situations. The models indicate that polarization will almost always affect contrast. For materials with glossy surfaces vertical polarization will probably be advantageous. More precise statements require data on the angular dependent reflectivities of the materials in question.

Reflection data as a function of angle and polarization have been published for the "reference" standard pencil task and its background. The "task" luminances include some of the immediate background of the pencil stroke, so contrast values are fairly low.[25] Table 1 lists selected values of contrast[12,13,25] computed from the published luminance tables. The angle θ is the altitude defined with respect to the normal of the task (in practice the task is always assumed to lie in the horizontal plane), and the angle ϕ is the azimuthal angle defined so that 0^o points from the task to the observer. The luminance tables are published to 4 digits; however, the data are only accurate[12,26] to about 1%. The values in Table 1 are rounded off in accordance with accuracy of the luminance data.

For this task, vertical polarization gives higher contrast than horizontal polarization for light coming from in front of the observer and lower contrast for light coming from behind or from the side of the observer. Therefore, the overall effect on task contrast will depend upon the location of the task and the lighting distribution of the installation. A different task with different reflectivities might give a different conclusion as to the importance of vertical polarization.[27]

Another potentially serious difficulty in using this data for ESI calculations lies in the present method of measuring contrast. The method of using the average luminance of the task and its immediate background versus the distant background is called the "flux" contrast method. It is used because it is a relatively simple measurement, is

Table I. Selected Contrast Values for the Standard Pencil Test

Orientation of Incident Light		Viewing Angle	Contrast Values	
θ_I	ϕ_I	θ_V	C_H	C_V
0	0	10	.083	.084
10	0	10	.069	.074
10	60	10	.085	.087
10	120	10	.106	.108
30	0	10	.126	.132
30	60	10	.149	.146
30	120	10	.158	.153
60	0	10	.201	.187
60	60	10	.204	.183
60	120	10	.198	.179
0	0	25	.137	.140
25	0	25	.046	.082
25	60	25	.139	.141
25	120	25	.167	.162
60	0	25	.163	.176
60	60	25	.202	.182
60	120	25	.205	.182
0	0	40	.159	.164
30	0	40	.0209	.103
30	60	40	.168	.164
30	120	40	.186	.179
40	0	40	(.0129)[I]	.102
40	60	40	.178	.171
40	120	40	.195	.181
60	0	40	.048	.165
60	60	40	.208	.188
60	120	40	.216	.193

[I](x) indicates contrast reversal with the task brighter than the background.

unambiguous and it correlated well with visibility in early experiments. Point contrast measurements are more difficult and somewhat ambiguous if there are high-frequency changes in reflectivity. However, since the eye can resolve detail in the area over which the flux contrast method averages the luminances,[6,7] the correlation to visibility should be regarded as partially fortuitous.

Blackwell[28] recently compared flux contrast visibility predictions to visibility meter studies for a polarized and an unpolarized lighting installation. The flux contrast measurements underestimated the visibility of the polarized lighting. These results have not yet been verified by other researchers. Thus, ESI values for polarized lighting installations may underestimate visibility relative to the ESI values for unpolarized installations and should be viewed as tentative and perhaps conservative.

So far, this analysis has discussed vertical and horizontal polarization independently of the means of preferentially producing one or the other type.

The most familiar method of producing polarization is the linear absorption polarizer. This is the type of polarizer that is found in sunglasses. Absorption polarizers are fairly inefficient since they work by absorbing the unwanted polarization. At typical office light levels (50 fc or more) a percentage change in contrast is equivalent to a 10-15 percent change in light level in terms of its effect on ESI;[18] hence this inefficiency is not necessarily a limiting factor. However, only tasks orientated along the polarization axis of the polarizer or properly tilted would receive vertically polarized light with an absorption polarizer. For most task orientations the linear polarized light from the luminaire is neither completely vertically or horizontally polarized and, therefore, will probably not improve task contrast enough to compensate for the reduced light level. Thus, the absorption polarizer appears to only be useful for situations where there is a fixed orientation between the fixture and the task. Thus, it conceivably might be useful in furniture modules with built-in task lighting.

The type of polarizer actually used in present polarizing panels is the multilayer polarizer. A multilayer polarizing panel is different from the absorption polarizer in that it polarizes light by utilizing a laminate whose multiple surfaces produces changes in index of refraction which preferentially reflect the horizontally polarized component of the light (just like a veiling reflection) back into the fixture. The reflected light is not totally lost since reflection off the back of the fixture depolarizes it and returns it for another pass through the panel. Since the back panel is not a perfect reflector, the polarization fixture will generally give slightly less light than the equivalent non-polarization fixture.

Clear polarizing panels appear to maintain a coefficient of utilization[29] (a measure of luminaire light output efficiency) within 8-21% of standard clear prismatic panels,[30,31] while reaching an all-angle average of approximately 25% polarization.[32] Typical diffusing panels or louvers may have lower coefficients of utilization than the polarizing panels. More important is the fact that the polarization is "radial" rather than "linear" in distribution so that with polarizing panels the degree and direction of polarization depends upon the direction of the light. This means for horizontal tasks, and all tasks viewed head on, all orientations are the same insofar as there is no preferred orientation axis with respect to the light fixtures since the axis of the polarization of the light depends upon which direction it came from. Note that this sentence does not imply that contrast values remain the same as you change the orientation of the task.

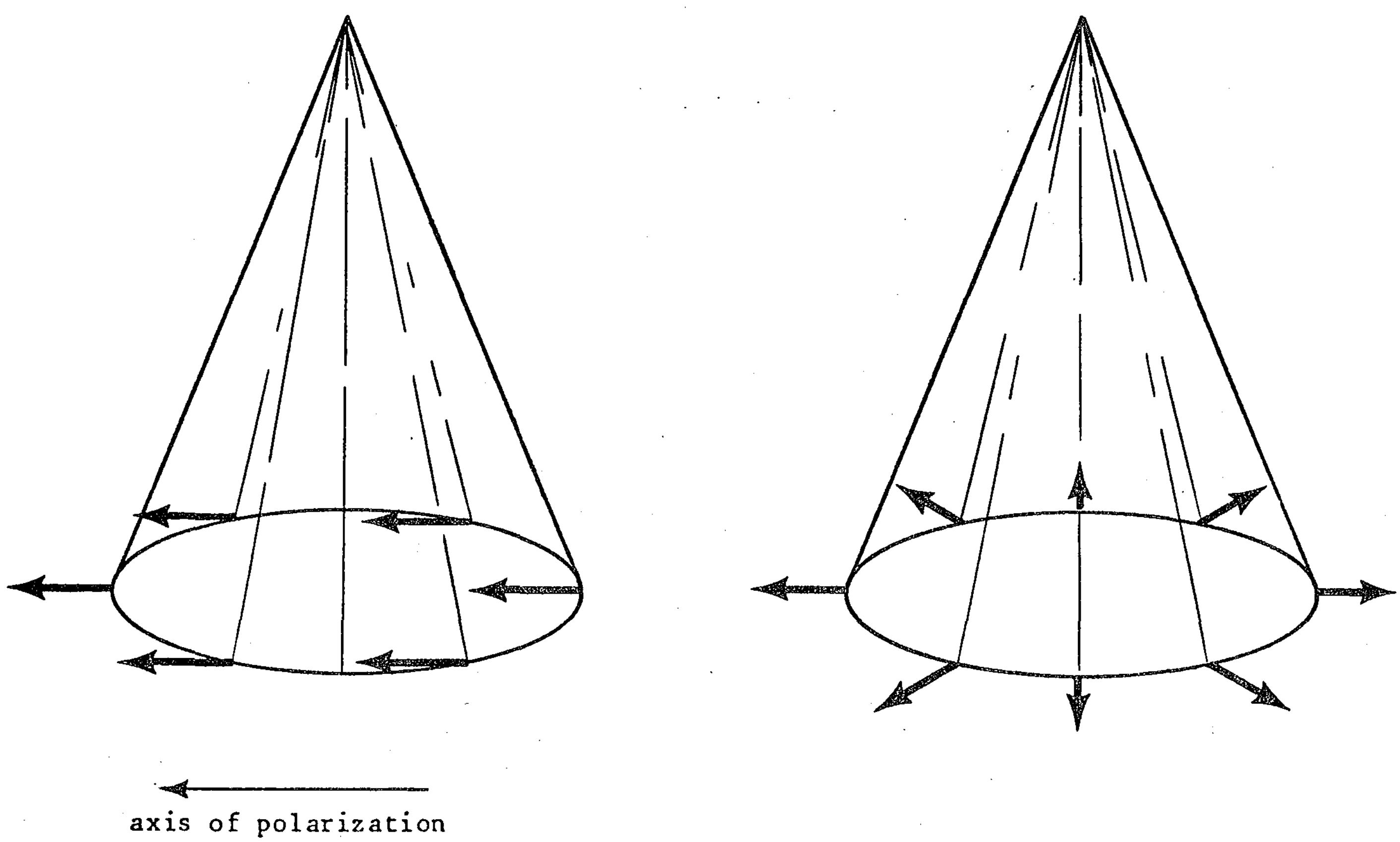
The distinction between linear and radial polarized light is important and is considered below. Figure 1 attempts to illustrate this difference.

Figure 1 shows the projection of the polarization vectors on a plane from cones of linear and radial polarized light. The figures clearly show that with linear polarization all the light is polarized along a single direction or axis in space. With radial polarization the polarization direction depends upon the direction of the light. Of course, what is important to visibility is whether the light is vertically or horizontally polarized with respect to the visual task. Linear polarized light will only be vertically polarized if the task is aligned properly with respect to the axis of polarization. To produce radially symmetric polarization the polarization component

Figure 1. The arrows give the projection of the polarization vector in the plane.

a) Linear Polarization

b) Radial (Vertical Component) Polarization



horizontal (parallel) to the polarizer is rejected (note that real polarizers are only partially effective). Therefore, the transmitted light is vertically plane polarized with respect to any surface which is parallel to the polarizing panel. Polarizing panels are generally used in the horizontal plane, hence, any horizontal task gets vertical polarization. In general, when a viewing surface is tilted, the vertical and horizontal polarization components defined with respect to the polarizing surface are mixed relative to the viewing surface. An exception is the case when the normal to the polarizing surface, the normal to the viewing surface, and the incident light ray all lie in the same plane. (This latter case corresponds to incident light that would normally be reflected toward an observer viewing the surface head on, i.e., viewing line normal to the reflecting surface. Since much viewing of tilted or vertical surfaces is head on, this is an important exception.) In short, for most realistic viewing conditions, the degree of mixing is fairly small. Appendix C derives these relationships algebraically so that the effects can be examined in more detail.

IV. ESI, VISIBILITY AND PRODUCTIVITY

The previous sections have used visibility, as measured by ESI, as the basis for comparing different lighting systems. In this section we discuss the limitations of treating lighting strictly in terms of visibility. A case is made for the view that in many situations small changes in visibility are peripheral or irrelevant to good design.

Ultimately the basis for judging any lighting system is cost effectiveness, that is, costs versus the benefits. The costs are typically labor, capital, maintenance and energy. The potential benefits are generally considered to be increased productivity or sales, and improved employee satisfaction and reduced turnover. In practice it is very difficult to isolate the effects of differences in lighting on productivity or employee turnover. Instead, a standard assumption is that these benefits are monotonically related to visibility, as measured by ESI. Thus, ESI per watt, or even better ESI per life-cycle dollar, is taken as a measure of the cost effectiveness of a lighting system.

There are two assumptions implicit in the use of ESI per dollar. The first assumption is that productivity is highly dependent on visibility in the work environment as distinct from a visual test laboratory environment. This means that visibility is the only important lighting factor with respect to the potential benefits, or it is positively correlated with the other important lighting factors, or at the very least it is completely independent of the other important lighting factors, such as glare. If other lighting factors are important, then ESI per dollar ratios lead to a sub-optimization of the lighting environment which may bear little relationship to the overall optimum. The second assumption is that a standard ESI measurement is a reasonable measure of visibility in a field environment as distinct from the test laboratory environment.

It is not hard to think of situations where within reasonable limits variations in visibility should have little or no effect on performance. Any situation where performance is not only limited by, but actually fixed by, external constraints fits this description. For example, in some Swedish auto plants productivity is determined by contractual agreement between labor and management.[33] In general we should expect that within reason visibility may be of little importance in sales areas, restaurants,[34] reception areas, conference rooms, assembly line areas, and in many executive or management-level offices.

In a sales area the major concern is that the lighting attract and hold the attention of the customer. The visibility is of secondary importance relative to this function. In many of the other areas the primary role of the lighting may be to maintain worker morale and motivation by creating a proper context for work or by aiding in providing a pleasing stimulating environment. Or instead, the lighting may be perceived as an amenity so that the lighting level designates the status of the worker or the image of the company. These are all examples of situations where visibility may not be the most important feature of the lighting.

Examples of visual factors which may be negatively correlated to visibility with respect to their effect on performance are glare, flicker, and color rendering ability. Although glare and flicker can be problems even at low lighting levels, they are progressively harder to avoid at high light levels. Color rendition is a problem in that it is negatively correlated with efficacy (e.g., lumens per watt) of gas discharge lamps.

There are numerous studies on the effect of glare on visibility,[2,3,4,35] yet this important factor is not presently treated by ESI. Furthermore, there don't appear to be any studies of the effect on performance of glare and flicker as irritants. Color can affect context, and can have a major effect on room (and personal) appearance. Again there appear to be no studies on how this affects performance except in the obvious situations such as in hospitals, museums, or other areas where the visual task involves color discernment.

A further problem with attaining high visibility with high light levels is the increase in the waste products (heat and noise) of the lighting systems. In an older building with no air conditioning more work may be possible with the lights off during a heat spell than with on. Air conditioning of course deals with this problem, but often not well, and at an increasingly high expense.

Most of the discussion presented above is either speculative or difficult to quantify. On the other hand, visibility and visual performance are easily defined and can be conveniently measured in a laboratory environment. There have been extensive studies[35] on the relation between visibility (as measured by ESI) and visual performance (as measured by speed in performing a task), and it is often assumed that these results can be used directly to estimate relative productivities.[36,37] The tasks are often highly visual, and performance gains are correspondingly high; one study[37] showed gains of 5-10% for an increase from 25 to 75 ESI.

These values are unrealistic for field estimates. Work situations commonly include both visual and non-visual (i.e., manual or cognitive) tasks or components of tasks. The non-visual component dilutes the effects of changes in the visual component. For example, if at two different ESI levels the visual component of a task takes times t_1 and t_2 and the non-visual component takes time t_n, then the relative improvement in the visual part of the task is $(t_1 - t_2)/t_1$ while the relative improvement in the whole task is diluted to $(t_1 - t_2)/(t_1 + t_n)$.

Thus, performance changes from visibility alone are more likely to be on the order of magnitude of 1% rather than the 5-10% quoted earlier. This is of small enough magnitude that it is unclear that other factors are not of comparable significance. If dilution is very large then extrapolating the results of visibility studies on visually demanding tasks to the more mundane work situation may become analogous to trying to extrapolate the results of a study of factors affecting marathon performance to estimate the time it takes someone to walk to and from the water cooler.[38] Appendix D discusses models of productivity in more detail.

In addition to our reservations about the relationship between visibility and performance, there appear to be ample reasons to have reservations about relating ESI to visibility in the work environmnet as distinct from the laboratory environment. For example, in Section II we mentioned that ESI values in a room cannot be averaged to give the average visibility in a room because of the non-linear relationship between the two. In Section III we mentioned that the "flux" contrast method used to measure contrast may be inadequate for polarized light. In addition, both Sections II and III point out that present ESI calculations are commonly only performed for a single reference task. There is no guarantee that the relative ESI rankings of different lighting systems will be the same for different tasks.[14] A lighting designer who wishes to optimize the lighting system in terms of visibility needs to know the age distribution of the employees,[35,39,40,41,42] the frequency distribution of the tasks, their locations and orientations (including tilt) as well as the frequency distribution of viewing angles and finally the lighting and room parameters. At present even the average values of some of these variables are unknown. Finally, even if these values were known, ESI might still be an incorrect measure of visibility for people who wear glasses because of the veiling reflections off the back surface of the glasses. Again, there appear to be no field tests[43,44,45,46,47] which have actually isolated the effects of visibility on performance. Nevertheless, it seems inherently reasonable that there must be some difficult tasks which are visibility limited in the work environment. This still does not imply that the most cost-effective solution is the lighting system with the highest ESI per life-cycle dollar. That is sub-optimization. If poor copy equipment, for example, is the justification for higher visibility lighting, then the building owner should consider better copy equipment as an alternative to changing the lighting.[48] The lighting and the copy equipment are competing investments and should be evaluated as such. This principle can be extended to other lighting factors. A dingy room might benefit from higher light levels, or just some paint or the services of an interior decorator to make it pleasant at a lower light level. Again, these are competing investments.

The last subject we discuss in this section is ESI and task-ambient lighting systems. Task-ambient lighting consists essentially of low-level general lighting for circulation and to provide a pleasant background environment, and higher level local lighting for task areas (e.g., a desk). Task-ambient systems are potentially very efficient (ESI/watt or footcandles/watt) and, therefore, are likely to become increasingly common.

A task-ambient system is efficient in terms of footcandles per watt delivered to the task area because it concentrates its light on that area. Consider the following example: a 1,000 ft^2 room with

10 desks that is uniformly lit to 100 footcandles by lamp fixtures rated at 30 maintained lumens per watt delivered to the work plane. This example[49] works out to 3.3 watts/ft^2. Now consider lighting the room to 30 footcandles and providing each desk with a 40 watt fluorescent lamp which provides 100 footcandles on the task area of the desk. This room[50] only requires 1.5 watts/ft^2. The addition of more work surfaces will raise the power level; fewer work surfaces will make it look even better.

Placement of the local lamp in a task-ambient system can be critical for visibility. Unfortunately many designs using a fixed lamp place it where it produces glare and low visibility on the desk surface. High visibility, or at least high ESI, is possible however. A recent study[51] of task-ambient systems claimed 50 to 100 ESI per watt/ft^2 depending upon the density of the desks in the room (50 ft^2 - 200 ft^2 per desk, 30 footcandles ambient lighting). In comparison general lighting systems usually give less than 30 ESI per watt per ft^2.

Unfortunately, it is not obvious how comparable ESI values for task systems are to ESI values for general systems. The computer programs are not easily used for this situation and there is a question of how accurate they are. Basically, the small size of the desk-local lighting area means that small variations in the surroundings or small deviations from the smoothed candlepower distribution of the fixture become non-negligible sources of error.

The DiLaura ESI meter is also of questionable accuracy because of its large size and the imprecision of the photographic mask relative to the small size of the desk-local lighting area. Furthermore, the DiLaura ESI meter cannot be used with polarized light.

The most serious objection to comparing the ESI values of task and general systems is that task lighting presents conditions even further from those used in the visual performance studies than does general lighting. In particular the luminance of the desk and its surround is often highly non-uniform in a task-lighting situation, whereas the visual performance studies used highly uniform lighting.[52] Evaluation of task-lighting systems in ESI should of course also take into account the rest of the material presented in this section.

V. CONCLUSION: QUALITATIVE EVALUATION OF POLARIZING PANELS

Evaluating polarized panels is simplified when ESI per dollar is used as the decision criterion. Where visibility is the concern but footcandles are used in place of ESI for the lighting specifications a correction factor applied to the footcandle level may be reasonable. From Section II we estimate the allowable reduction in intensity factor to be probably about 0.7 for polarizing panels and 1.0 for the standard prismatic panels. Other systems would have different correction factors. This approach is less precise than the direct calculation of ESI but is justified if the factor is found to be reasonably stable for different lighting arrangements and where precision in ESI is not critical.

The material in Section IV suggests that in most cases precision in ESI is not justified and that in many work situations visibility is important only when it is noticeably bad.[53] From Section III we know that polarizing panels can reduce veiling reflections and glare resulting from light coming from in front of the worker. This can make the difference between poor visibility with an unpleasant and distracting lighting environment, and acceptable visibility with a relatively benign environment.

The polarizing panel may be particularly useful in this fashion for retrofit situations where the lighting from the existing fixtures has been found to be unpleasant or glaring but the expense of relocating or replacing the fixtures is prohibitive or disruption of the existing working arrangement is unfeasible or undesirable. This problem of surface glare and veiling reflections is apt to be especially noticeable in rooms with data terminals where the operator may have to contend with reflected lamp images in his screen. It may also be an annoying problem wherever accurate color appraisal is important (e.g., museums, many retail stores, or paint or yardage stores) since the veiling reflection from surface gloss has the color of the light source rather than the underlying object. This factor may even account for some of the appeal of north-facing daylighting which is strongly polarized.[54]

In many cases it may be possible to combine some delamping with the retrofit of polarizing panels and still get improved lighting. In this case, the system may also benefit from reduced noise, flicker and heat. The direct glare from the fixture may also be reduced, but it depends as much upon location and distribution as it does upon intensity. Although the multilayer polarization produces a roll off of the light intensity at high angles from the vertical, the actual candlepower distribution of a polarizing panel may be modified by the prismatic elements of the panel. Therefore, direct glare should be evaluated from the candlepower distribution data for the panel in question.

The same general considerations for veiling reflections and surface glare apply to task-ambient lighting, but the details are somewhat different. For instance, visibility considerations may be more important for some task lighting since it is more efficient (less expensive) to use highly localized lighting for the tasks which are substantially more demanding than the normal office task. Another difference is that there is less flexibility in locating built-in lamps (as distinct from movable desk lamps) with respect to the worker than with general lighting. Furthermore, once a location for a built-in lamp is chosen the physical relationship between the worker and the fixture is fairly rigidly defined, whereas with general lighting moving a desk changes the distribution of the light on it.

A convenient and commonly used location for built-in lamps is under a shelf facing the worker. Vertical polarized light should be very beneficial for visibility and for reducing veiling reflections and surface glare for lamps located in this manner. Since the relationship between lamp and worker is very constrained it may not be necessary to use a multilayer polarizing panel to get vertical polarization; a properly orientated linear absorption polarizer may be as adequate. At the moment neither of these possibilities appears to be widely known.

In summary, essentially the unique feature of polarization is its beneficial effect, with respect to visibility and surface glare, on light incident from in front of the observer. If this feature is useful for a particular problem then polarizing panels will improve the overall quality of the lighting environment as compared to standard prismatic panels.

APPENDIX A: VIEWING ANGLES

One effect of viewing angles on visibility is that changes in viewing angle change the intensity of reflected light as a function of its angle of incidence and its polarization. Qualitatively, an increase in viewing angle (as measured between the view line and the normal to the viewing surface) increases the amount of the mirrorlike or "specular" reflection from the surface (see Section III). This decreases the contrast obtainable from light that is incident on the surface from near the specular angle, and increases the contrast from light incident from other directions. Furthermore, polarization has a bigger effect on contrast at high viewing angles than it does at low viewing angles. Since contrast is a dominant factor affecting visibility at normal office lighting levels, viewing angle values can have a decisive effect on judgments on the relative merits of different lighting systems.

The present procedure[13] of the Illuminating Engineering Society is to calculate ESI values at a 25^{o} viewing angle. However, visibility has been measured at other angles. Blackwell's 1963 paper[9] on reflected glare reports calculated values of "adjusted Visual Effectiveness Factor" or "VEF" at 25^{o}, 40^{o}, and 60^{o}. The adjusted VEF is proportional to ESI and is in a sense its precursor. In a later attempt to analyze this visibility data Blackwell essentially weighted the VEF values at each viewing angle by both a relative difficulty (contrast) of the task and an estimated relative frequency of viewing, and then averaged. The resultant "average" visibility when used in comparisons of different lighting systems takes into account the changes in visibility at different viewing angles.

Another 1963 paper by Crouch and Kaufman[10] presents the case for using just the 25° viewing angle. They noted that the Illuminating Engineering Society design procedure is based on the "commonly used most difficult" task.[10,55] Crouch and Kaufman analyzed data on viewing angles from photographs in the files of the Illuminating Engineering Research Institute plus data from a study by Allphin.[56] The most common viewing angle in these studies was 25°. In addition, 25° was the average of the viewing angles that were 40° or less. Crouch and Kaufman felt that this was significant because viewing angles above 40° were infrequent and lead to sub-optimal visibility. In particular, the high viewing angles give a geometric foreshortening effect which reduces visibility. In addition, examination of photographs of school children using viewing angles above 40° showed that a) the school desk was too large, b) interpretation of the viewing angle from the photograph was ambiguous and lower values were possible or c) the child was not in a posture conducive to serious study. They felt that these findings confirmed the essential validity of the IES design procedure of designing for the "commonly used most difficult" task.

Since 1963 comment on viewing angles seems to have been mainly centered on whether high viewing angles are in fact reasonable and common. The Lighting Research Lab[57] computed the percentage of the surface area of a desk visible at a given viewing angle or below, with respect to a fixed viewing position. In this work, it is claimed that the results, 6% of the area at 25^{o} and 15% of the area at 40^{o}, are a vindication of Blackwell's claim that higher viewing angles are both reasonable and probably not uncommon. Actually Blackwell no longer averages his data,[12] but he does continue to perform experiments and calculations over a range of angles.

On the other side of the question Crouch and Buttolph[58] examined viewing angles and distances for a small sample of stenographers for both reading and writing tasks. The viewing angle data were consistent with the earlier data of Crouch, Kaufman and Allphin.

The problem of attempting to evaluate lighting systems in terms of visibility (ESI or VEF) was discussed in detail in Section IV. One of the major problems mentioned was that performance cannot be estimated from average visibility because of the non-linear relationship between them. Thus, the very high average visibility rankings that Blackwell assigned to polarizing panels in 1963 do not imply a correspondingly very high visual performance. The use of a single viewing angle gives a similarly vague estimate of visual performance. It does, however, have the advantage of being simpler to use than the average visibility.

At present, the viewing angle problem is actually fairly intractable. Lack of data is a major problem. Viewing angle, age, and the type of task interact in their effects on performance. In addition, there may be feedback between visibility and viewing angle. Thus, these parameters should be measured as functions of each other.

This type of cross tabulation is simply not available. Simply averaging each of the factors independently yields an average value with an unknown bias. Furthermore, without more information on different conditions it is not obvious how suitable this single average is for different work situations.

The data on viewing angles have internal problems as well. Crouch and Buttolph only looked at 5 subjects, a statistically insignificant sample. The data of Allphin and that of Crouch and Kaufman appear flawed in that the subjects were aware of the photographer. All of the samples appear flawed in that they seem to be samples of "convenience" rather than randomly chosen. The use of a sample of convenience[59] introduces an uncertainty of unknown magnitude into the results.

The lack of good data on viewing angles may also be affecting evaluations of lighting systems indirectly through its effect on experimental accuracy. Here the major problem is that the viewing angle is generally not measured so there is no way of knowing whether test situations have different viewing conditions than would be present in a normal work situation.

The sum of the above considerations is that the lack of information on viewing angles introduces substantial uncertainty in evaluations of the merits of different lighting systems. A comparison of any two systems gives unambiguous results only when one system is uniformly better over all viewing angles than the other system. In general, if a polarizing system provides better contrast than a standard prismatic or diffusing panel system at 25^{o} then it will be better at higher angles as well. However, this type of comparison cannot be generalized to high efficiency prismatic or batwing panel systems, as these systems also appear[12] to get relatively better than standard prismatic systems at higher angles.

APPENDIX B: SAMPLE COMPARATIVE ESI AND FOOTCANDLE DATA FOR PRISMATIC VERSUS POLARIZING PANELS

The Lighting Research Laboratory cost-benefit summary for the World Trade Center project[21] provides extensive ESI and footcandle calculations for a standard prismatic lighting system and a high efficiency polarizing system. Although each room and lighting system studied produces a different comparison, a review of an example is useful in showing trends and in developing a qualitative intuition of the effects of polarizing systems. Note that this comparison uses the present IES method based on flux contrasts of computing ESI. The point contrast method[28] may give the polarizing panel a substantial advantage over the prismatic panel used for comparison in this study.

There are two sets of calculations in the Lighting Research Laboratory cost-benefit summary. An analysis of the calculations for the private office area is presented here, as it was easier to perform than the analysis for the general area. Raw footcandle and ESI foot candle comparisons[60] are presented in Tables B.1 and B.2, respectively. It is essential to note that this comparison is for a fixture with a standard prismatic panel and <u>3</u> lamps versus the same fixture with a polarizing panel and <u>2</u> lamps. Thus, as expected, column 1 of Table B.1 shows that the light levels in the polarized system are lower than those in the standard system. Column 2 of Table B.1 shows that the variability in light levels (as measured by the percentage variation, 100 times the standard deviation over the mean x) remains very low in the delamped system.

Table B.1 Fixture footcandle comparison: Two lamps and polarizing panel versus three lamps and prismatic panel.

System	Mean footcandle (x)	% Variation ($100\ \sigma/\bar{x}$)
Prismatic lens	110 fc	16%
Polarizing panel	72 fc	13%
Ratio: Pol./non-pol.	66%	80%

Table B.2 Eixture ESI footcandle comparison: Two lamps and polarizing panel versus three lamps and prismatic panel.

System	Mean ESI level ($\bar{y}$)	% Variation	$\bar{y} - \sigma$	$\bar{y} + \sigma$
Prismatic lens	45 ESI	45%	25 ESI	66 ESI
Polarizing panel	38 ESI	30%	26.5 ESI	49 ESI
Ratio: Pol/non-pol	84%	67%	106%	75%

Column 1 of Table B.2 shows that the mean ESI footcandle level also drops, but not as much as the raw footcandle level. Column 2 shows that the variability of ESI levels for both systems is substantially greater than their footcandle variability. The polarizing panel has a more uniform distribution than the standard panel. The implications of this difference in variablity are displayed in Columns 3 and 4, which list the footcandle level one standard deviation below and above the mean, respectively. Only about 1/6 of the locations in the room will have an ESI level about or below one standard deviation from the mean.

If average ESI levels are fairly high, it may be more important to maintain a minimum ESI level over a major fraction of the area than it is to maintain a high average. This is essentially the logic used in the interim recommendations for buildings whose task location is unknown.[16] As can be seen from Column 3 of Table B.2, the two-lamp polarizing panel system suffers no loss of performance under this criterion relative to the more energy-intensive three-lamp prismatic panel system. Conversely, if work locations are known beforehand, it may be possible to design the system to utilize the high ESI locations in the room.

The comparison given in Tables B.1 and B.2 is between a fixture delamped to two lamps and utilizing a high efficiency polarizing panel versus the same fixture with three lamps and a standard (not high efficiency) prismatic panel. High efficiency panels are not strictly comparable to standard panels because the lamp image is more visible through the panel. This may be an aesthetic consideration in some designs. Furthermore, a two-lamp fixture is generally more efficient than a three-lamp fixture because of added optical losses due to the third lamp and added heat build-up. To examine just the effect of the polarization, an estimate has to be made of the size of these two effects. Tables B.3 and B.4 give the estimated comparison between a standard prismatic panel and a standard polarizing panel in the same three-lamp fixture in the small office.

The mean footcandle levels in Table B.3 are consistent with the earlier statement that polarizing panels are generally less efficient than prismatic panels in terms of raw footcandles. In terms of ESI footcandles, Column 1 of Table B.4 shows the polarizing panel to be more efficient that the prismatic panel. Column 2 again shows that the ESI levels for this lighting system are more uniform with the polarizing panels. Column 3 shows that the polarizing panels are substantially more efficient at maintaining a minimum footcandle level over a major fraction of the room area than are the prismatic panels. Column 4 shows that polarizing panels offers little advantage if work locations are to be placed in the optimum locations (and orientation) in the room. (They do offer a larger margin of safety in case of error.)

As stated earlier, a different lighting installation would produce a different comparison. The private office area considered is moderately small (room cavity ratio approximately 5); a larger space generally produces a comparison more favorable to the polarizing panels. The walls and ceiling area of the office considered were very lightly colored; a darker area would have produced a less favorable comparison for the polarizing panel examined. A different layout of the fixtures would also affect the comparison. These tables are presented as qualitative guides only.

Table B.3 Footcandle comparison: Standard prismatic versus polarizing panels in a three-lamp fixutre in a private office.

System	Mean footcandle level (x)	% Variation (100/x)
Prismatic lens	110 fc	16%
Polarizing panel	97 fc	13%
Ratio: Pol/prismatic	89%	80%

Table B.4. ESI footcandle comparison: Standard prismatic versus polarizing panel in a three-lamp fixture in a private office.

System	Mean ESI Level	(100σ/y)	$\bar{y}-\sigma$	$\bar{y}+\sigma$
Prismatic Lens	45 ESI	45%	25	66
Polarizing Panel[1]	50 ESI	32%	34	66
Ratio: Pol/Prismatic	111%	70%	137%	101%

1 Estimated values. The footcandle estimates were calculated from Jones' values by applying a -7% correction factor for the addition of a third lamp and a -4% correction factor for the use of a standard polarizing panel (type "P") in place of the high efficiency panel (type "E"). ESI values were calculated from the new footcandle levels by assuming a fixed contrast rendition factor.

APPENDIX C. QUANTITATIVE RELATIONSHIPS BETWEEN VERTICAL POLARIZATION AND THE ORIENTATION OF THE VIEWING SURFACE FOR TWO TYPES OF POLARIZERS

Consider a coordinate system (θ,ϕ) where θ is the angle from vertical (altitude) and is the azimuthal angle. For a linear polarizing panel the azimuthal angle of the polarization vector is fixed by the axis of the polarizing panel which we can arbitrarily set at $\phi_p = 0^o$. An arbitrarily chosen light ray has an orientation (θ_o,ϕ_o). The polarization vector is always normal to the direction of the light ray. It is also normal to the vector in the plane of the linear polarizing panel that is orthogonal to the polarizing axis $(\theta=90^o, \phi=90^o)$. Therefore, we can use the cross product of this vector and the vector along the light ray to determine the orientation of the polarization vector. In cartesian coordinates (i,j,k) the cross product is:

$$\vec{p}_1 = (0,0,1) \times (\cos\theta_o, \sin\theta_o\cos\phi_o, \sin\theta_o\sin\phi_o) \qquad (C.1)$$

$$\hat{p}_1 = N_1\ (-\sin\theta_o\cos\phi_o, \cos\theta_o, 0) \qquad (C.2)$$

N_1 is a function of θ_o, and ϕ_o which normalizes $\vec{p}_1$ to the unit length vector $\hat{p}_1$. We now need to determine under what conditions $\hat{p}_1$ is vertically or horizontally polarized with respect to a task. The plane containing the incident and reflected light rays also contains the normal to the reflecting surface (θ_s,ϕ_s). The light ray is horizontally polarized with respect to the surface if its polarization vector is orthogonal to the normal. Since the horizontal polarization vector $\hat{p}_h$ is orthogonal to both (θ_o,ϕ_o) and (θ_s,ϕ_s) we can use their cross product to determine its orientation. Again, in cartesian coordinates:

$$\vec{p}_h = (\cos\theta_o, \sin\theta_o\cos\phi_o \sin\theta_o\sin\phi_o) \text{ X } (\cos\theta_s, \sin\phi_s\cos\theta_s, \sin\theta_s\sin\phi_s) \quad (C.3)$$

$$\hat{P}_h = N_h \begin{Bmatrix} \sin\theta_o\sin\theta_s\sin(\phi_s - \phi_o), \\ \sin\theta_o\cos\theta_s\sin\phi_o - \cos\theta_o\sin\theta_s\sin\phi_s, \\ \cos\theta_o\sin\theta_s\cos\phi_s - \sin\theta_o\cos\theta_s\cos\phi_o \end{Bmatrix} \quad (C.4)$$

The extent to which linear polarized light is horizontally polarized relative to a given surface now can be determined by taking the inner or dot product of the two polarization vectors:

$$\text{Fraction horizontally polarized} = F_{hl} = \hat{P}_l \cdot \hat{P}_h \quad (C.5)$$

$$F_{hl} = N_l N_h \begin{Bmatrix} \sin\theta_s\sin^2\theta_o\cos^2\phi_o\sin(\phi_o - \phi_s) \\ + \cos\theta_s\cos\theta_o\sin\theta_o\sin\phi_o \\ - \sin\theta_s\cos^2\theta_o\cos\phi_o \end{Bmatrix} \quad (C.6)$$

For the special (but important) case of a horizontal surface, $\theta_s = 0^o$, which leaves only the second term in the expansion for F_{hl},

$$F_{hl}(\theta_s = 0^o) = N_l N_h \cos\theta_o \sin\theta_o \sin\phi_o \qquad (C.7)$$

This expression goes to zero (vertical polarized light only) for $\phi_o = 0^o$ and 180^o. It goes to 1 (including the evaluation of N_l and N_h) indicating that the polarization is completely horizontal with respect to the surface for $\phi_o = 90^o$ and 270^o. This confirms the statement in the text that a linear polarizer only gives vertical polarized light along a preferred axis.

The situation is substantially different, and better, for a multilayer polarizer. The normal to the polarizing panel is at $\theta = 0^o$. Light striking the polarizing panel is split into vertical and horizontally polarized components with respect to the panel. The horizontal component is weaker because more of it is reflected back into the fixture where it is depolarized and reflected back to the panel. The horizontal polarization component is orthogonal to both the incident ray (θ_o, ϕ_o) and the normal to the panel so $\theta_H = 90^o$ and $\phi_H = \phi_o + 90^o$ or $\phi_o + 270^o$. The vertical or "radial" component is normal to the incident ray and the horizontal component so $\theta_R = \theta_o + 90^o$ or $\theta_o + 270^o$ and $\theta_R = \phi_o + 0^o$ or $\phi_o + 180^o$.

We will continue to call this the radial component in order to avoid confusion when evaluating the extent to which it is horizontally or vertically polarized with respect to an arbitrary surface.

The radial polarization vector $\hat{p}_R$ in cartesian coordinates is:

$$\hat{P}_R = (\cos(\theta_o+90^o),\ \sin(\theta_o+90^o)\cos\phi_o,\ \sin(\theta_o+90^o)\sin\phi_o) \quad (C.8)$$

$$\hat{P}_R = (-\sin\theta_o, \cos\theta_o\cos\phi_o, \cos\theta_o\sin\phi_o) \quad (C.9)$$

N_R is equal to 1 and is therefore suppressed in these equations. We can now evaluate the inner product F_{hR} of $\hat{P}_R$ and $\hat{P}_h$ to determine the extent to which the radial polarized light is horizontally polarized with respect to an arbitrary surface.

$$F_{hR} = \hat{P}_R \cdot \hat{P}_h \quad (C.10)$$

$$F_{hR} = N_h \left\{ \begin{array}{l} \sin^2\theta_o \sin\theta_s \sin(\phi_o - \phi_s) \\ + \cos\theta_o \sin\theta_o \cos\phi_o \sin\phi_o \cos\theta_s \\ - \cos\theta_o \sin\theta_o \cos\phi_o \sin\phi_s \\ + \cos^2\theta_o \sin\theta_s \sin\phi_o \cos\phi_s \\ - \cos\theta_o \sin\theta_o \cos\phi_o \sin\phi_o \cos\theta_s \end{array} \right\} \quad (C.11)$$

Lines 2 and 5 cancel and the rest simplifies to:

$$F_{hr} = N_h \sin\theta_s \sin(\phi_o - \phi_s) \qquad (C.12)$$

Equation (C.12) shows that there are surface orientations where the radially polarized light is horizontally polarized. However, note that for $\theta_s = 0^o$, all horizontal surfaces, and for $\phi_o = \phi_s$, the specular angle for head-on viewing of a tilted surface, the radial polarization is vertically polarized with respect to the surface. These are the most common viewing conditions for office tasks. In addition, for most other reasonable viewing conditions in an office or commercial environment, the degree of horizontal polarization from the radial component should remain very small.

APPENDIX D: ESI AND PRODUCTIVITY

Define the general productivity function as $P(X_0, X_1,...X_n)$, where the X_i includes such things as the nature of the task, the method used to do it, the motivation to do it, and the ability to do it. Since we expect that the visibility (V) of the task will affect the ability of the worker to do it, we can explicitly list it as one of the variables. In fact we can to one step further by noting that visibility is a function of task equivalent contrast (TC) and ESI (E).

The simplest model that we can make is to assume that $P_1(E, X_1...X_n) = F_1(E)F_2(X_2,...X_n)$, that is, the dependence $P(E, X_1,...X_n)$ on E is totally separable from the dependence of P( ) upon the other variables. The derivative $dP_1/dE = (P_1')$ now becomes:

$$dP_1/dE = (dF_1(E)/dE) \times F_2(X_1...X_n)$$

(D.1)

If P_{1ab}' is the value of dP_1/dE measured in a laboratory then it differs from P_{real}' by a factor $F_2(X_1...X_n)_{real}/F_2(X_1,...X_n)_{lab}$. However, fractional changes in performance can be measured exactly since for two levels of ESI, E_1 and E_2,

$$P_1(E_1, X_1,\ldots X_n)/P_1(E_2, X_1,\ldots X_n) = F_1(E_1)/F_1(E_2) \qquad (D.2)$$

with the factor for the non-visual component cancelling out.

In fact this model is too simple. Laboratory studies and analysis by Smith and by Blackwell[35,61,62] have shown that fractional changes in visual performance don't translate into fractional changes in total performance. A functional form which does not have this problem and which has the proper asymptotic form for dilution effects[63] is:

$$P_2(E,X_1,\ldots X_n) = (G_1(E) + G_2(X_1,\ldots X_n))^{-1} \qquad (D.3)$$

If $G_1 \geq 0$ and $G_2 > 0$ then $P_2 > 0$ as it must be to make sense.

Laboratory studies of performance have been designed to minimize the non-visual portion of the task so that the visual portion can be examined accurately. From Eq. (D.1) we see that P_2 ( ) is maximized as $G_2(X_1,\ldots\ldots X_n)\rightarrow 0$. Since the derivative of P_2 is

$$\frac{dP_2}{dE} = -G_1'(E)P_2^2 \qquad (D.4)$$

mimimizing G_2 maximizes dP_2/dE. When dealing with P_1, we found that the non-visual aspects of the work cancelled out when we considered relative changes in production dP/P. This is not true for P_2,

$$P_2'/P_2 = -G_1'(E)P_2 \qquad (D.5)$$

(The primes indicate differentiation with respect to E.) To determine how P_2 changes in the real world it is necessary to have a value of $P_2(E,(X_1,\ldots X_n)_{real})$ in addition to the laboratory measurements of P_2.

One way to examine this model is to consider that the non-visual portions of the task $G_2(X_1,\ldots X_n)$ "dilute" the visual portion of the task. Since the laboratory measurement is for $G_2(X_1,\ldots X_n)\to 0$, real world tasks will have lower performances and will be less sensitive to changes in $E(P_{lab}'/P_{lab}>P_{real}'/P_{real})$ since $P_{real}<P_{lab}$, and $G_1' < 0$. When productivity over cost, C, is optimized, where C is dependent on ESI, E, the optimal point will depend upon the non-visual portion of the task.

$$\frac{d\,(P_2/C)}{dE} = \frac{[-G_1'(E)C(E)-C'(E)(G_1(E)+G_2(X_1\ldots X_n))]\,P_2^2(E,X_1\ldots X_n)}{(C(E))^2} \qquad (D.6)$$

Thus, in this model "dilution" for real tasks decreases the importance of visibility $(P_{real}'/P_{real}<P_{lab}'/P_{lab})$ and lowers the optimal value of E (assuming that $C'(E)>0$). The basic idea of maximizing P_2/C with respect to E is, however, unmodified.

Laboratory data appear to fit this second model quite well. However, laboratory studies cover a different domain of the $(X_1,\ldots X_n)$ than common work situations. Two assumptions are made when extending P_{lab} to P_{real}. One is that P has the same functional form over the domain $(X_1,\ldots X_n)_{real}$ as it does over the domain $(X_1,\ldots X_n)_{lab}$. The second is that the E and the X_i are independent, that is, $dX_1/dE = 0$ for all X_i.

The "Humanistic" school of George Mayo[64] proposed that productivity is strongly affected by motivation (M) and social factors (S). For a restricted domain of E and X, not including M and S, the productivity function may reduce to $P_3(M,S)$. Thus, small changes in E may have no effect on P unless E affects M or S, (M/ E 0). An example of this type of productivity function is where there is a contractual agreement between management and labor as to what constitutes a fair day's work.[33] Changing the number of ESI footcandles will not affect the output in this situation unless a new contract is agreed upon. A major change in the production technique or lighting or management practice will call for a new contract and will lead to a new productivity function (possibily $P_4(M,S)$).

Another factor which can affect the productivity function is the availability of work. Before a theoretical improvement in the productivity function can be translated into a real improvement there has to be extra work available, or the potential of laying off employees. If, instead, the available work (AW) is well within the capacity of the employee, then the real productivity function simplifies to P = AW. Office, clerical, reception, and sales clerk type jobs may fit this pattern. These types of jobs have variable load patterns. Enough employees have to be hired to handle the normal peak load. In this situation an increase in P_{1ab} is important if it translates into an improvement in the ability to handle peak loads, or if it reduces the number of required employees. If some of the load can be shifted to non-peak periods, i.e., postponement of non-critical work, the improvement in P_{lab} are less likely to be important. During the non-peak periods, improvements in P_{lab} affect only the load factor P(actual)/P(potential). This will cause no change in total productivity unless it affects the ability to handle peak loads (e.g., through morale), or causes excessive employee dissatisfaction with resultant increased turnover rate and reduced general productivity.

The effect of polarizing panels upon both ESI and footcandles is a practical example of how ESI may be correlated with other variables. When a variable which affects productivity is also related to ESI, the change in productivity with respect to ESI is given by:

$$dP/dE = (\partial P/\partial E)_{X_i} + (\alpha P/\alpha X_j)_{E,X_i \neq X_j}(\alpha X_j/\alpha E)_{X_i \neq X_j} \qquad (D.7)$$

In laboratory studies, footcandles have been replaced by ESI as a guide to visual performance. However, "raw" footcandles do seem related to people's feelings of satisfaction and perceptions of spaces.[65] If Mayo[64] is at all right about motivation being a major factor in productivity, raw footcandles may well be correlated to productivity in real situations. Experiments such as the GE keypunch experiment[44] which show startlingly large changes in productivity as light levels are changed (a sample calculation based on estimated visibility levels with pencil tasks predicts a 6 percent change[66] in productivity for this experiment as compared to the 12 percent change measured) may be explained by this effect.

Some of this effect may be transitory. Furthermore, the sign and magnitute of $(\partial M/\partial L)X_n$ probably varies widely (where L is the footcandle level), and may even be a learned response. Certainly many people know that "poor" (low level) lighting is bad. High light levels in offices may then be considered an amenity, and reduction of light levels resisted. Residential light levels, however, tend to be much lower than office light levels. A population that is convinced that fluorescent lighting is "unhealthy" or unpleasant will want as little of it as possible.

Lighting level, wall luminances (vertical footcandles), and perhaps lighting in daylighting applications are the most likely factors which may be correlated with both ESI and motivation. Without quantitative data on the effects of these variables the easiest approach is probably optimization of ESI subject to the constraint that these factors fit "good lighting practice."

Those models in which $P_{lab} \neq P_{real}$ cover situations where the theoretical estimate of performance (P_{lab}) is greater than the level actually achieved (P_{real}). In situations where real performance approaches theoretical values, i.e., for self-motivated or highly motivated individuals, the function P_{real} should be approximated by P_{lab} and the value of the lighting can be estimated. The more diluted the visual performance, the more likely that P_{lab} deviates for P_{real}. The existence of a myriad of different situations simply means that ESI should not be used as a standard blindly. Each situation should be evaluated on its own merits.

NOTES AND REFERENCES

1. Cobb, Percy W. and Moss, Frank K. 1928. Four Fundamental Factors in Vision. Trans. Illum. Eng. Soc. 23: 496-504.

2. Cobb, Percy W. and Moss, Frank K. 1928. Glare and the Four Fundamental Factors in Vision. Trans. Illum. Eng. Soc. 23: 1104-1120.

3. Holladay, L. L. 1926. The Fundamentals of Glare and Visibility. J. Opt. Am. and Rev. Sci. Instr. 12: 271-319.

4. Holladay, L. L. 1927. Action of a Light Source in the Field of View in Lowering Visibility. J. Opt. Soc. Am. and Rev. Sci. Instr. 14: 1-15.

5. Blackwell, H. R. 1946. Contrast Thresholds of the Human Eye. J. Opt. Soc. Am.

6. The modulation transfer function used in most of the optometry literature (for a good description of this function, see the basic text, Visual Perception, Cornsweet, T. N., Academic Press) converges into the illuminating engineer's definition of contrast if the task is a negligible part of the total visual field.

7. Blackwell, H. Richard 1959. Specification of Interior Illumination Levels. Illum. Eng. 58: 163-216.

8. Blackwell, H. Richard 1963. A General Quantitative Method for Evaluating the Visual Significance of Reflected Glare Utilizing Visual Performance Data. Illum. Eng. 48: 163-216.

9. Blackwell, H. Richard 1963. A Recommended Engineering Application of the Method for Evaluating the Visual Significance of Reflected Glare. Illum. Eng. 58: 217-235.

10. Crouch, C. L., and Kaufman, J. E. 1963. Practical Application of Polarization and Light Control for Reduction of Reflected Glare. Illum. Eng. 58: 277-283.

11. R. Q. Q. Report #4 1970. A Method Evaluating the Visual Effectiveness of Lighting Systems. Illum. Eng. 65: 504.

12. Blackwell, H. Richard; Helms, Ronald H.; and DiLaura, David L. 1973. Application Procedures for Evaluation in Terms of ESI: Numbers I-IV. Illum. Eng. 2: 230-328.

13. R. Q. Q. Report #5. 1973. The Predetermination of Contrast Rendition Factors for the Calculation of Equivalent Sphere Illumination. Illum. Eng. 2: 157.

14. The R. Q. Q. #5 Report lists the reflectance on the standard pencil task (ref. 13). Reflectance data for other tasks have since been measured, but evidently not published. Nevertheless, there is at least one ESI analysis using non-pencil tasks. See: Lewis, Ian 1976. An ESI Study for Different Tasks. Illum. Eng. 6: 44-51.

15. DiLaura, David L. 1975. On the Computation of Equivalent Sphere Illumination. Illum. Eng. 4: 129-149.

16. Design Practice Committee of the IES. 1977. Recommended Practice for the Specification of an ESI Rating in Interior Spaces when Specific Task Locations Are Unknown. Illum. Eng. 6: 111-123.

17. Personal communication with GE sales engineers, with confirmation through conversations with lamp and fixture sales personnel.

18. Christianson, J. F. and Kaufman, J. E. 1972. IES Lighting Handbook. 5th ed. New York: Illuminating Engineering Society of North America.

19. Marks, Alvin M. 1959. Multilayer Polarizers and Their Application to General Polarized Lighting. Ill. Eng. 54: 123-135.

20. Jones had done consulting work for Polarized using standard IES computer programs to compare existing installations against possible "Polarized" replacements. See, for example, his reports #975-3, #375-3, #777-1DR, and #577-1. These reports are available from Polarized Corporation of American, 8921 Quartz Avenue, Northridge, California 91324.

21. Report #577-1 of reference 20.

22. See almost any basic text on optics, for instance: Jenkins and White 1950. Fundamentals of Optics. McGraw-Hill.

23. Strong, J. 1958. Concepts of Classical Optics. Freeman, W. H. and Company. See p. 115.

24. Beckmann, P., and Spizzichino, A. 1963. The Scattering of Electromagnetic Waves from Rough Surfaces. Pergamon Press, Inc., New York.

25. The tabulated values are actually "equivalent flux" contrast values, and are considerably lower than would be measured by using just a photographer's spot photometer. Real contrast measurements are hard to define unambiguously because of the prevalence of edge effects and other non-uniformities in the task and background. The equivalent flux contrast measurement averages these non-uniformities in the task, and in part of the background. Thus, though it can be precisely defined, it is lower than standard contrast measurements.

26. Based on preliminary analysis of the variance in the data for $\theta = 0^{o}$ and with ϕ for vertically polarized light equal to $\phi + 90^{o}$ for horizontally polarized light.

27. Note that Marks' model totally fails to capture even the qualitative features of the data other than the peak of luminance at the specular angle. The rough surface model catches the reversal in relative illuminances for side lighting, but fails to catch the higher contrast of horizontally polarized light from back lighting. This provides emphasis to the point that the effect of polarization cannot be determined solely from existing theory, it has to be measured for the task interest.

28. Blackwell, H. Richard 1978. Discovery of Substantial Error in Current ESI Values for Lighting Installations Involving Polarized Light. Lighting Design and Appl. 8 (5); 44-47.

29. The coefficient of utilization is a ratio of actual footcandles delivered to a task to the rated output of the lamps in the fixture, divided by room area. (See reference 18 for more detail.)

30. Although the published literature does not directly list coefficients of utilization it does give comparisons of footcandle levels. See, for example, Blackwell, H. Richard 1962. Dr. Blackwell Explains Glare Research. Lighting 78: 21-33. See also reference 12.

31. Bill Jones, head of Lighting Research Laboratory, has computed coefficients of utilization of "Polarized" and standard panels. Polarized Corporation published his results in "A Guide to Effective Task Lighting for Improved Visual Effectiveness and Maximum Energy Utilization."

32. Based on published specifications of "Polarized" panels.

33. Schleicher, F. 1977. Volvo--New Directions in Work Systems and Technology. Machine and Tool Blue Book 72 (10): 74-85.

34. A footcandle check in a sample of restaurants in Berkeley gave footcandle readings from .02 to 4 in the dining areas.

35. Publication CIE #19/2. Preliminary 8th draft 1980. An Analytic Model for Describing the Influence of Lighting Parameters upon Visual Performance. Technical Committee Report of the Commission International Eclairage.

36. Crouch, C. L. 1975. Philosophy of Determining Illumination Levels for Various Tasks in Commerce and Industry. In Proceedings of the Symposium on the Basis for Effective Management of Lighting, October 29 and 30, 1975, Federal Energy Administration, Donald K. Ross. Ross and Baruzzini, Inc. 7912 Bonhomme Avenue, St. Louis, Missouri, 63105.

37. Hughes, P. C. and McNelis, J. F. 1978. Lighting, Productivity and the Work Environment. Lighting Design and App. 8 (12): 32-40.

38. For an extreme example of dilution, compare the IES standard for emergency lighting for offices (2 fc) with the 0.03 fc recommended in the following study of emergency lighting: Simmons, R. L. 1975. Illuminance Diversity and Disability Glare in Emergency Lighting. Light Res. Technol. 7 (2) 125.

39. Blackwell, H. R. 1975. Energy Conservation by Selective Lighting Standards Graded in Terms of Task and Observer Characteristics. In Symposium Proceedings, see reference 36.

40. Blackwell, Mortenson O. and Blackwell, H. Richard 1971. Visual Performance Data for 156 Normal Observers of Various Ages. Illum. Eng. 1:3.

41. Guth, Sylvester K., and McNelis, John K. 1969. Visual Performances--Subjective Differences. Illum. Eng. 64: 723.

42. Blackwell, H. Richard 1976. Analysis of Individual Differences in Visual Performance to be Expected with the Current IES Method for Prescribing Illumination. Illum. Eng. 6:3.

43. There are, however, numerous studies which examine lighting versus productivity. These experiments do not separate out the effect of visibility. See references 44 and 45 for two studies which claim to show higher productivity with more light and references 46 and 47 for two studies showing no effect.

44. See Studies Show Lighting Affects Productivity. Electrical World 183 (12).

45. See Lighting Improvement Pays for Itself in Productivity Gains: A Case Study. Illuminating Engineering 64: 646.

46. Stein, Richard G. Necessary Lighting as a Part of the Total Building Design. In Symposium Proceedings, see reference 36.

47. The "classic" lighting and productivity experiment is the Hawthorne experiment. This experiment is discussed in many management texts. See, for example, Dale, Ernest 1975. Readings in Management: Landmarks and New Frontiers. McGraw-Hill.

48. Ross and Baruzzini 1975. Energy Conservation Applied to Office Lighting. Federal Energy Administration Contract No. 14-01-0001-1845.

49. This is a typical value for a modern office building. See reference 48.

50. Florence, Noel 1979. The Energy Effectiveness of Task Oriented Lighting Systems. Lighting Design and Appl. 9 (1): 25.

51. Kusuda, T.; Hill, J. E.; Lin, S. T.; Barnett, J. P.; and Bean, J. W. 1975. Pre-design Analysis of Energy Conservation Options for a Multi-Story Demonstration Office Building. NBS Building Science Series 78, November 1975.

52. The only English study of non-uniform lighting that includes the effect of a surround darker than the background seems to be a 1932 study by Lythgoe. See Lythgoe, R. J. 1932. X. The Measurement of Visual Acuity, Medical Research Council, Special Report Series #173, published by His Majesty's Stationary Office, London.

53. See the articles by Robert D. Reiniche, Alan L. Lewis, Robert M. Boynton, Gary T. Yonemura, and Richard G. Stein. In Symposium Proceedings, see reference 36.

54. Sekera, Zdeneh, Polarization of Skylight. Handbuch des Physik, Band ILVIII, Geophysik II.

55. Goodbar, Isaac; Buttolph, L. J.; Breneman, E. J.; and Crouch, C. L. 1974. Applying Veiling Reflection Factors to Practical Field Use and Measurement. Lighting Design and Appl. 4 (5): 45-53.

56. Allphin, W. 1963. Sight Lines to Desk Tasks in School and Offices. Illum. Eng. 38: 244-246.

57. Personal communication with Bill Jones, Lighting Research Laboratory, P. O. Box 6193, Orange, California, 92607.

58. Crouch, C. L., and Buttolph, L. J. 1973. Visual Relationships in Office Tasks. Lighting Design and Appl. 3 (5): 23.

59. Freedman, David; Pisani, Robert; and Purves, Roger 1978. Statistics. W. W. Norton and Co., New York.

60. Both of these values are higher than would be expected from the coefficient of utilization for these panels because the sampling procedure does not include any points at the walls of the room.

61. Blackwell, H. R. 1975. Energy Conservation by Selective Lighting Standards Graded in Terms of Task and Observer Characteristics. In Symposium Proceedings, see reference 36.

62. Smith, Stanley W. 1975. Summary of Our Research on Task Performance as a Function of Illumination Level. In Symposium Proceedings, see reference 36.

63. This function gives similar results to the fits used by Blackwell in Publication CIE 19. 1972. A Unified Framework to Evaluating Visual Performance Aspects of Lighting. Technical Committee Report of the Commission International Eclairage. The difference is that function used by Blackwell does not have the proper asymptotic behavior.

64. See, for example, Delaney, W. B.,; Hughes, P. C.; McNelis, J. F.; Sarver, J. F.; and Soules, T. F. 1978. An Examination of Visual Clarity with High Color Rendering Fluorescent Light Sources. Illum. Eng. Soc. 8: 74-84. Or see Tregenza, P. R.; Romaya, S. M.; Dawe, S. P.; Heap, L. J.; and Tuch, B. 1974. Consistency and Variation in Preferences for Office Lighting. Light Res. Technol. 6: 205-211.

65. Mayo performed the analysis of the Hawthorne experiment. See note 47.

66. This is a rough calculation from the material in reference 61.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720