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Multilayer Polarizers: A Review of the Claims

Robert Clear

Building Technologies Program
Energy and Environment Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
1 Cyclotron Road
Berkeley, California 94720

Richard G. Mistrick

Department of Architectural Engineering
Pennsylvania State University
104 Engineering A
University Park, PA 16802

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Robert Clear[1] and Richard G. Mistrick

Abstract

Multi-layer polarizing panels are a technology that has been proposed for improving lighting quality in interior environments. Different authors have examined a variety of different conditions, have used different performance models in their evaluation of the potential of this technology, and have come to markedly different conclusions. This paper discusses how variations in conditions and performance models affect the evaluation of the performance potential of polarized lighting systems. The importance of the light source-task-eye geometry, which determines the benefit that can be achieved with polarizing luminaires, is discussed in detail.

Introduction

Recent papers on polarized lighting from researchers at Rensselaer Polytechnic Institute's Lighting Research Center have come to substantially different conclusions than those that were reported a number of years ago by Blackwell and others. Boyce and Rea state "Overall, this study offers little support for the notion that ... polarized lighting has a major effect on visual performance and user preference".[1] Rensselaer's Lighting Answers report (A National Lighting Product Information Program publication) is even more dismissive: "Therefore, NLPIP does not consider multilayer polarizer panels to be energy-saving devices".[2] Compare this to Blackwell's statement that "The multilayer polarizing panel always produces a contrast improvement compared with normal non-polarizing panels", and John Belcher's recent endorsement: "Polarizing lenses are cost-effective.".[3,4]

We reviewed some of the original papers to determine why there is such wide divergence of opinion about polarized light. In this paper we examine the properties of polarized light, and describe the conditions of the experiments that appear to have led to such different findings. We will also show the results of computations comparing performance from polarized and unpolarized panels. The information should be useful to anyone interested in using polarizing panels.

Background

The Argument Summarized

Reflectivity depends in part on the polarization of the incident light. The claim made for multilayer polarizers is that polarization will enhance the contrast between the reflectivity of a task and its background, and thus improve its visibility. However, the visibility of a task also depends upon background luminance. Fixtures equipped with multilayer polarizing panels have lower optical efficiencies than those equipped with standard patterned lenses, against which they are often compared. The critics of polarizers have argued that major contrast improvements only occur in special cases, and that usually there is no significant difference in the visibility of tasks

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[1] Ernest Orlando Lawrence Berkeley National Laboratory, (510) 486-4094.

1) The polarization efficiency of the panel:
The multilayer polarizer is not like an absorption polarizer which can be designed to give 100% polarization efficiency. The polarization efficiency of a multilayer polarizer depends upon the angle of the light and the construction of the polarizer. Early studies examined a number of different multilayer polarizers, while more recent studies have used commercially available panels.

2) The optical efficiency of the luminaire:
A multilayer polarizer generally reflects more light than a standard lens. This makes the optical efficiency of the fixture much more sensitive to the reflectances of the other surfaces inside the fixture. The optical efficiency of fixtures with clean specular reflectors will be much less affected by the addition of a polarizing panel than a fixture with a degraded enamel surface.

3) Candlepower distribution of the fixture:
The directional reflectance of materials depends on the angle of incidence and reflectance. Changing the candlepower distribution of the fixture changes the relative amount of light incident on a task from different angles, and thus can change the contrast. The candlepower distributions of polarizing and non-polarizing fixtures are generally quite different, so most studies actually examined the combined effect of both polarization and candlepower distribution changes.

4) Layout of fixtures, and location and orientation of tasks:
For the reason noted above, changes in geometry may affect contrast. Any given study will usually use a fixed geometry for both the polarized and non-polarized fixtures, but different studies are unlikely to use the same geometry.

5) Task tilt:
This is again an issue involving geometry. It is listed separately because changes in ceiling fixture location, or task location and orientation, generally only involve changes in a horizontal plane. Tilting the task out of the horizontal plane has a qualitatively different effect on reflectance as compared to changes within the plane. Tilting the task strongly limits the view angles from which polarization can be expected to be useful.[5]

6) Type of task:
Tasks differ in their specularity and roughness. Relatively smooth specular tasks are prone to veiling glare from sources near the mirror angle, while more matte tasks show little veiling glare. Relatively rough specular tasks will have a wider veiling glare zone than smooth tasks. Polarization improves contrast by reducing the veiling glare, so the magnitude of any effect in a study will depend upon the task(s) studied. It is also possible for the dark and light areas of a task to have different directional reflectance characteristics, with one being more specular than the other.

7) Method of evaluating visibility:
Since polarization affects both luminance and contrast, visibility has to be evaluated either directly by measurement, or by means of a model that includes the effects of both factors.

Blackwell's evaluations were based on his threshold contrast sensitivity function; either directly or by extension via a computation of Equivalent Spherical Illumination (ESI). Boyce and Rea directly measured acuities, and reaction times. Boyce and Rea measured the combined effect of both polarization and full spectrum lighting, which introduces a further complexity in interpreting their results with respect to polarization alone. Rensselaer evaluated polarization potential in terms of Rea's relative visual performance (RVP) model. The different models, and measurements, can lead to very different perceptions of the benefit of polarized lighting.

Polarized Light

Light consists of electromagnetic waves which vibrate in a direction perpendicular to the direction in which the light waves propagate. In unpolarized light, these waves vibrate in all possible directions in essentially equal quantities. When a collection of light rays is 100% linear (plane) polarized, all rays vibrate in the same direction (a polarization vector in a fixed direction traces out a plane as the light ray moves through space so the terms linear and plane polarized are used interchangeably for this situation—see Figure 1). Partially polarized light occurs when more rays are polarized in one direction than another, with the result being a non-uniform distribution across all possible angles.

Polarization Efficiency

The reflectance and transmittance of light off a dielectric surface, such as glass, is described by Fresnel's equations, and depends upon the angle of incidence of the light, the dielectric constants of the material and its surroundings, and the plane of the polarization relative to the plane defined by the incident and reflected light rays. Light that is polarized in the plane of the incident and reflected rays is called parallel polarized, while light polarized perpendicular to this plane is not surprisingly called perpendicularly polarized (see Figure 2).

Figure 3 shows the reflectivity and transmissivity of one glass surface as a function of angle and polarization. Unpolarized light will become partially polarized upon transmittance (or reflectance) because of the difference in transmissivity (reflectance) of the two polarization orientations. Adding more surfaces makes this effect even larger. This is the principle of a multilayer polarizer.

Multilayer polarizers have been built with a variety of different materials, with different surface textures, and with different numbers of layers. Figure 4 shows the polarization efficiencies for some of the panels that were used in different studies of polarized lighting. The two panels labeled MP-F4 and MP-F14 cover the range of efficiencies of the almost twenty panels examined by Blackwell in his 1963 paper.[6] The curve labeled Blackwell73 is from one of Blackwell's 1973 studies, and appears as if it was a commercially available panel.[7] The curve labeled PCTechnologies is 1982 catalog data for a multilayer polarizer available at that time. The curve labeled NLPIP is from the Lighting Answers report from Rensselaer, and represents a measurement from a commercially available panel circa 1992.

The three commercially available panels are very similar, and produce very little polarization at 30° and below. The Lighting Answers report cites this as a reason why polarizers should have little effect on task visibility. The best of the Blackwell panels has three times the polarization efficiency of the commercially available panels, and even the lowest polarizing panels were about the same as the commercially available panel at the lower angles. Blackwell found much larger effects with the more highly polarizing panels.

Discussion

The Optical Efficiency of the Luminaire

Blackwell, unfortunately, did not report the optical efficiencies of the fixtures he studied. Catalog data from PCTechnologies and more recently from Sterling show a range from 51% (a 2 x 2 u-lamp luminaire) to 71% for a reflectorized 2 x 4 recessed luminaire.[8]

As noted earlier, polarized panels are expected to have a lower efficiency than standard prismatic panels. Dilaura and Jongewaard recently reported candlepower measurements on a standard enameled fixture with both a polarizing and a prismatic lens.[9] Their results show a 12% drop in efficiency for the polarizing panel versus the prismatic panel (57% versus 64.7%). NLPIP estimated a 7% to 8% drop in efficiency on the basis of field measurements. On the other hand, the PCTechnologies fixtures appear comparable in efficiency (51 to 66%) to the equivalent prismatics listed in the IESNA Lighting Handbook, while Sterling's reflectorized fixture at 71% is 18% less efficient than one of its high-efficiency prismatics (86% efficient).

The limited data available supports the argument that polarizing fixtures are less optically efficient than comparable prismatic fixtures - although there is clearly some variability in how much less. A polarized system of equal or less wattage than a standard prismatic fixture is going to give lower illuminance levels. This is an important issue when lighting is specified only in terms of wattage and illumination levels. A more appropriate design procedure is in terms of visibility, and the polarizing panel, to be effective, must provide an increase in contrast that compensates for any reduction in illuminance.

Prelude to Geometric Issues: Reflectance of Materials

In the 1959 paper introducing the multilayer polarizer, Marks stated that "Theory and tests show contrast always to be greater with polarized light at all angles of incidence, ...".[10] Blackwell's 1963 measurements appeared to confirm the latter half of this statement. Blackwell also found that the angle of incidence made a large difference in contrast, so much so that some light control panels gave better contrast than some of the poorer polarizers.

Nonetheless the material in Marks and Blackwell leads one to the conclusion that polarizers have almost universal applicability, but the recent work of Clear and Berman, NLPIP and Boyce all emphasize the importance of geometrical factors such as candlepower distribution, fixture layout and task orientation and tilt. Somebody is wrong. On inspection it turns out that Marks' theoretical analysis is over-simplified, while his measured data only covers those angles where a strong positive effect is expected. There also appear to be problems with Blackwell's data, and these data were not confirmed by his later work.

Marks based his theoretical conclusions on a model that only considers the geometry where the observer is at the mirror angle from the source, and splits the reflectance from the object (such as paper) into a mirror-like "specular" reflection from the surface plus a diffuse or "Lambertian" reflectance from below the surface, or what we shall call the body reflection (see Figures 5 and 6). For a task consisting of a pigmented (print) area on a white background, Marks made another simplification by assuming that the specular reflection from the pigmented and background areas was the same. These simplifications, the assumption that the viewer is at the mirror angle, and the assumption that unpolarized light always has a larger specular reflectance than the polarized light from a multilayer polarizer, leads to the conclusion that polarization always improves contrast. This conclusion is not true for more general models when the observer is not at the mirror angle from the source.

Are Marks' assumptions reasonable? Consider the assumption that the pigmented and background areas have the same specularity. Writing or printing on paper puts a new surface on top of the paper. The ink or graphite may have a different index of refraction than the paper, and thus reflect differently, or it may create a smoother surface than the paper and thus concentrate the specular reflection into a narrower cone of reflectance. The act of writing or printing may emboss the paper slightly, or the ink may have a rounded shape on top of the paper, so that in either case the angles of incidence and reflectance for light from a source may be different for the task and background areas. Any of these effects can make the specular reflection from task and background different.

A simple numerical example shows how the relaxation of the Marks' stringent assumptions leads to different conclusions. Assume diffuse reflectances of 80% and 10% for the background and pigmented areas, respectively. For simplicity assume that 100% parallel polarization is incident at what is called Brewster's angle, where its specular reflection is zero. The contrast is then (0.8 - 0.1)/0.8 = 0.875. Now assume that the specular reflection for the unpolarized source is 10% off the background, and 20% off the pigmented area, and further that you are not at the mirror angle to the source, so that you do not see the specular reflection. The reflectances to your eye are then 0.8 x 0.9 = 0.72 for the background and 0.1 x 0.8 = 0.08 for the pigmented area, and the contrast is now (0.72 - 0.08)/0.72 = 0.889, which is higher than that of the polarized source.

The above example shows that Marks' theory is incomplete, but it does not speak at all to the question of how significant the various simplifications are in practice. This is a question that can only be answered by measurement. Marks made measurements and stated that "...polarized light always improved contrast...", but he only examined reflection at the specular angle. His data, therefore, do not provide any information on contrast when there is light which is not at the specular angle to the viewer.

In his 1963 paper, Blackwell describes measurements in a real room, and reflectance and contrast measurements as a function of angle. However, we again find problems. The room measurements were taken at up to 9 locations/orientations, but all of them included fairly severe specular reflections. Blackwell concluded from the contrast measurements as a function of angle that polarization improves contrast at all angles, but he actually only measured "seventeen separate locations", and these didn't cover the entire angular range. The measurements themselves also are problematical. The targets consisted of a small dot on a background. Because the luminance profile of the dot is not constant Blackwell measured what he called an "equivalent flux" contrast which required the measurement of very small signals.

Bernecker has stated that "A direct refutation of either the procedures or results of Blackwell's work does not appear in the research literature...", but in fact Blackwell's own later work states that "Unfortunately, Helms has presented evidence that the precision of measuring CRF by the most refined procedure reported by Blackwell is unsatisfactory".[11,12] In 1973, Blackwell and his colleagues wrote a series of papers describing more precise reflectance measurements of a target consisting of a series of concentric penciled rings.[7,13,14] The use of a large target with multiple rings allowed for a well defined field of view, eliminates most of the ambiguity in target size that was present in the 1963 flux contrast measurements, and increases the signal strength. A total of over 550 measurements covering the entire incident angle range were made for each polarization, at each view angle, and for both the concentric rings and a blank background. Figure 7 shows a sample of the ratio of contrasts for horizontal versus vertical polarized light off the horizontally oriented task at a 25° viewing angle. The vertical polarized light is what is preferentially emitted by the multilayer polarizer when installed in a ceiling fixture, while horizontally polarized light is what it preferentially suppresses. The figure clearly shows that vertical polarization improves contrast near the specular angle (25° altitude, 0° azimuth), but it does not improve contrast at angles away from it.

Figure 7 is a comparison between 100% (vertical) and -100% (horizontal) polarization. In practice, the comparison of interest is between a polarizer with polarization levels ranging from 0 to 40%, and a non-polarized panel with a polarization of close to 0% at all angles. Figure 8 shows a comparison of the contrast ratios for an unpolarized panel and the Blackwell73 panel plotted in Figure 4. The figure shows that the magnitude of the contrast effects expected (for 25° viewing) are small.

This review shows that the early sweeping pronouncements in support of polarization were not correct. Issues having to do with the candlepower distributions of the fixtures, the geometry of the layout, and the location and orientation of the task are important in evaluating studies of polarized lighting, and in designing polarized installations.

Candlepower Distribution of the Fixture

Polarizing panels typically have prisms on the top, and are flat on the bottom. The combination of this geometry and the drop in transmissivity at high angles due to multiple reflections results in a panel which meets the glare candlepower cut-off limits at 65° and above, but as is shown in Figure 9, has relatively more output in the 40° to 75° range than a standard K-12 prism pattern.

An idea of the significance of this difference in candlepower distribution can be gleaned by looking at Figure 10, which shows how contrast varies with the altitude of the incident light. In this figure each point shows the contrast from incident light coming from a ring at a fixed altitude, with luminances for angles blocked by the body shadow being set to zero. Figure 11 shows the average over altitude, which corresponds to light coming from an arc of fixed azimuth. Figure 9 illustrates the truth of your mother's admonition to have the light to your side or over your shoulder.

Figures 10 and 11 show that geometry and light distribution are generally more important than polarization. Differences in candlepower distribution are the most likely reason that studies such as Slater's found little or no polarization effects.[15] Both geometry and candlepower distribution may well have had an important influence on Boyce's findings too.[1] On the other hand, looking at Figures 9 and 10 together, it appears that many of the positive effects found for polarizers may also be more due to candlepower effects, rather than polarization effects.

Layout of Fixtures, and Location and Orientation of Tasks

Many of the early studies on polarized lighting were performed during an era where illuminance levels were much higher than today's standard practice. Consequently, there were many more luminaires in the ceiling and the tendency for a luminaire to cause a veiling reflection was also greater. Today, with lower illuminance levels and wider spacing between luminaires, there is less opportunity for veiling reflections, but perhaps more chance that the remaining veiling reflections will be a problem, because they won't be balanced out by light from other luminaires.

To provide some information on what happens over a range of points we performed an analysis in 15.2 m. x 15.2 m. x 3.0 m. room with luminaires spaced 3.0 m. on center in both directions. Both a standard K12 patterned lens and a white K12 polarizing lens were analyzed. A special version of the Lumen-Micro analysis program, which considered polarized photometry and BRDFs when appropriate was used. Room reflectances were 80/50/20. Two different tasks were considered—a glossy magazine task and a laser printer task. BRDFs were taken from DiLaura and Jongewaard.[9] Results from this analysis are presented in Figures 12-15. A 3.0 x 3.0 m. analysis grid was positioned around the mirror angle condition for a 45 degree viewing angle, which is at the upper limit of the range of typical viewing angles and where polarized lighting is likely to provide greater benefit.

Figure 12 shows that contrast increases primarily in the vicinity of the mirror angle, although approximately half of the points receive no benefit or experience a slight reduction in contrast. Since the polarizing panel provides about 10% less luminance, it is important to look at visibility, not just contrast. Rea's 1986 RVP metric (the default for the program) varies by at most 0.004 for the conditions studied because it is almost saturated, so we have plotted ESI instead.[16] Figure 13 shows that, as expected, the area receiving benefit from the polarized light is smaller than when contrast alone was considered. It is important to note that the large increases are occurring at points where the visibility is poor. The magnitude of some of the ESI values at the mirror angle with the luminaire are below 10 ESI for both luminaire types (the overall range is 1 to 205 ESI). This magazine task, which is highly specular, shows the improved performance that is provided near the mirror angle. This is consistent with performance reported by Blackwell.[6]

The laser task, a more matte background with a slightly glossy print area, provides very different results. Figure 14 shows that for this task, contrast improves very slightly at all locations within the analysis grid. However, when the reduction in luminance is factored in through the analysis of ESI, only two points show a slight increase in ESI, and most points experience a slight decrease in ESI (see Figure 15). The ESIs in this case are very uniform (65 - 101 ESI).

These simple examples show the importance of a variety of different components—the importance of task location relative to the lighting system, the importance of task reflectance characteristics, and in some respects, the importance of the visual performance model.

Task Tilt

Multilayer polarizers are installed horizontally in a ceiling fixture. A task flat on a desk, or some other horizontal plane, is parallel to the polarizer, so light that is parallel polarized with respect to the light travel plane through the polarizer is also parallel polarized with respect to the task. If the polarizer were mounted on a wall, then the same relationship would hold for tasks mounted flat on the opposite wall. Light that is parallel polarized with respect to a ceiling mounted multilayer polarizer is vertically polarized with respect to the space as whole, but this is not true for a wall mounted polarizer. Light transmitted through multilayer polarizer is polarized in a radial orientation, so light through a wall mounted multilayer polarizer will be predominantly horizontally polarized if it is in a horizontal plane, and predominantly vertically polarized if it is in a vertical plane. The ceiling mounted polarizer is not optimal for a vertical (or tilted task) whenever the plane of light travel (from source to task to eye) is not vertical.

A very common situation where vertical polarization helps in some locations and hurts in others, is in the viewing of a visual display terminal (VDT).[5] Assuming that the viewing direction is normal to the center of the screen, veiling reflections near the top center of the screen form a vertical light travel plane, whereas veiling reflections off the left and right sides are the result of a horizontal light travel plane (see Figure 16).

When viewing a wall, the straight-on view, up or down, will have predominantly horizontally polarized veiling reflections, while a view to the side will give predominantly vertically polarized veiling reflections. In a small room veiling reflections from the side are likely to be off another wall, and are therefore less likely to be a problem than in a large room.

Type of Task

Marks and Blackwell, in their early studies, both examined a number of different tasks, but they did not make detailed measurements of the bidirectional reflection distribution factors (BRDFs). Blackwell reported BRDF measurements for a concentric ring pencil task in 1973, and it is these measurements that were used for many years to calculate visibilities in terms of ESI. Detailed, validated BRDFs for other materials are not currently publicly available, although this situation appears to be changing.

In lieu of more recent information, one can note that the trends found by Blackwell in his 1963 paper agree with rough theoretical expectations. Tasks with low contrasts near the specular angle: soft pencil, thermo-fax, glossy magazine, and ballpoint pen on matte paper, appear to have the greatest improvement from polarized light. Fountain pen ink on matte paper, mimeograph, and typewritten text had less improvement. In general, we expect that a matte pigment will have low veiling glare, and thus will not show substantial improvement with polarization. Tasks with relatively specular pigments and backgrounds will have high veiling glare and will improve under polarization. These trends are the same as what was shown in Figures 12-15. An important issue here, is that modern tasks have been reported to be mostly of good contrast.[2]

Early studies appear to have focused on demonstrating an effect, and thus looked at the more specular tasks. More recent studies have focused on the typical task found in today's office environment.

Method of Evaluating Visibility

Marks only examined situations where there was a high degree of polarization, and where the polarization made large differences in contrast. Under such circumstances there was no real need to have a sophisticated model for how contrast and luminance affect visibility. Blackwell faced more subtle effects. His solution was to calculate the luminance (illuminance) needed for the unpolarized panel to have equal visibility as the polarized panel. This is a very different solution than that chosen by Boyce and Rea, or that expressed by Rensselaer's Lighting Answers report.[1,2] They chose to directly measure or evaluate the effect of polarization on performance. For the conditions they examined, the effect seemed small, so they dismissed polarization as being unimportant.

The problem of direct assessment of performance is that there needs to be some way of judging what magnitude of performance difference is important. Boyce's report partially addressed this issue, in that one of the polarized installations had a lower light level and a lower measured performance than the reference unpolarized installation. In this case any contrast improvements from the polarized lighting were clearly insufficient to balance the reductions in illuminance. For the other case, Boyce and Rea simply note that "...polarized lighting gives a slight improvement in task visibility when veiling reflections occur." Similarly, the Lighting Answers report simply states that "Contrast improvements within this range have very little effect on visual performance." However, at moderately high performance levels light level also has little effect on performance. There is a subtle but important point here. If modern light level recommendations lead to visual performance levels which are insensitive to illuminance and contrast variations, then either the recommendations are inappropriate, or the residual variation is significant, small though it may be. In the latter case one needs to assess the performance improvements due to contrast increases from a polarized panel (if any) against the performance decrements due to lower light levels, to see if the polarized panel can be used to save energy. If the recommendations are currently too high, then presumably more appropriate recommendations would result in significant sensitivity to contrast and luminance, and thus would again require a procedure that assesses contrast improvements in terms of luminance losses. Neither the Lighting Answers report nor the Boyce study provide this information.

Blackwell's evaluations were based on his contrast sensitivity function, which was derived to explain how luminance and contrast affect accuracy of detection near threshold. More recently the emphasis has shifted towards modeling how contrast and luminance affect the speed of visual work. Figure 17 plots the luminance decrement that just compensates for a 1% contrast increment for Blackwell's contrast sensitivity function, Rea and Ouellette's 1991 Relative Visual Performance (RVP) model, and Clear and Berman's 1993 visibility level (VL) model.[17,18] The Blackwell and VL models are independent of absolute contrast level, while the RVP model is not. At high contrasts (0.8) the RVP model is significantly less sensitive to contrast changes than the Blackwell or VL models. This is a major reason for the negative appraisal of polarization in the Lighting Answers report.

By 1973, the comparisons Blackwell and others were doing were done in term of Equivalent Spherical Illuminances (ESI). Computer programs made it possible to evaluate ESIs for many locations and orientations. There is a difficulty, however, in that average ESI values are not meaningful, because of the extreme non-linearity of the relationship between ESI and visual performance. Instead, evaluations are typically done in terms of the minimum ESI level that is found over a given fraction (percentile) of the area.[19] This procedure has been criticized as being arbitrary.[20] Figure 18 shows a comparison for two ESI distributions that cross several times, so that different percentile choices give different answers as to which installation is better. Visual performance calculations do not have these problems, and the average visual performance level is a more appropriate measure of the quality of a lighting installation.

Be that as it may, past evaluations of polarized installations were done in terms of percentile ESI. The percentile approach emphasizes uniformity of performance. Our review of the information on polarization indicates that its effect on uniformity is larger than its effect on average performance, thus the percentile procedure will give a slightly more favorable view of polarization than does an average performance approach.

Summary and Conclusion

The early, sweeping pronouncements in favor of polarized lighting were clearly too optimistic. Yet our review does not lead us to feel that one can totally dismiss polarizers. Even the recent reports from Rensselaer agree that polarizers may improve visibility for tasks suffering veiling reflections. The issue is whether the effects are so small, and the situations so limited, that polarizers need only be thought of as special purpose devices. This issue has not been fully resolved, because the negative reports have not actually evaluated the balance between polarizer's positive and negative effects. This evaluation must involve the application of an accepted model of visual performance. The existing ESI and RVP models provide very different results. This analysis is also complicated by the fact that the area of improvement is limited and depends on lighting system layout, task, and on the hardware being considered.

We would be remiss, if we did not note that we have not reviewed all the issues surrounding the polarization controversy. It has been suggested (and disputed) that the eye's physical sensitivity to polarization may make vertical polarization effects larger than is accounted for by simple photometry.[21,22] It has also been suggested that the contrast measurements and visibility models are ignoring the effect of local inhomogeneities (speckle) on visibility.[23] Either of these effects, if significant, would probably make polarizers look better than judgments based only on pure physical effects.

While this review does not provide a definitive judgment for or against polarizing panels, it does provide some guidance as to where polarizers are most likely to be useful and explains many of the complex geometry issues related to the veiling reflection situation and polarized light. It also provides a perspective on the claims made related to the performance of polarizing panels. Polarizers improve visibility by reducing veiling glare. Veiling glare is a problem where light sources will be located at a mirror angle from the view to the task, and when the task is relatively specular. The extent to which veiling reflections can be significantly reduced through the use of polarized light depends on a number of different parameters related to both the task and the lighting system.

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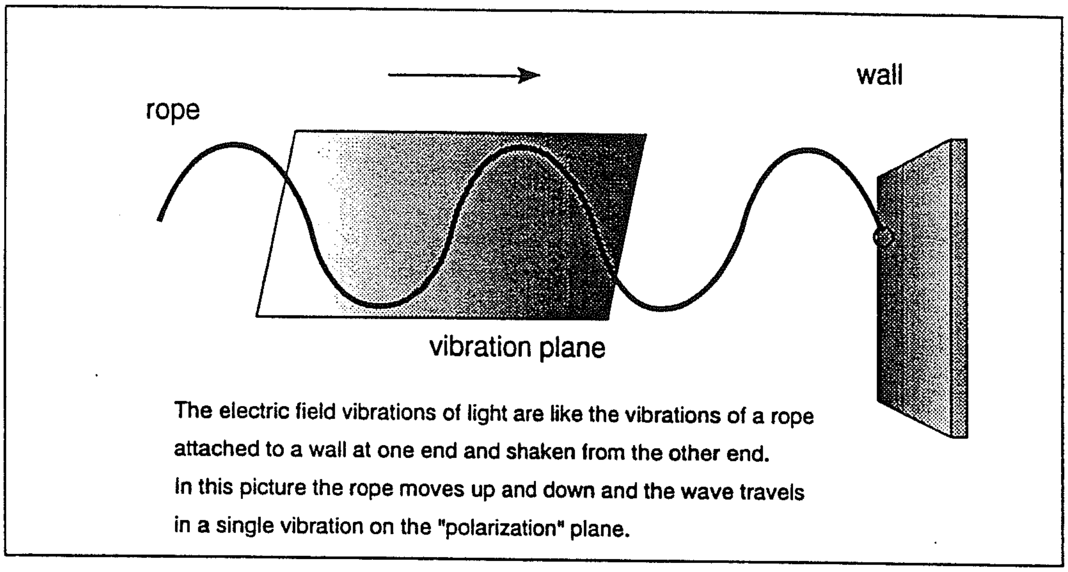
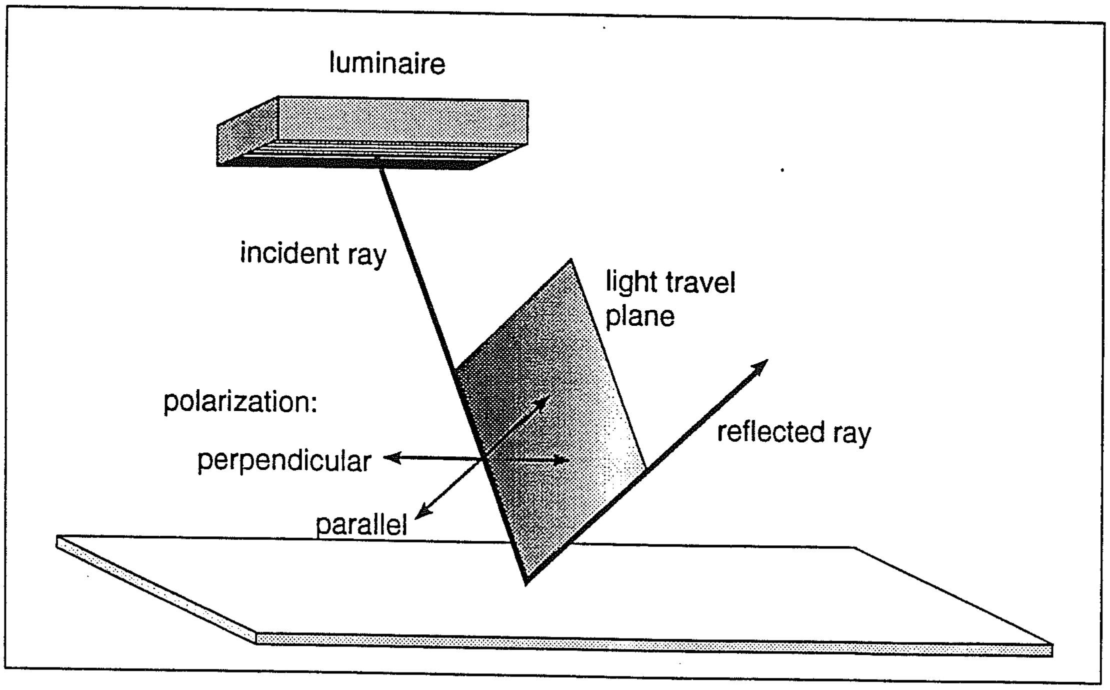


The electric field vibrations of light are like the vibrations of a rope attached to a wall at one end and shaken from the other end.
In this picture the rope moves up and down and the wave travels in a single vibration on the "polarization" plane.

Vibration Plane

Figure 1



Perpendicular and Parallel Polarization

Figure 2

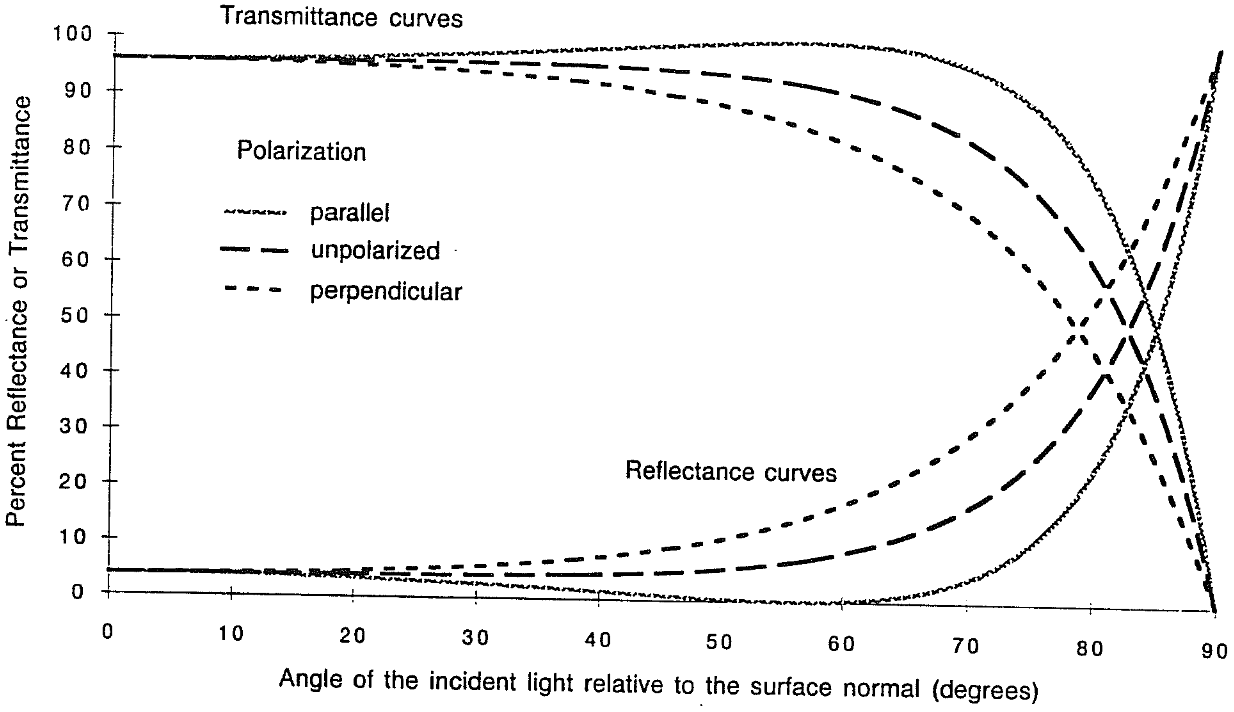


Figure 3. Reflectance & Transmittance of single glass surface as a function of angle & polarization.

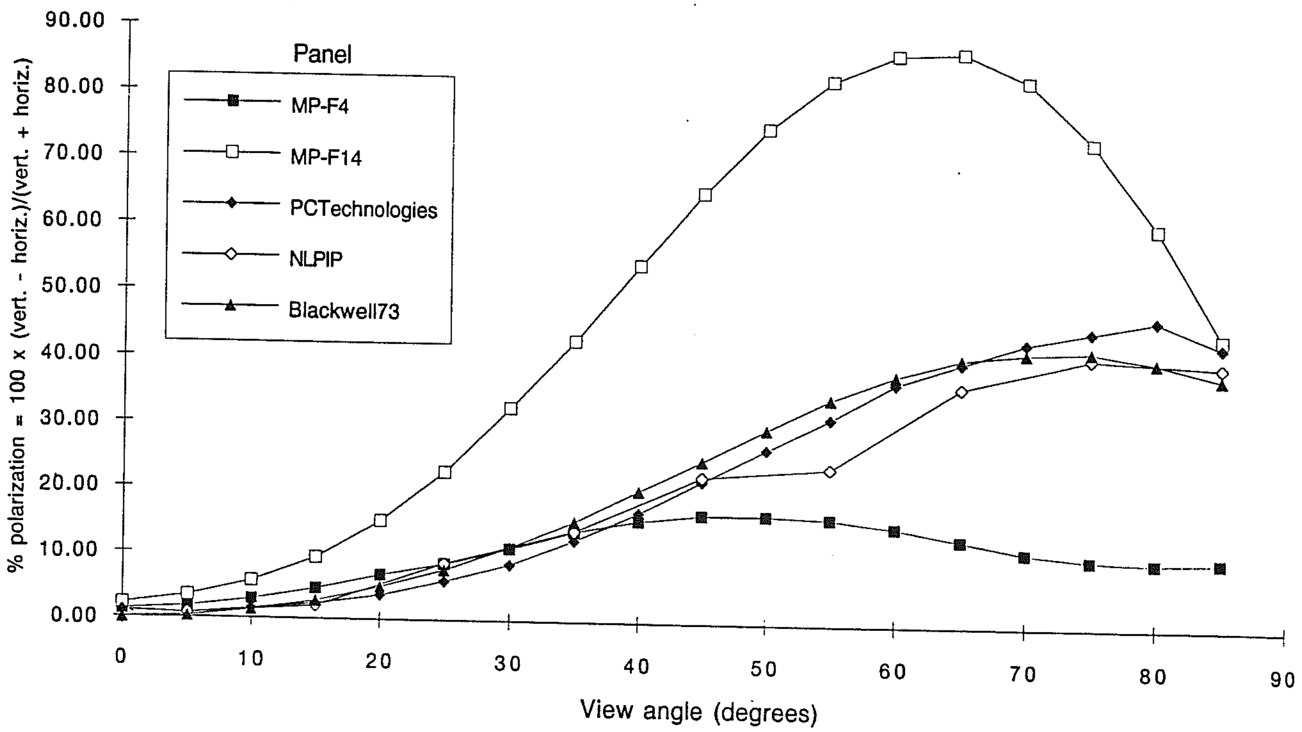
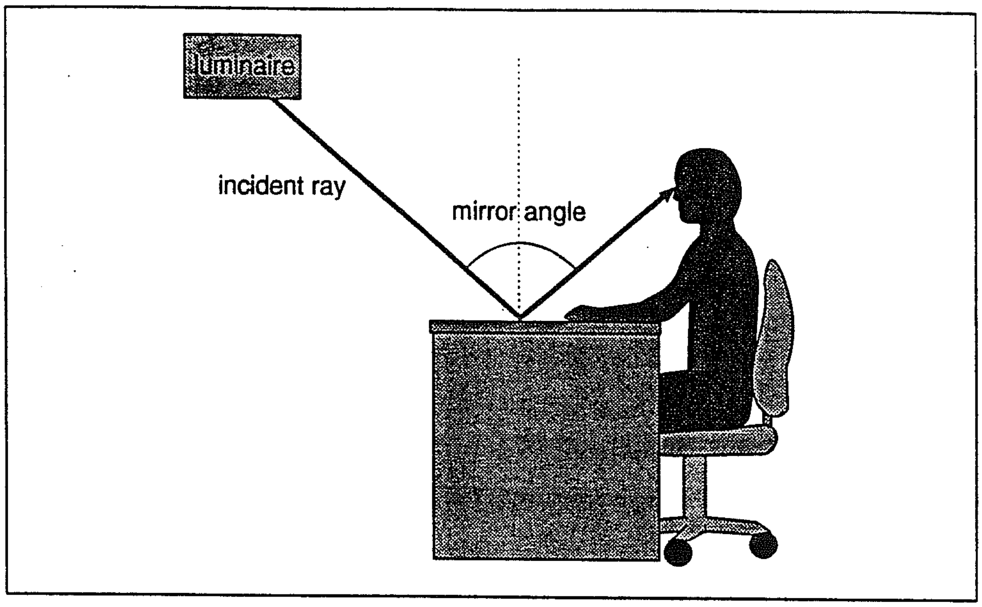


Figure 4. Polarization of fiv multilayer polarizers as a function of view angle.



Mirror-Angle Reflection from Glossy Surface

Figure 5

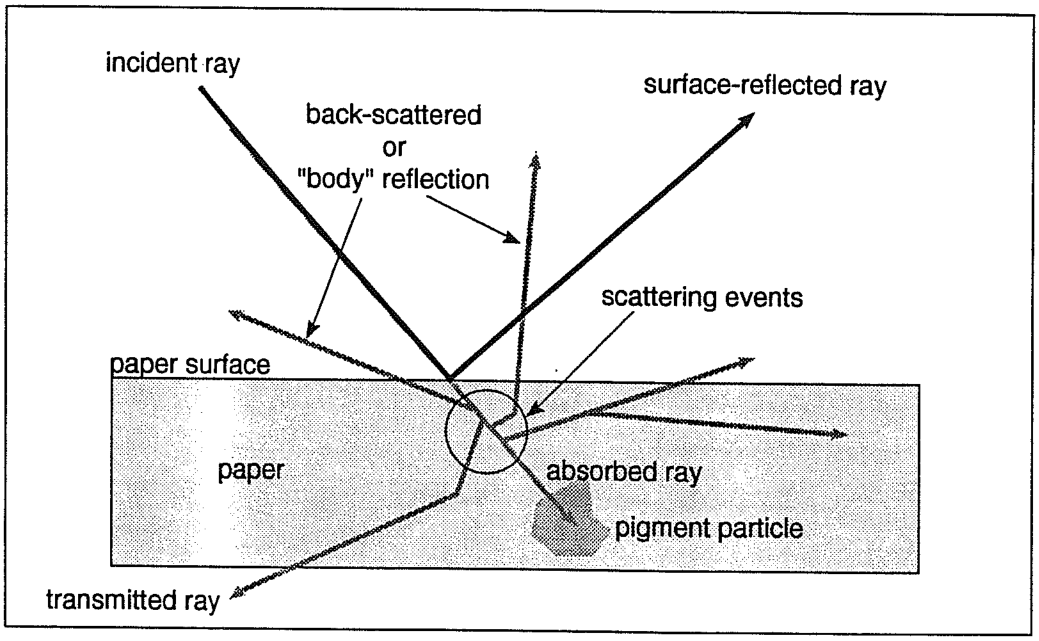


Figure 6. Two-Component Reflection Model

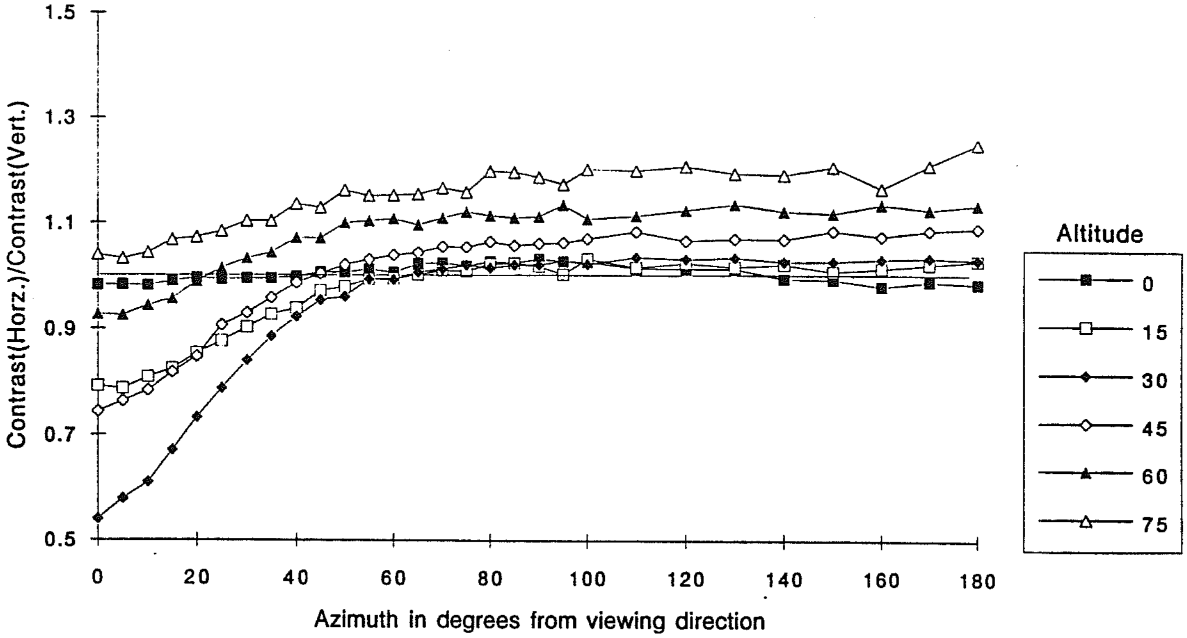


Figure 7. Contrast(horizontal polarization)/Contrast(vertical polarization) 25° Viewing angle - Blackwell pencil task

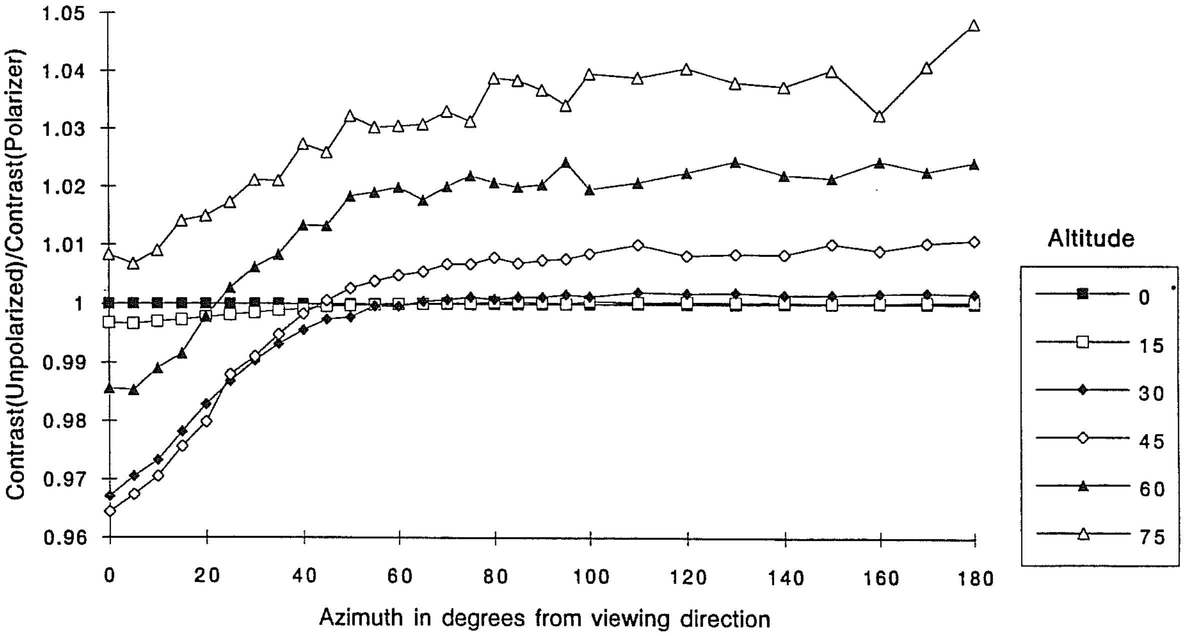


Figure 8. Contrast(unpolarized source)/Contrast(multilayer polarizer) 25° view angle - Blackwell's 1973 panel

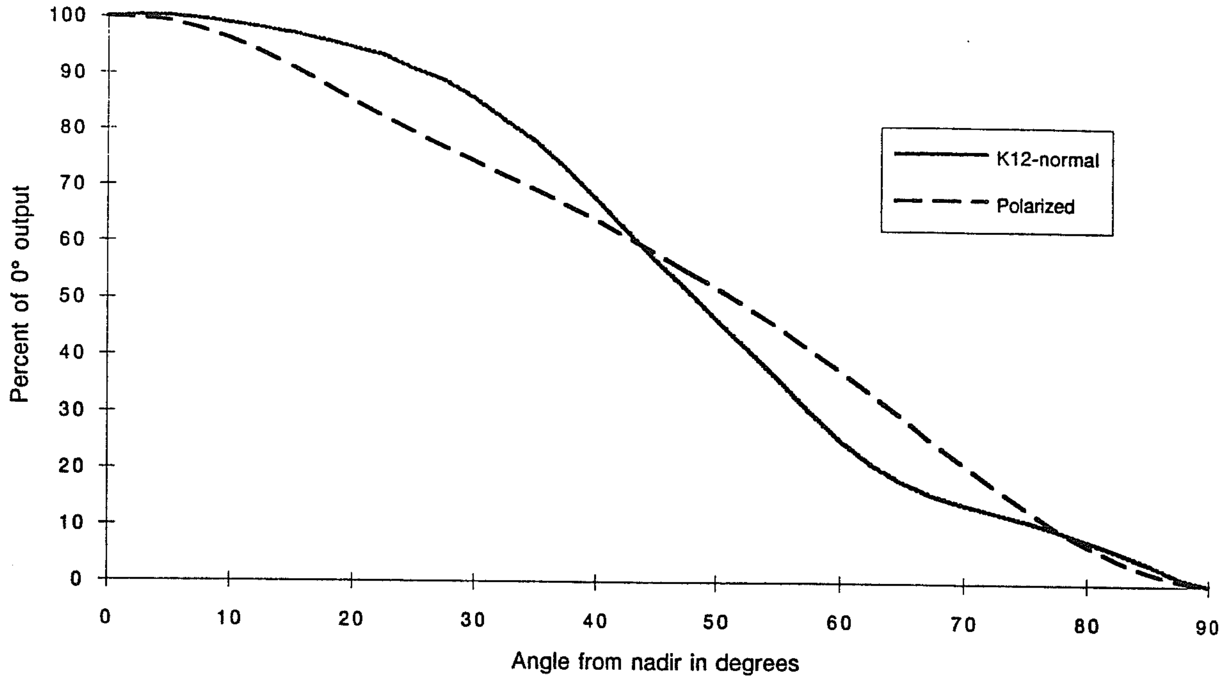


Figure 9. Normalized candlepower distributions: Pattern K-12 & Polarized lenses

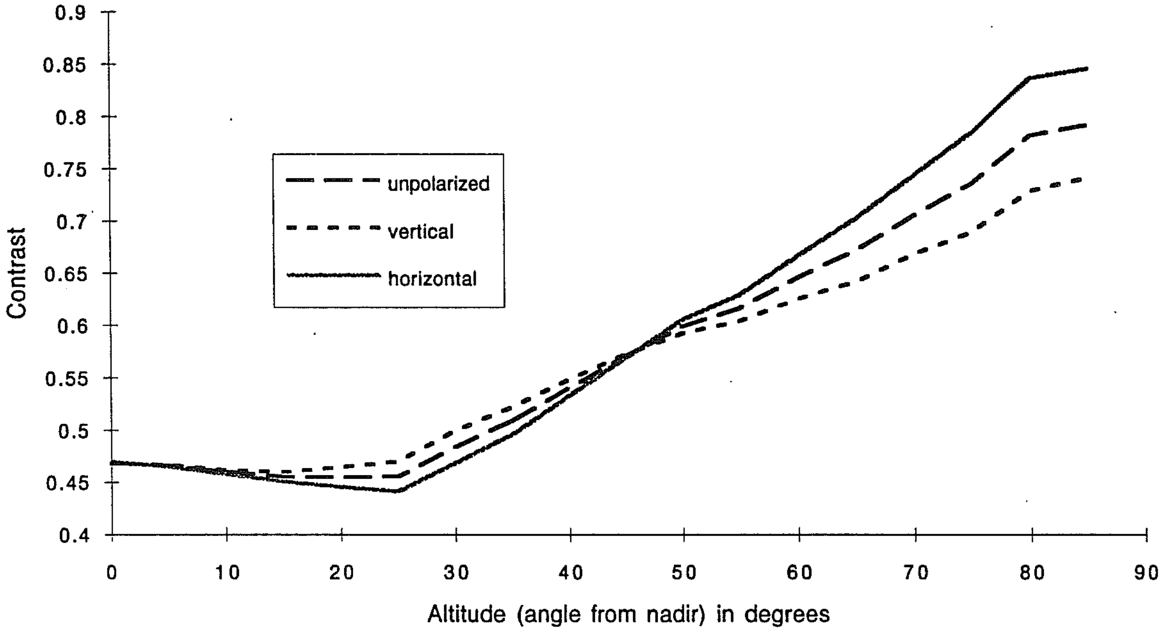


Figure 10. Contrast versus altitude (luminances averaged over azimuth) Blackwell pencil task at 25° viewing angle

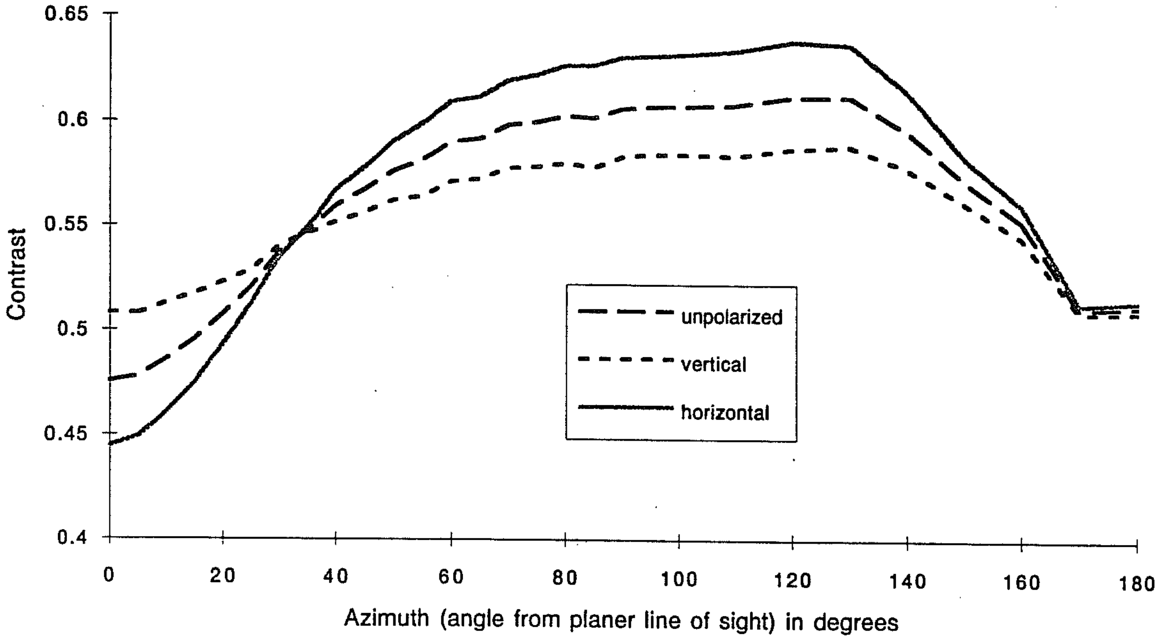


Figure 11. Contrast versus azimuth (luminances averaged over altitude) Blackwell pencil task - 25° viewing angle

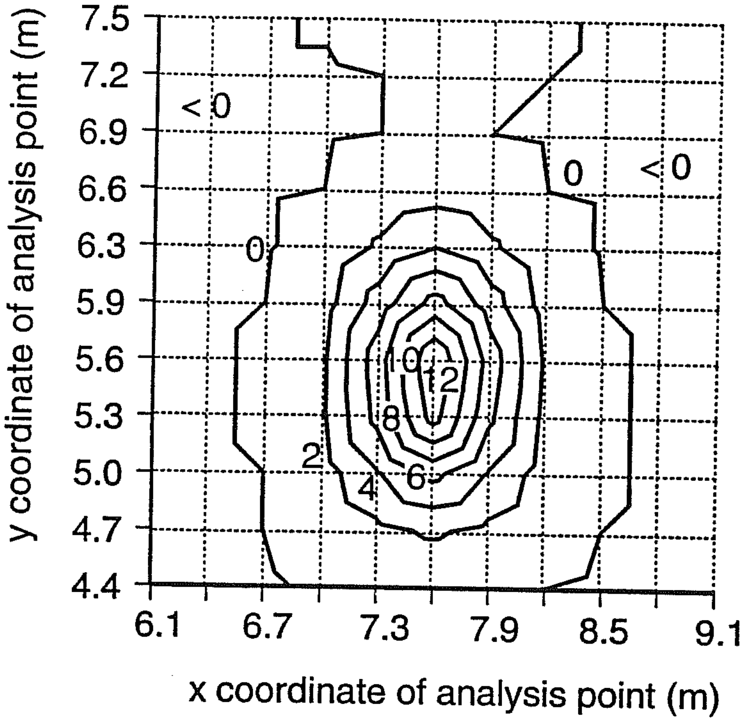


Figure 12. Percent increase in contrast, magazine task, 45 degree viewing angle, polarizing panel relative to K12 lens, luminaires 3 m. x 3 m. on center.

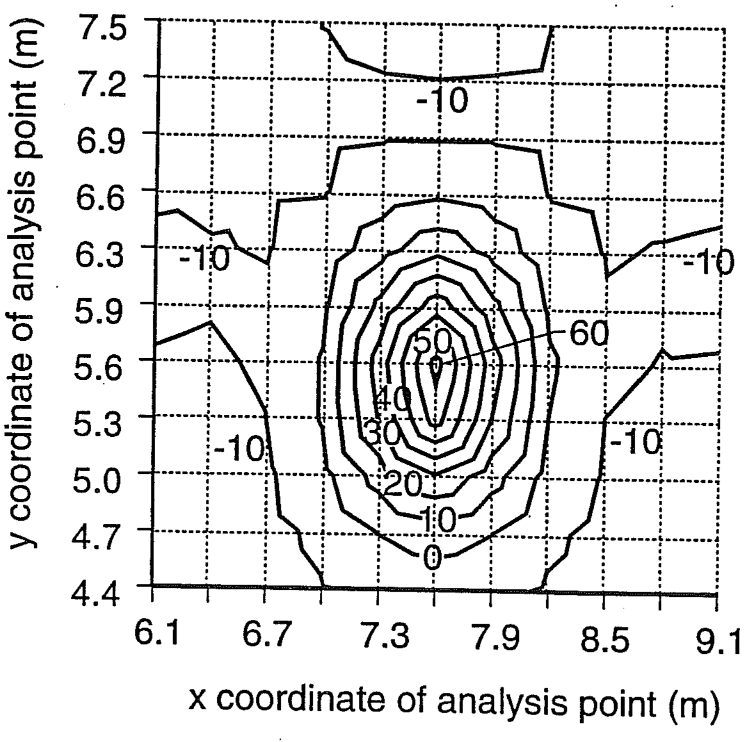


Figure 13. Percent increase in ESI, magazine task, 45 degree viewing angle, polarizing panel relative to K12 lens, luminaires 3 m. x 3 m. on center.

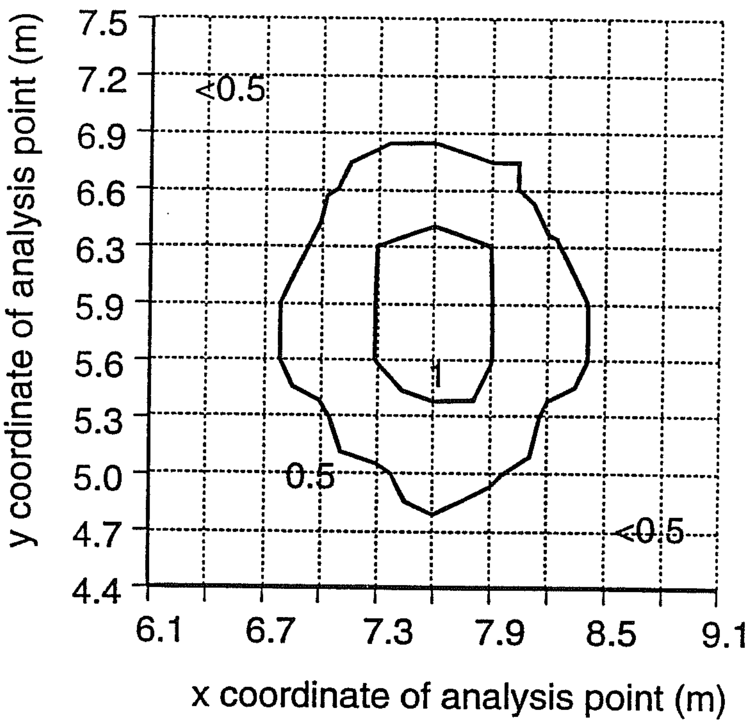


Figure 14. Percent increase in contrast, laser task, 45 degree viewing angle, polarizing panel relative to K12 lens, luminaires 3 m. x 3 m. on center.

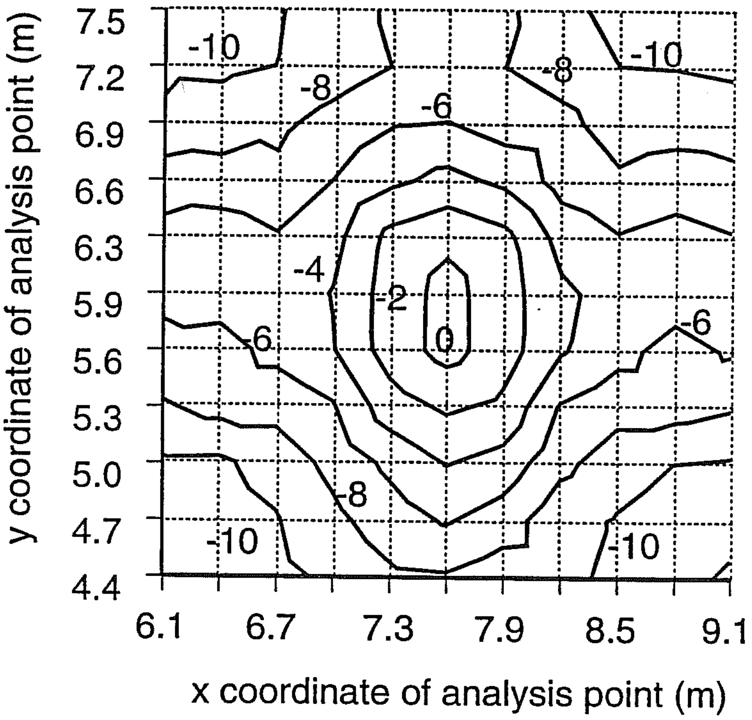


Figure 15. Percent increase in ESI, laser task, 45 degree viewing angle, polarizing panel relative to K12 lens, luminaires 3 m. x 3 m. on center.

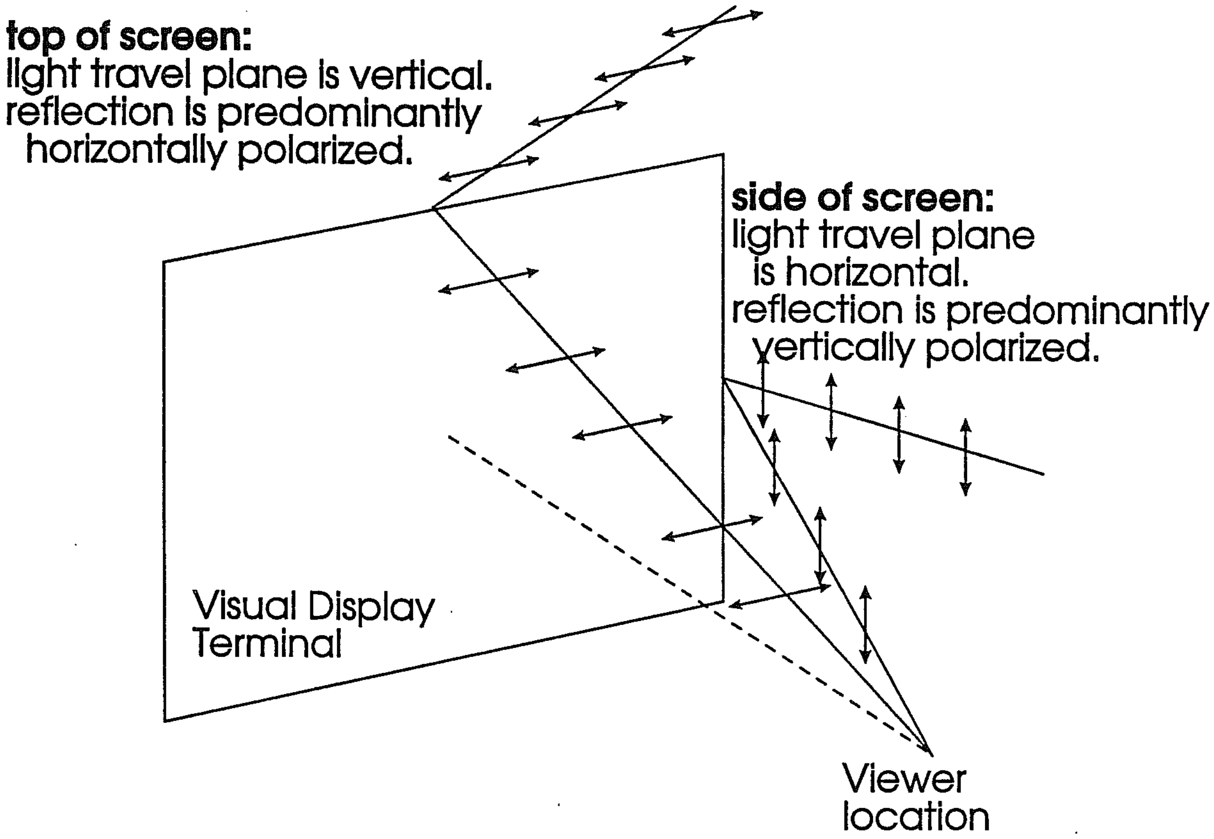

top of screen:
light travel plane is vertical.
reflection is predominantly
horizontally polarized.
side of screen:
light travel plane
is horizontal.
reflection is predominantly
vertically polarized.
Visual Display
Terminal
Viewer
location

Figure 16

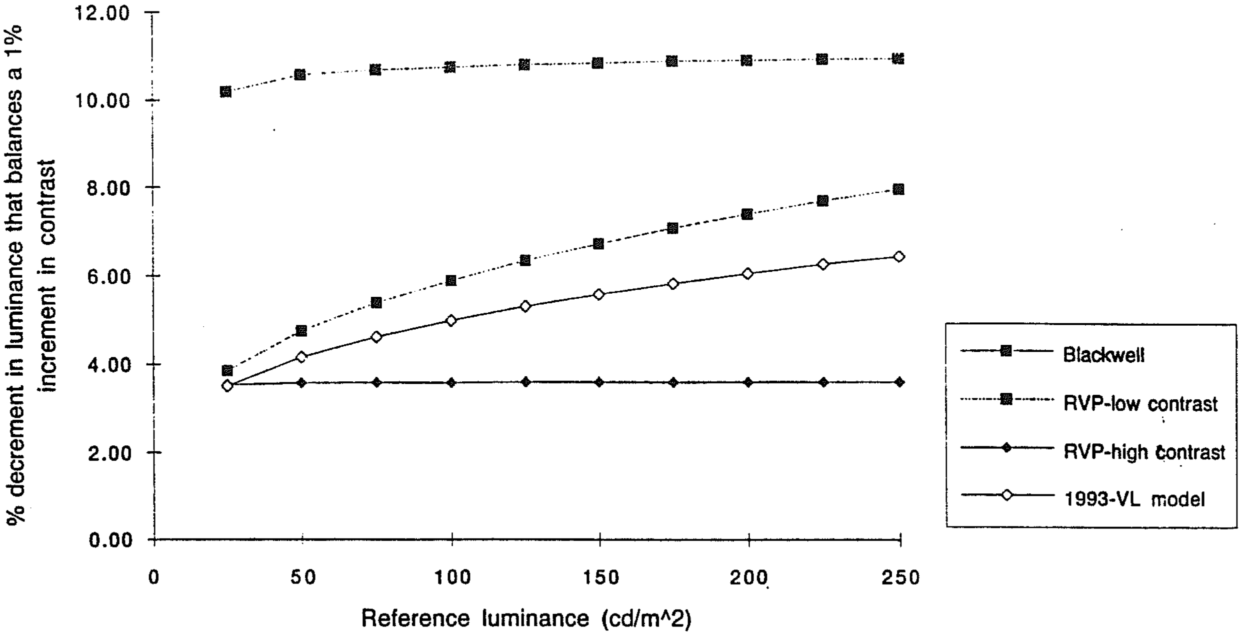


Figure 17. Percent Luminance decrement needed to maintain equal visibility when contrast is incremented 1 percent - plotted versus the initial luminance.

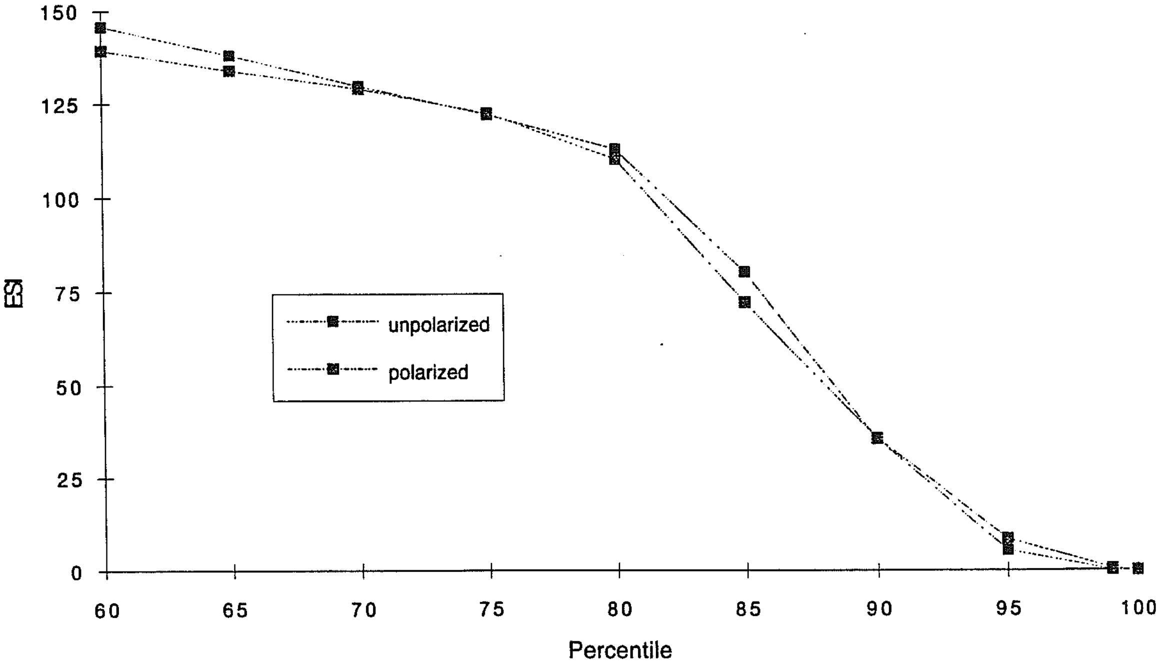


Figure 18. ESI distributions for a magazine task in a large room.