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ABSTRACT

The problem of veiling reflections in flat reading matter is examined in three theoretical analyses. These assumptions are made: (1) The surface is shiny, so that surface reflections can be treated as creating a mirror image. (2) The light source has a non-zero area. (3) Insofar as it matters, the reading material has non-zero area also. The first analysis assumes that the reader can tilt the reading material. The extent to which a larger luminaire forces him to tilt farther from his line of sight and from the incident light is then computed. The second analysis assumes that the luminaire image is not avoided. Then, the smaller the luminaire is, the brighter its image will be, relative to a diffuse white surface; this effect is expressed in a formula and in graphs. The overall implication of the first two analyses is that while veiling reflections are not negligible with spherical illumination, the worst light sources are those of intermediate size, whose image is hard to avoid, yet brighter than in the spherical case. The final analysis shows that when veiling reflections cannot be avoided, they desaturate colored objects. For instance, spherical illumination reduces the accessible volume in the CIELAB uniform color space by 37%.

Key words: color; lighting; lighting geometry; Munsell value; object color; surface reflections; veiling reflections.

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1. Introduction

Your mother, or perhaps a teacher, told you always to read with a light over your left shoulder. The traditional engineering recommendation is that when reading from a flat piece of paper, you should not have a luminaire in "the offending zone." That is, if you lay a mirror on the paper, you should not see the image of a bright source. (The image of a bright source in the surface of an object such as a printed page is called a veiling reflection.)

These traditional recommendations give essentially excellent advice; but their correctness depends on assumptions your mother did not tell you about the size and number of light sources. Newer methods such as "Contrast Rendering Factor" are perhaps intended to work where the traditional simple advice cannot be applied, but they lack the virtue of giving direct advice, and depend on further hidden assumptions. The present paper is concerned primarily with the effects of luminaire size and the difficulty of keeping a large source out of the offending zone. The results quantify a fact that lighting designers and others may know intuitively: large sources are difficult to work with.

A word should be said about the topic of "assumptions." The interactions of light source, luminaire, objects lighted, and human observer, in a practical lighting situation, constitute an optics problem of tremendous complexity. To analyze such a situation, we must make simplifying assumptions concerning the overall purpose of the lighting system, the nature of the objects being lighted, and human responses. Since our results will depend on the assumptions made, the assumptions should be realistic and clearly stated. Discussions of veiling reflections in terms of "contrast rendering factor" (CRF) are usually based on the assumption that the positions of task and eye are not critical. Therefore, it is implicitly assumed that the task is semi-specular, and that veiling reflections arise from some combination of large luminaires and other light-colored surfaces. These may be reasonable assumptions in certain existing situations, but many very functional lighting systems and visual tasks do not conform to this model. In the present paper, I make an alternate set of assumptions: that tasks may be highly specular, that luminaires may be small, and that the observer may have some freedom to re-orient the task. I assume that the purpose of the lighting system is to provide clear seeing; this implies that black surfaces should be made as dark as possible, while colors should be made saturated, since these are the visual features most compromised by veiling reflections. A basic motive for doing this is simply to encompass cases not dealt with by the CRF assumptions. A deeper motive is that by considering extreme and physically simple cases, I am able to state my assumptions precisely and to calculate results for a wide variation in parameters such as luminaire size.

This is a theoretical paper, based largely on original calculations. A secondary purpose, beyond the reporting of numerical results, lies in discussing the concepts of surface reflections and "color solids" as they apply to problems of lighting. While these are well-known topics among those who make paints, plastics and so forth, it may be worthwhile to explore their significance for lighting. The sequence of topics is somewhat arbitrary, but follows the order in which the work was done.

2. Luminaire Size and the Problem of Tipping the Book

For purpose of discussion, let us assume a reading task which is flat and has a very shiny surface. Then the "veiling reflections" due to a light source amount to an image of the source, and to avoid the veiling or distracting effect of this image, the reader must tip his paper so that the image is not in view. In this connection, one may consider that the image always exists at the mirror-image position, but the piece of paper is an aperture (window) through which it may or may not be in view. The primary effect of tipping the paper is to move the image, though it will also foreshorten the paper and the image, and reduce the luminance of the paper. Luminance is reduced because, as we shall see, the paper must be tipped away from the source.

As the basis for calculation, consider the geometry of Figure 1. The eye E looks at a flat, circular, mirror-finish book of radius b cm. Or, equivalently, the eye is looking at a circular mirror of radius b. Without loss of generality, we may specify that E lies on the z-axis a distance d from the origin, and that the center of the luminaire is in the x-z plane; further, the origin of co-ordinates O is at the center of the book. Thus, the y-axis is not necessarily directed straight downward. Line OL to the center of the luminaire, of length a, makes an angle ϕ with the z-axis. Angle ϕ is defined as positive when the luminaire is over the observer's left shoulder, so that in the sketch, ϕ is negative. The luminaire is flat and circular of radius R, and subtends 2ρ at the origin, giving the auxiliary equation $R = a \tan(\rho)$. Angle σ is not a parameter of the luminaire, but an angle used internally in the calculation to step around its circumference.

Angle α locates the axis in the x-y plane about which the book is tipped. Angle β from the z-axis to N, the normal to the book, measures how far the book is tipped from being viewed square-on. The choice of a circular book, of course, ensures that rotation about N can be ignored.

Now the question of whether the observer sees the luminaire in the mirror depends on all the parameters. To learn something about the effect of luminaire size, it was necessary to fix some dimensions and vary others in a restricted, systematic way. The eye-book distance d was fixed at 40 cm, a typical reading distance; the book-luminaire distance a was fixed at 200cm. Distance a is comparatively unimportant, since luminaire size was expressed in terms of the angular semi-subtense ρ; this is not to assert that a is irrelevant, since this is a problem involving vector algebra, not just angles. Book radius b was set to only two values: 10.795 cm and 17.655 cm. These are the radii of circles inscribed and circumscribed on a rectangle of standard letter size: 8.5 x 11 inches. The offset of the luminaire from the sighting line, ϕ, was set to 30° and 0 degrees, and results are presented only for the 30° case.

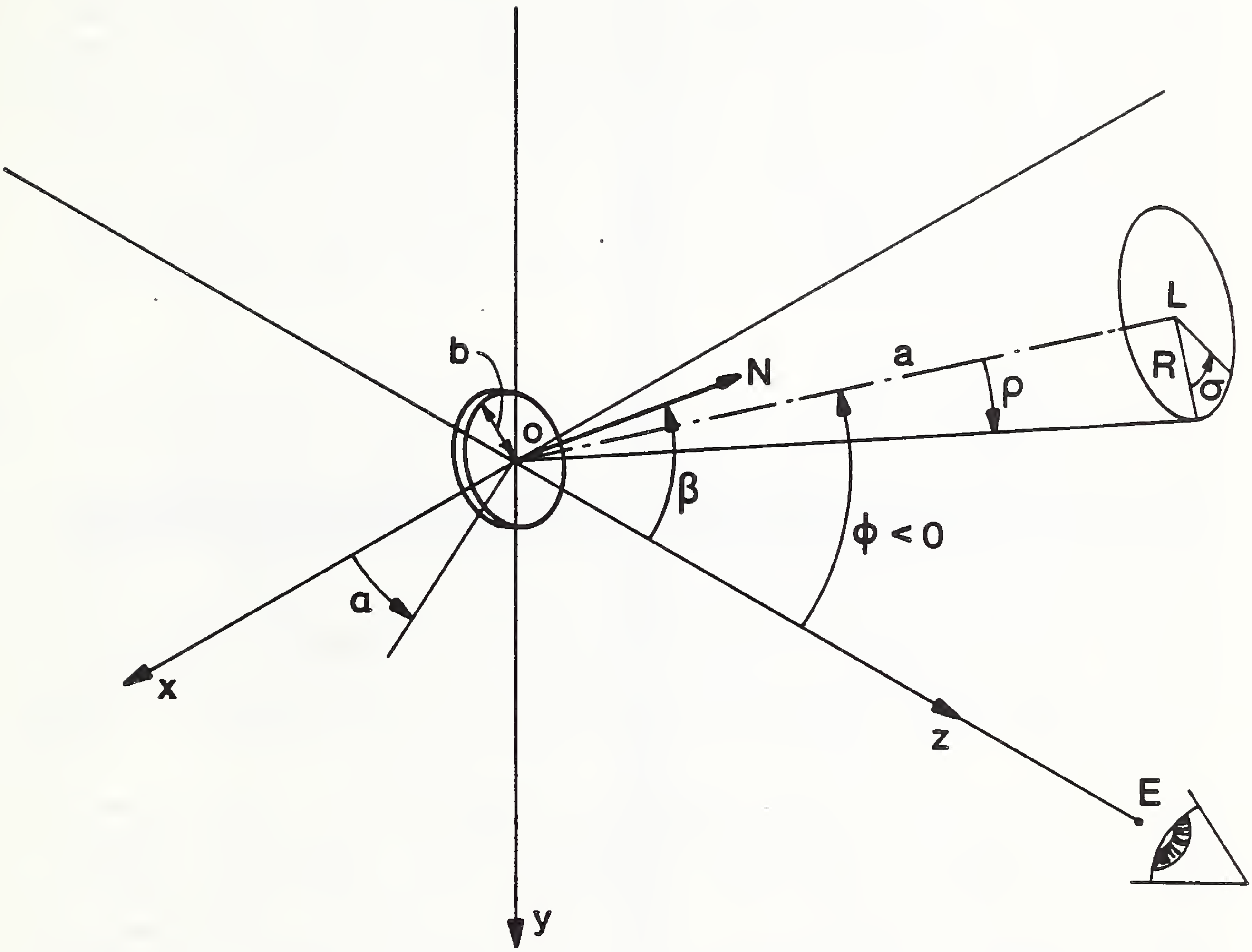

Figure 1. Geometrical relationships in tilting a book to avoid veiling reflections. The book is flat and circular of radius b cm. The book is centered on the origin 0, while the eye is on the z-axis d cm away. The normal to the book, N, is tipped through angle β away from the z-axis, about a line in the x-y plane which makes angle α with x-axis. Without loss of generality, we require that the luminaire lie in the x-z plane; thus the $+y$ direction may not be straight down. The luminaire is flat, and circular of radius R, and perpendicular to a line through the origin making angle ϕ with the z-axis. It is a cm from the origin. Angle σ is not a parameter of the luminaire, but a variable in the calculation which steps around the circumference.

With these restrictions on the other parameters, this question was asked: for a given luminaire semi-subtense ρ, what is the minimum tip required, as a function of α, in order that the image of the luminaire not be seen? Further, what is the overall minimum β and at what setting of α did this occur? Since these questions were answered through a computer simulation, rather than a closed-form algebraic solution, the process was very like what a person would do: test successive values of α and increase β from zero until the image of the luminaire slides out of the field of view. For each setting of α and β, the variable σ was stepped through 360 degrees in one degree steps, making this a time-consuming program of nested loops. Figure 2 shows β(minimum) as a function of α for $b = 17.7$ cm and $\phi = 30°$. The bumps on the oval curves result from the fact that all angles were stepped in 1° increments, and are a measure of precision. Since these plots are not shown with an actual polar co-ordinate grid, it must be understood that α is measured from the + x-axis, while β is plotted radially.

Careful reading of Figure 1 then shows that β is a minimum as a function of α when the book is tipped away from the light source. All the contours of $\beta(\alpha)$ reach a minimum when $\alpha = -90°$. Since α is measured from the $+x$-axis, this means that the tip will be about the y-axis, and towards $-x$. Before completing this calculation, the author felt unsure whether the observer could always minimize β by tipping directly away from the light, or whether perhaps the best tip would be out of the x-z plane. In the event, it appears that tipping away from the source is always best. Some readers may feel that this was obvious from the outset, and of course it would be hard to argue that what is indeed true "should not" have been obvious. Also generated from the simulation---essentially from Figure 2---were graphs of β(minimum) as a function of ρ. These are not presented, but similar graphs are given below, derived differently.

If it is given that the book should be tipped in the x-z plane, then a more direct algebraic solution is possible. Figure 3 shows the set-up of this two-dimensional problem in a convenient form, involving a slight change of notation from Figure 1. The x-axis is fixed in the mirror, which still has half-width b. The eye remains d cm from the origin and an angle β from the y-axis, now identical with N, the normal to the mirror. A further angle ψ from the line of sight is point P on the rim of the luminaire. Thus, $\psi = \phi - \rho$, where ϕ and ρ retain their meanings. All angles are now positive as drawn. Point I is the image of P. The distance c from the origin to the rim is given by $c = a/\cos\rho$. Points E and I and the point on the edge of the mirror are easily written in coordinate form as shown on the figure. The condition on β then is that the edge of the mirror lie on line EI as sketched. Writing this condition in vector-algebra form and simplifying through trigonometric identities eventually leads to the condition

$$c\ d\ \sin(\psi+2\beta) - b\ d\ \cos(\beta) - c\ b\ \cos(\psi+\beta) = 0. \qquad (1)$$

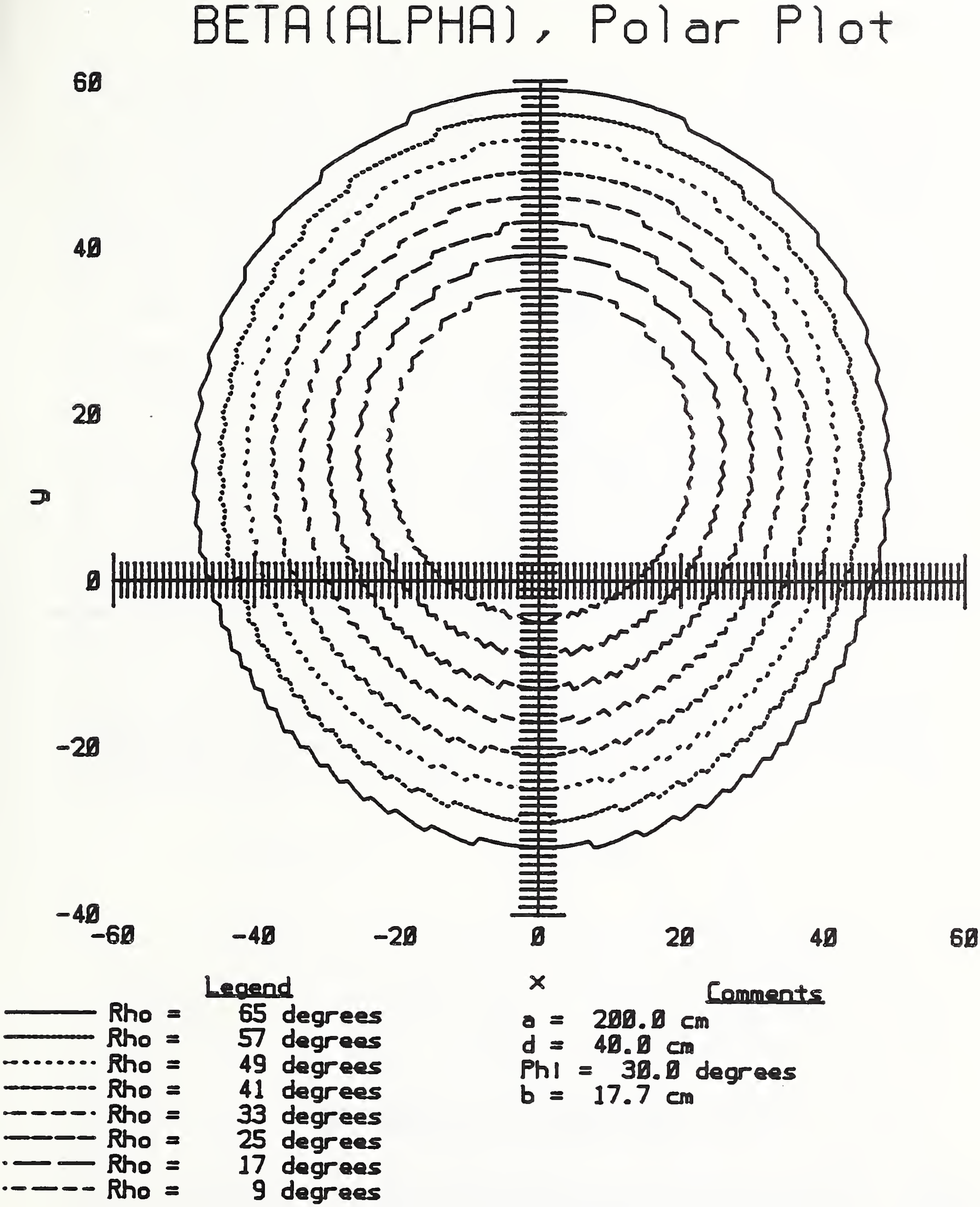

Figure 2. Polar plot of β (minimum) as a function of α. α is the azimuthal angle, while β is the radial coordinate. For a given luminaire size---given by ρ---the minimum tip required in order to dump the luminaire image is a function of the direction of tip---given by α. For a certain α, the grand minimum β occurs; from this graph, one sees that $\alpha = -90°$ always minimizes β.

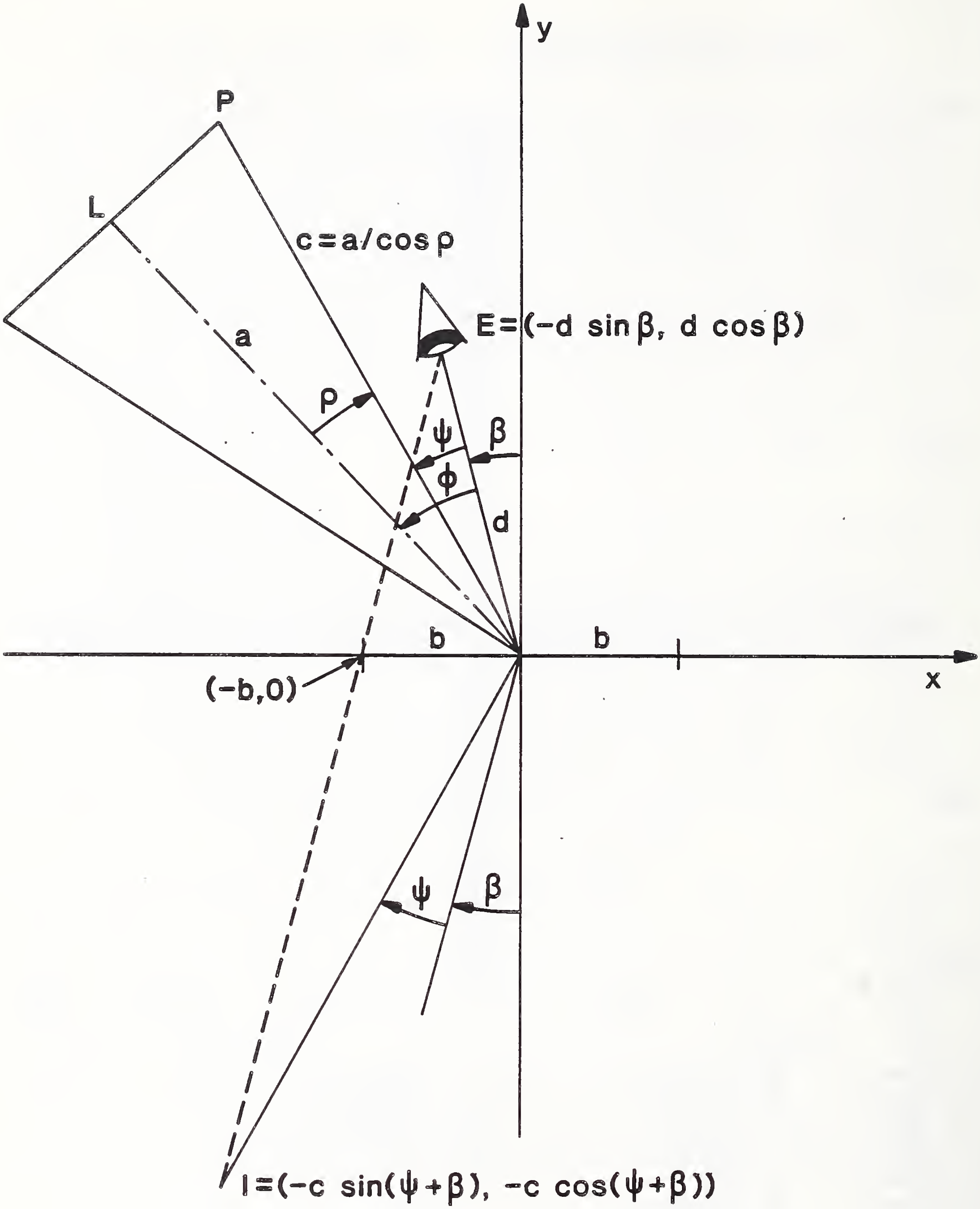

Figure 3. Two-dimensional version of Figure 1, with some important changes in notation. The eye and luminaire are in the x-y plane; the normal to the book coincides with the y-axis. Variables β, ρ, ϕ, a, b, and d have approximately their former meaning except that all angles are now positive as drawn. Fixing the mirror (book) in the x-axis simplifies finding the mirror image of a point; it has the same x-coordinate, but minus the y-coordinate. The final form of the answer is simplified by introducing two auxiliary variables: $\psi = \phi - \rho$, and $c = a/\cos\phi$.

While it does not appear that Eq. (1) can be solved for β in closed form, a numerical solution is easy---much simpler than the previous simulation. Eq. (1) would be expected to apply not only for a circular light source and circular book, but in any case, such as a rectangular book aligned with a long rectangular light source, where it is obvious what it would mean to tip away from the source. Then ψ should be interpreted as the angular separation between the line of sight and the near side of the luminaire. Also, c is the distance to that point from the center of the book. For instance, if the luminaire is a segment of a sphere centered on the origin, rather than a plane circle, Eq. (1) applies with c equal to the sphere radius.

Numerical solution of Equation (1) gives smooth versions of the graphs that could have been derived from Figure 2. These, giving β as a function of ρ are shown as Figures 4 and 5.

Figure 4 expresses quantitatively the extent to which the observer must tip his book farther as the light source becomes larger, for the case in which the source is at the convenient over-the-shoulder position of $\phi = 30°$. Where the β indicated is < 0, no tip is required. Figure 5 shows the more symmetrical case $\phi = 0°$. This placement of the light behind the head might give veiling reflections but not a strong shadow on the book, for large ρ. In any event, it is clear that some small tipping of a book from the line of sight is normal, and will serve to eliminate the image of the source if it is not too large; as the source becomes larger, the observer is forced to tilt farther.

Tilting away from the source has the detrimental result of reducing the luminance of the book, while the luminance of other background objects remains fixed. For the circular disk just considered, if the luminaire has exitance M and is a Lambertian emitter, and the book is a white Lambertian reflector, then the book's luminance is given by

$$L = cos(\tau) M \sin^2(\rho)/\pi. \tag{2}$$

Here τ is the book's angle of tilt measured from the luminaire axis; $\tau = \phi + \beta$. Eq. (2) was derived by integrating the contributions to luminance from each infinitesimal area of the luminaire. (Eq. (2) reduces to a formula in the IES handbook when τ=0, but it would be a false derivation simply to insert "cos(τ)" into the handbook formula.) In short, tilting it darkens the book, not what your mother had in mind when she told you to have a bright light over your shoulder. Tipping away from the line of sight has an unfortunate effect, beyond the obvious foreshortening of print on the page; it brightens the veiling image of whatever surface is now at the mirror angle from the eye---the wall, ceiling, or whatever. To describe this, we need first to discuss what surface reflection is, and why reading material is often printed on shiny paper. These topics are often misunderstood.

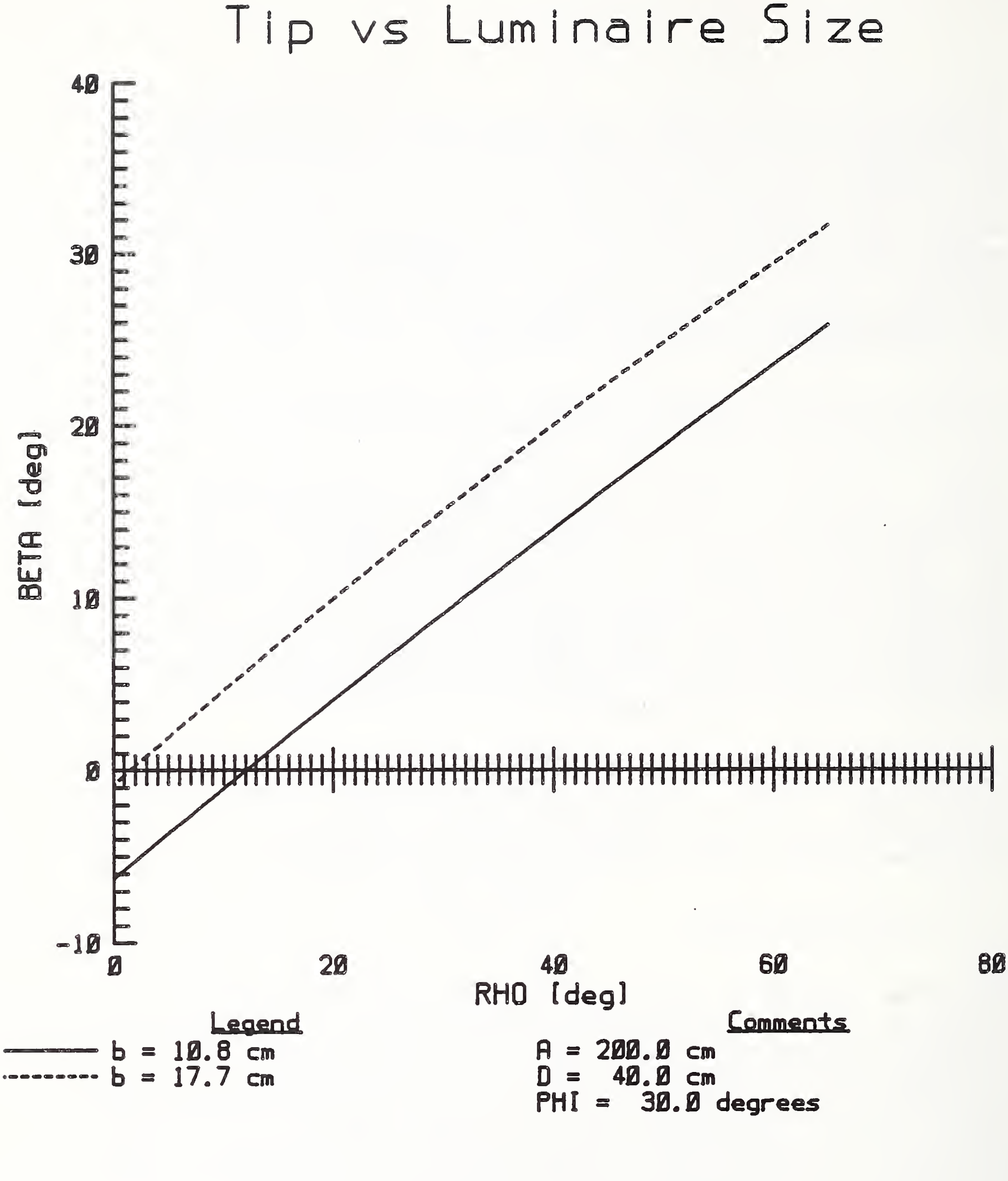

Figure 4. Minimum tip β, versus the luminaire size parameter ρ, for two values of the book radius. These curves, computed by numerical solution of Equation (1), are not quite straight lines. Here, the luminaire is over the shoulder ($\phi = 30°$).

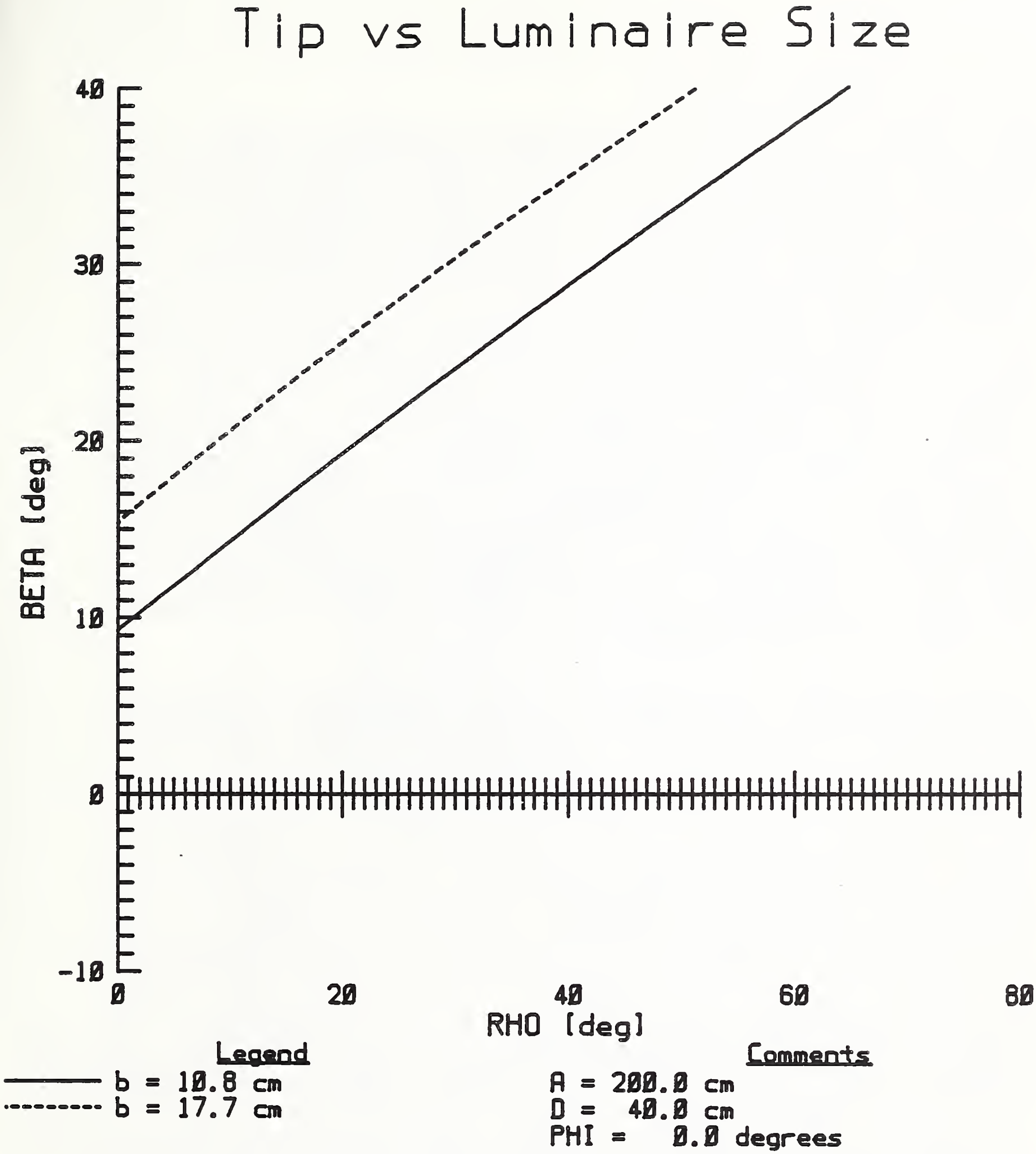

Figure 5. Similar to Figure 4. Now the luminaire is directly behind the head ($\phi = 0°$).

3. Surface and Body Reflections

Most objects in the everyday environment are dielectric solids[1]. While metals and self-luminous gases would fit quite different descriptions, dielectric solids generally fit the model of Figure 6, which is taken from Richard S. Hunter's classic book *The Measurement of Appearance*[2]. In this model, the non-metallic object consists of pigment granules dispersed in a transparent medium. Light which suffers multiple reflections from the pigment granules has two important properties: it is diffuse, even if the incident light was directional, and it is partly absorbed by the pigment, so that it differs in spectral power distribution from the incident light. That is, assuming that the incident light is more or less white, the diffusely reflected light has a color characteristic of the object. (We assume that the light provides good color rendering.) A fraction of the incident light which never reaches the pigment particles is shown in Figure 6 as Specular Reflection (white highlight). Light is reflected at the surface because of the difference in index of refraction between air and the object. In the case illustrated, the surface is shiny, so if the incident light is directional, as when lighting is by a point source, then the surface reflection will be directional, and will be seen by an observer as a highlight, that is an image of the point source. The highlight will NOT be colored by the pigment, but will have approximately the color of the incident light.

To reiterate, light is reflected from a shiny dielectric object in two distinct components. The specular, or surface component, is directional, and has approximately the color of the incident light---usually white. The diffuse, or body component, is non-directional and has the color of the object.

Considering such examples as a shiny black telephone, or a drinking glass, or the water in the glass, where the diffuse component is more or less absent, we see that the specular reflection can give important visual information, particularly regarding the shape of objects. This information is also available from shiny objects with a diffuse component, such as a pastel telephone, an oil painting, or a glossy magazine page. If lighting is by one or a few compact sources, or more generally if there are strong contrasts in the environment, then these contrasts will be imaged in the surface, and will give cues as to object shape. For example, highlights will tend to pile up in regions of high surface curvature. Thus, in many contexts, specular surface reflections give contrast, and visual information; in short, they give "sparkle."

A shiny object directionally lighted will display small, bright highlights; there are two ways these highlights can be lost. One way is to roughen the surface, by sanding it or painting it with a matte surface paint. The other is to make the light sources larger. Neither of these steps eliminates the reflections at the surface, which can only be reduced by anti-reflection coatings, as often used on camera lenses and now in some luminaires[3]. Roughening a surface only alters the nature of reflection at the surface, making it more diffuse, and less distinguishable from the reflection by the underlying pigment granules.

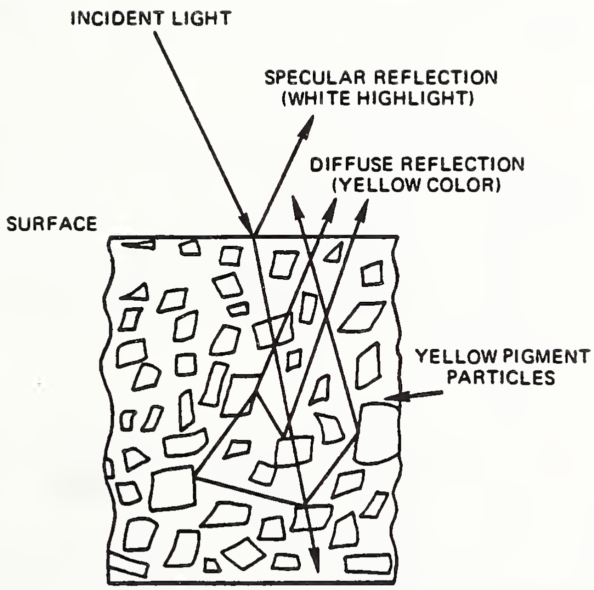

Figure 6. "Microscopic view of light striking a yellow plastic box. Diffuse reflection from an opaque, nonmetallic object is the result of many reflections by the particles inside the body of the object. These yellow particles selectively absorb some of the wavelengths of light, causing our eventual perception of the diffuse reflection as being yellow." (Figure and caption from *The Measurement of Appearance* by Richard Sewall Hunter, Copyright c 1975 by John Wiley and Sons, Inc. Reprinted by permission of John Wiley and Sons, Inc.)

Enlarging a light source also makes its image stand out less from the diffusely reflected background.

Perfectly shiny and perfectly matte objects are of course only extreme and idealized cases. Hunter[2] examines in some detail the ways in which glossy objects can depart from perfect specularity. Torrance and Sparrow give a theory of such departures[4]. Shafer[1] suggests using the terms "surface reflection" and "body reflection" to distinguish the two types of reflection without implying a particular degree of gloss. For present purposes, however, it will be instructive to think in terms of dichotomies: shiny and matte objects; specular and diffuse components of reflection from a shiny object. A purpose of this paper is to see what insights can be gained by putting aside the semi-specular examples that lead to "contrast rendering factor" and so forth.

Surface reflections can become "veiling reflections" when the underlying pigment consists of text or pictures, and the image of a light source or other surface is big enough and bright enough to lighten blacks and desaturate colors significantly. As we shall see, the surface-reflected image of a luminaire is almost always bright enough to do this. Veiling reflections are surface-reflected light that might have created a highlight and added sparkle (had the source been smaller), but instead are smeared across details of interest.

3.1. Poor Man's Anti-Reflection

Since making a surface matte does not eliminate surface reflections, a decision to have a matte surface is a decision to have a certain fixed level of surface reflections, with lightened blacks and washed-out saturated colors. This is a reason that many photographic prints, magazines, and other printing are given shiny surfaces. If the viewer is able to put a dark surface at the mirror angle, then the surface component of reflection at the eye can be well below that for a matte surface. In short, a shiny surface on a page is a poor man's anti-reflection coating. Of course a printer or photographer may not explain shiny surfaces in just these terms, but that doesn't matter. They don't need to understand what they are doing on such an abstract level, but an illuminating engineer should.

We now address the question of the intensity of surface reflections.

3.2. Some Basic Optics

In Figure 7, a ray of light passes from a medium whose index of refraction is n to one whose index is n'. Angle of incidence i, angle of refraction r, and angle of reflection r' are measured, as usual, from a line normal to the surface. The relationships among angles and amplitudes can be derived by assuming plane-wave solutions to Maxwell's equations and applying the proper boundary conditions at the surface[5,6]. Although we are not concerned with the refracted ray here, r is needed as an intermediate variable. Remembering Snell's law, $n\sin(i) = n'\sin(r)$, we have $r = \arcsin(n \sin(i)/n')$. Of course, $r' = i$. Now the incident

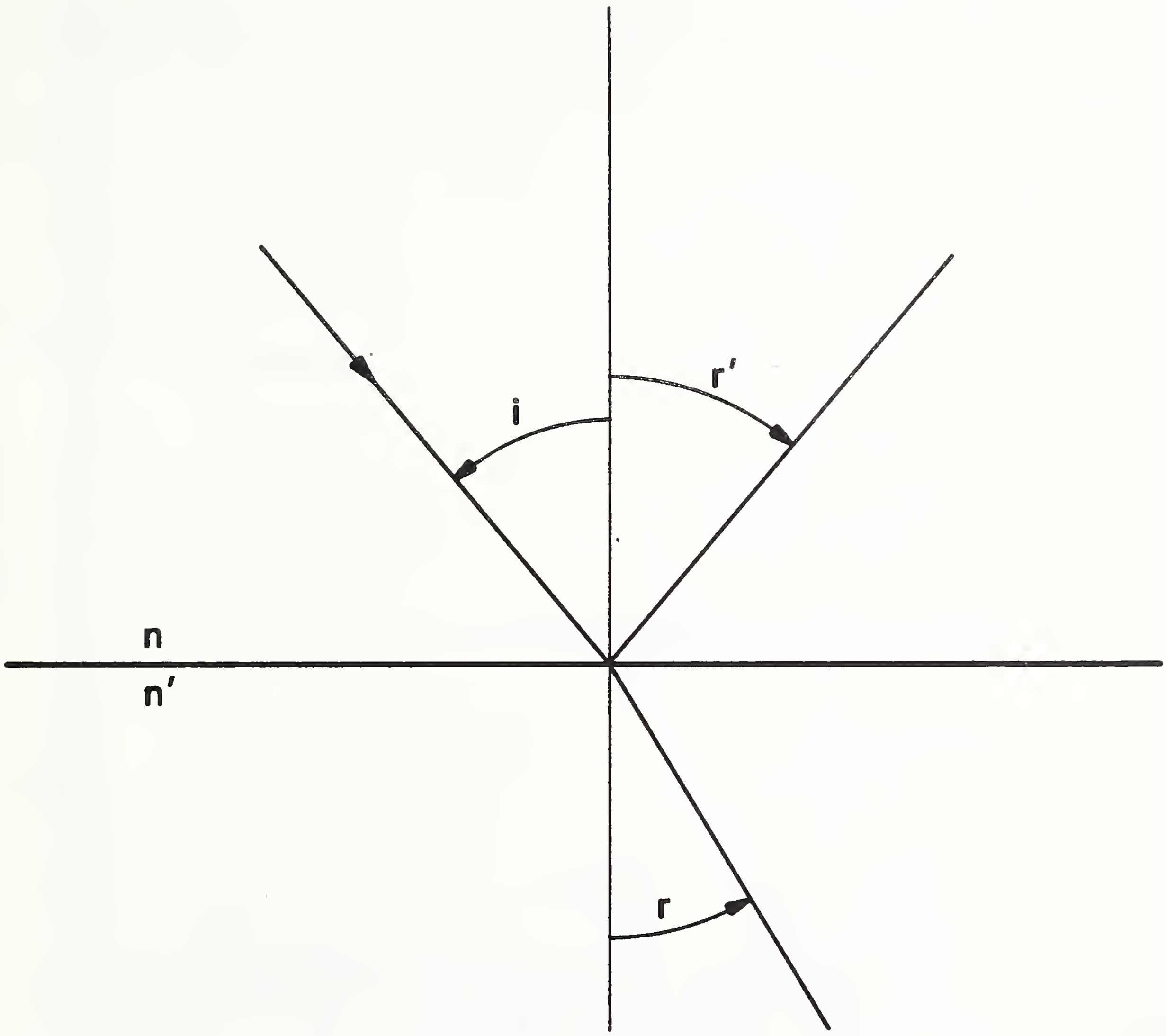

Figure 7. Definition of terms for the reflection and refraction of a light ray at a dielectric interface. The ray is incident within a medium of refractive index n. Angle of incidence i, angle of reflection r' and angle of refraction r are all measured with respect to the surface normal as shown.

ray and the normal line define a plane normal to the surface, the "plane of incidence." The reflected amplitude depends on the polarization of the incident light, that is whether the electric vector is parallel or perpendicular to the plane of incidence. If we let f be the "reflectance" of the interface, that is the ratio of reflected to incident light intensity, then for light polarized perpendicular to the plane of incidence,

$$f = \frac{\sin^2 (i - r)}{\sin^2 (i + r)} , \tag{3}$$

while for light polarized parallel to the plane of incidence,

$$f = \frac{\tan^2 (i-r)}{\tan^2 (i+r)} . \tag{4}$$

For normal incidence (i=0) both Eq. (3) and Eq. (4) reduce to

$$f = \frac{(n' - n)^2}{(n' + n)^2} . \tag{5}$$

Unpolarized incident light is equivalent to a mixture of the two polarizations in equal parts[5].

Figure 8 shows reflected fraction (in percent) as a function of incident angle, for the two polarizations and the polarized case. The indices of refraction were chosen as n=1 (corresponding to air) and n' = 1.5 (corresponding to some types of glass). This particular choice, often made in textbooks, gives a simple result for normal incidence: $f = (.5)^2/(2.5)^2 = 0.04$. That is, 4% of the incident light is reflected; for unpolarized light, the reflected fraction appears to remain constant up to about $i = 45°$. After that, it rises rapidly toward 100%; this says that for grazing incidence, almost any smooth dielectric surface will act like a mirror. This offers one reason why long corridors may present a particularly blank appearance; the walls and floor, seen at high angles of reflection, act like mirrors. Any pattern in the floor tiles or on the wall is subject to large veiling reflections. If what is seen in these mirror surfaces consists of blurred images of walls and ceiling that already were lacking in strong contrasts, the blankness of the scene is amplified. When it is considered that the main function of corridors is

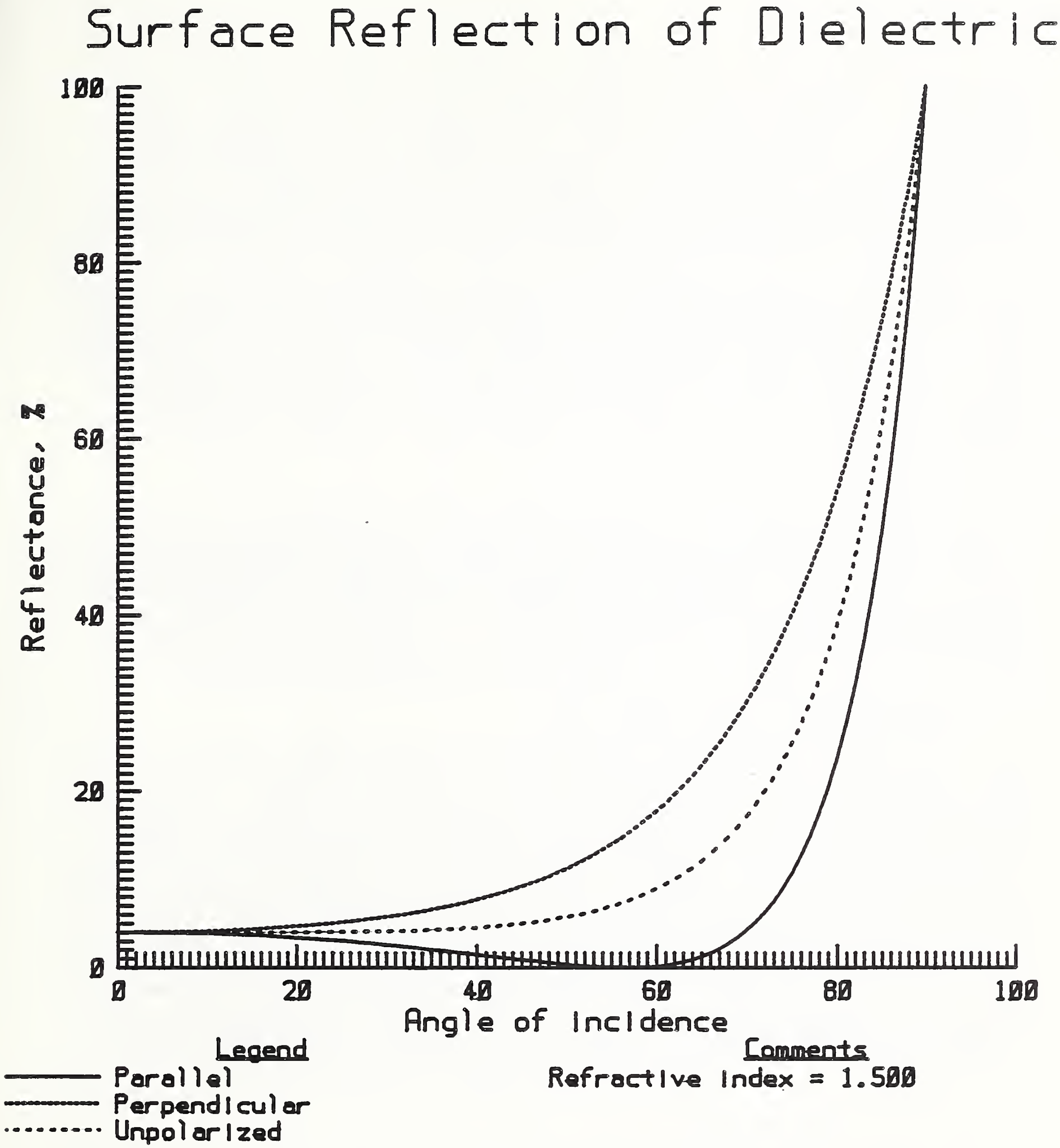

Figure 8. Surface reflection amplitude as a function of angle of incidence, for a ray striking a dielectric interface; $n = 1.0$, $n' = 1.5$. Amplitude is expressed as a fraction of incident, hence as a reflectance.

to permit people to walk down them, it does not seem out of place that these people should be given some strong contrasts by which to orient themselves, whether or not these contrasts encode other urgent information. Obvious remedies for the blankness of corridors include lighting them non-uniformly (with compact sources), or putting a window at the end. Realizing the role of surfaces seen at grazing angle, one sees that just putting a pattern in the floor tile or wallpaper on the walls will not go to the heart of the problem.

Over a wide range in the angle of incidence, a perpendicularly polarized beam is reflected much more strongly than a parallel-polarized one. At some critical angle of incidence---about 58 degrees when $n' = 1.5$---only the perpendicular-polarized light is reflected. In an optics laboratory, this can be exploited to make polarized light[6]. It has been the basis for various schemes to reduce veiling reflections by putting polarizers on light sources or over the eyes.

3.3. The Four-Percent Rule

In the remainder of this paper, "four percent of incident" will be used as a convenient estimate of the luminance of a veiling reflection. For precise work, one would want to measure the luminance of a veiling reflection, or refer to the formulas above. Of course, each dielectric interface contributes about four percent; a glass pane, or a spectacle lens, reflects a total of about eight percent of incident radiation.

3.4. Veiling Reflections in Black Glass

We now compute the magnitude of veiling reflections in an idealized case where the image of the luminaire is seen rather than avoided. Consider a small sheet of black glass next to a small matte white surface (a perfect, Lambertian reflector). Directly above the white surface is a uniform circular light source. (So long as the source is a Lambertian emitter, all that matters is the diameter it subtends at the object; it may be thought of as flat or as a segment of a sphere centered at the object.) Let the source have luminous exitance of M lumens/m^2, and let its subtense at the object be 2ρ. Then referring to Figure 9-29 in the 1984 Reference Volume of the IES Handbook[7] and the attendant discussion, we find that the illuminance at the object is $E_p = M \sin^2(\rho)$. Since the luminance of a perfect Lambertian reflector is E_p/π, the luminance of the white surface is given by

$$L(\text{white}) = M \sin^2(\rho)/\pi \qquad . \qquad (6)$$

In this idealized example at least, the diffuse component of reflection from the black glass may be taken as zero. Its luminance is thus the luminance of the luminaire image, seen reflected in the surface. If we let f_g be the fraction of incident light reflected by the surface (expressed as a percentage in Figure 8), then simply,

$$L(\text{glass}) = f_g \, M \,/\, \pi \qquad (7)$$

The ratio $L(\text{glass})/L(\text{white})$ is properly a "reflectance factor," that is the light reflected by an object in a particular geometry, divided by that which a diffusely reflecting white object would reflect in the same geometry[8]. For work related to vision of objects, it is useful to define "gray level" g as any ratio of a surface luminance to that of a white chosen as a reference. (In what follows, "a white" means "a diffusely reflecting white surface.") Thus, gray level may express reflectance of and/or illuminance on a surface. The gray level of the black glass is:

$$g = L(\text{glass})/L(\text{white}) = fg \,/\, \sin^2(\rho) \qquad (8)$$

If the white is assumed to have a shiny surface of reflectance f_w (still overlying a matte white, of course) then as the light source becomes smaller, the background gets brighter along with the glass, and the gray level---referred to the shiny background---approaches a limit of 1 (= 100%). Specifically,

$$g = f_g \,/[\, f_w + (1-f_w)\sin^2(\rho) \,] \qquad (9)$$

(Eq. (9) is only approximate for large ρ, but gives the correct limit as $\rho \to 0$.)

In Figure 9, the logarithm to base 10 of gray level (in percent) is graphed against ρ, assuming that $f_g = 4\%$. In such a plot, when the glass presents the same luminance as the white surface, log(gray level) = 2. The solid line corresponds to the matte white, while the dashed line is for the shiny white background. Thus, for small luminaire diameters, the black glass can be much brighter than the white surface. Letting ρ become 90° gives $g = f_g = 4\%$. In this case, the luminaire covers a hemisphere, and since the objects are flat, the result is the same as if they were in an integrating sphere. Thus we have another four-percent rule: for viewing perpendicular to the surface, veiling reflections under spherical lighting have four percent the luminance of a white.

Yet another simple rule can be noted here. When the lighting reaches hemispherical---equivalent to spherical so long as the task is flat---then the white has the same luminance as the luminaire. This gives a simple way to compare a lighting installation to spherical lighting. If the ceiling or other "dark" surface that is imaged in the task, after it has been tipped to hide the luminaire image, has a luminance equal to that of the white part of the task, then the veiling reflection has the gray level that it would have under spherical lighting. If it is darker or lighter, then the veiling reflection will be lower or higher.

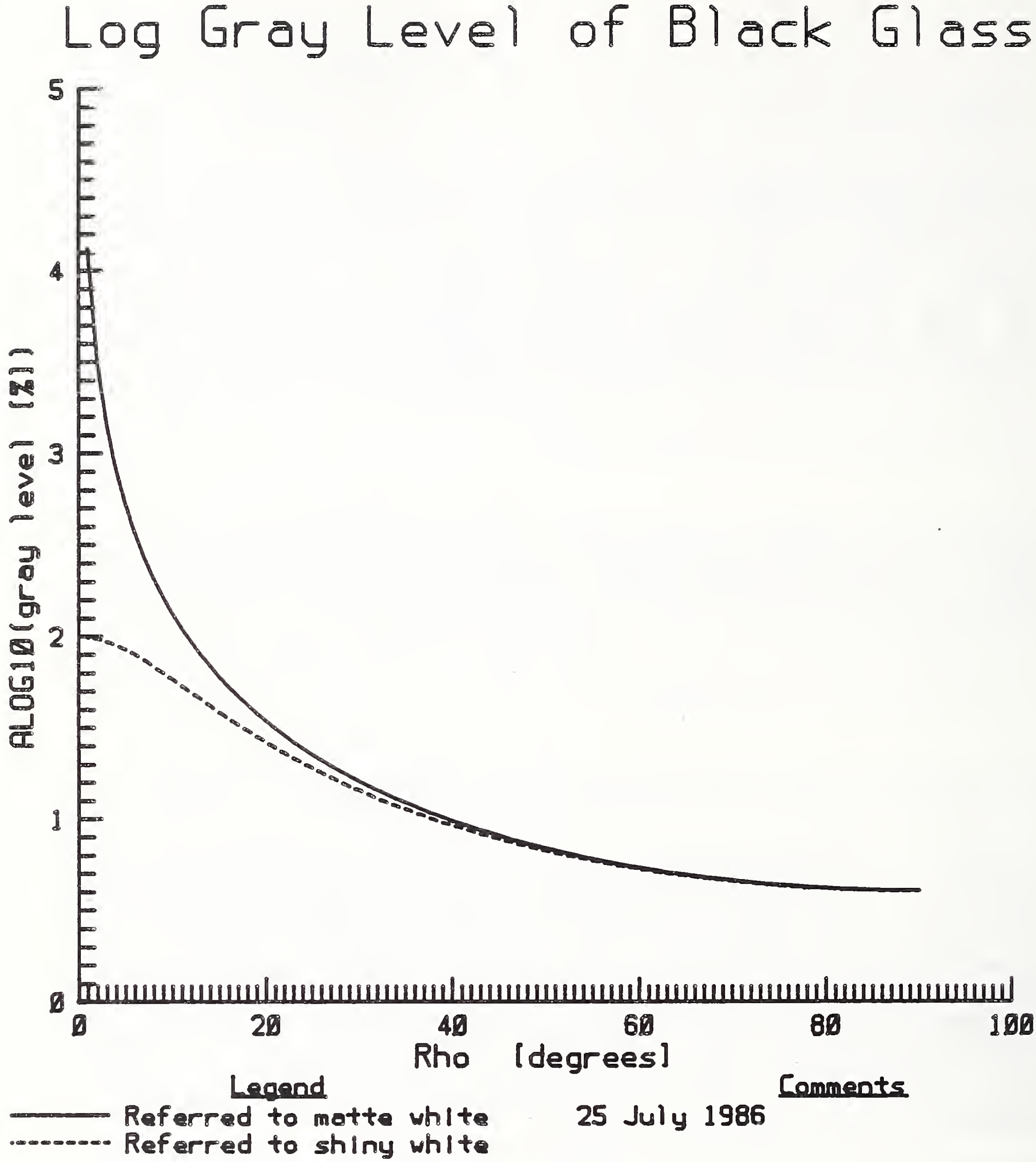

Figure 9. Logarithm to base 10 of the gray level of black glass, for viewing normal to the surface, as a function of the luminaire size parameter ρ. If a matte white is the reference, the black glass gets ever brighter than white as ρ decreases [Eq. (8)]. If the reference white is shiny, the gray level approaches a limit of 100% [Eq. (9)].

3.4.1. Interpretation

The black glass can be considered a model for black print on white paper. If the paper is not tipped to remove the image of the light source from the field of view, veiling reflections cause the gray level of what is nominally "black" to be four percent or higher. Of course, if the luminaire image can be moved off the paper then, in this idealized case, the gray level of the black can be reduced to zero. While it has a luminance higher than a diffuse white, the image of a single small light source is not a veiling reflection but a highlight, easily moved off the paper, or even a source of information concerning a curved surface.

3.5. Non-Linearity of Lightness Perception

It might appear that four percent is a "negligible" gray level, but this is not so. The human visual system responds non-linearly to gray level, in such a way that the bottom few percent of the gray scale correspond to a comparatively large fraction of the perceptual scale between black and white. This fact is expressed by the cube-root nonlinearity incorporated into the definition of the CIELAB uniform color space[9], as well as the nonlinear relationship of Munsell value V to luminous reflectance Y. In fact, Munsell value can be well approximated by a cube-root relationship (for $Y > 0.384$ %)[10]:

$$V = 2.539\, Y^{(1/3)} - 1.838 \qquad (10)$$

where Y is luminous reflectance in percent. Thus, the choice of a method to represent the non-linear relationship of perceived lightness to directly measurable gray level is not a critical one. Of course the CIELAB scale maps white (100% reflectance factor) into $L^* = 100$, whereas in Munsell value, white is 10. The Munsell value scale was determined so that equal value increments represent equal numbers of just-noticeable differences in lightness to a human. This scale was found to be consistent with a different set of data produced by asking subjects to choose a gray that bisected the interval between two other grays[11]. Thus, Munsell Value is a reliable and non-controversial means to describe the way humans see blacks, grays and whites.

On the Munsell scale, a gray level of four percent corresponds to value = 2. In other words, spherical illumination discards 20% of the dynamic range of black-white perception. If the image of a smaller-than-hemispherical light source veils a surface, even more of the gray range is lost. Perhaps the most troublesome lights, in the range of simple ones discussed here, are those of intermediate angular radius, say 30-50 degrees. These do not contribute sparkle, do block a large range of orientations if one seeks to prevent veiling reflection, and make a veiling reflection that is even brighter than that in the spherical case.

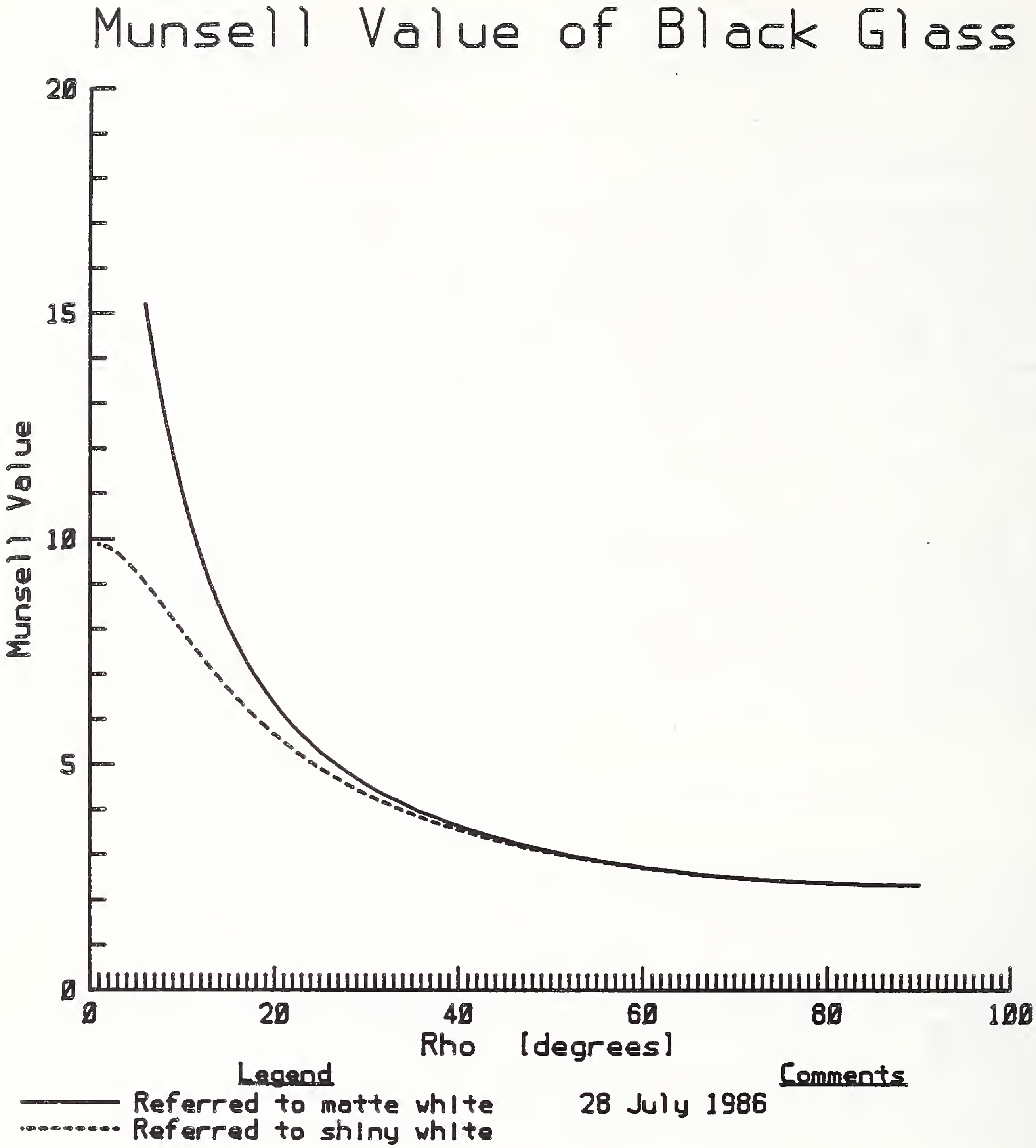

Figure 10. Munsell value of black glass, for viewing normal to the surface, as a function of the luminaire semi-subtense ρ.

Figure 10 is similar to Figure 9, but displays Munsell value rather than log of gray level on the y-axis. Figure 10 was derived using the defining polynomial for Munsell value[12], rather than Eq. (10). We see, for instance, that veiling reflections from a luminaire of angular semi-subtense 27 degrees (diameter 54 degrees) put a floor under lightness that discards half the eye's gray scale.

The reader may object that veiling reflections do not "really" make blacks look lighter to the extent indicated. After all, the eye can recognize the veiling reflection for what it is, discount it, and see what is behind it. Gilchrist and Jacobsen showed experimentally that this is true in some situations; however, it is not true for a flat abstract-art collage of black and gray papers (a Mondrian)[13]. Thus it is least likely to be true for the kind of flat task that "veiling reflections" work is traditionally concerned with. Also, Gilchrist notes that even when a veiling luminance is "discounted," it may still be seen; it still degrades perception. There is also a simple physical reason why a veiling reflection of a few percent may not be negligible. That is that a veiling reflection which is a few percent of white may equal or exceed the luminance of a detail that it veils. Imagine, for instance a dark wooden (or wood-grained plastic) table-top. Its average reflectance factor (with surface reflections excluded) is about five percent (author's measurement). Variation about this average is what constitutes the visible wood-grain. A veiling reflection of four percent of white is comparable to the mean body reflection and details involve variations of even smaller amplitude. In short, the veiling reflection is not small relative to the thing it veils.

4. The Concept of a "Color Solid"

We now examine the effect of veiling reflections on colored objects, and in particular on the range of colors which can be seen.

If a patch of light is created in a physics laboratory by a mixture of red, green, and blue lights, then this light may be described by a set of three numbers which may vary independently from zero up to the limit of radiant power available. If the three numbers are taken to comprise a vector in cartesian space, then this vector can vary within a rectangular parallelepiped bounded by the energy limits---a simple and perhaps not very interesting fact.

Now consider the range of ordinary non-self-luminous objects, which are seen only by reflected light. If the illuminant spectral power distribution (SPD) is specified, then three numbers (called tristimulus values) can be calculated, or measured, which describe the object as a stimulus to vision. This would be done by the ordinary methods of colorimetry, and might lead to the familiar tristimulus values X, Y, Z, for instance. If the illuminant is held fixed, the variation of the vector (X, Y, Z) is now limited by the condition that the spectral reflectance function of the object varies only between zero and one. This limits (X, Y, Z) to a curved solid, whose shape incorporates information concerning the light source, human vision, and the constraint on spectral reflectance. This "color solid" expresses the trade-offs involved in attempting to make pure colors with pigments; a pigment can isolate one wavelength band only by absorbing other wavelengths. Therefore, a saturated ("strong") pigment color will in general be a dark one; only yellow pigments can be both light and saturated.

Now the luminance of an object, on an absolute scale, is a poor measure of whether a person will see the object as white, gray, or black; the object's luminous reflectance factor is a much better measure[13]. This fact, that perception of lightness is comparatively independent of light source intensity, is called "lightness constancy." Put a different way, blacks and grays are perceived in relation to white. Similarly, colors are seen in comparison to white, so some color constancy may occur[14]. Since the eye, in short, tends to see the reflectance properties of pigments, it is customary to express the range of possible pigment colors in a way that ignores absolute illuminant intensity.

If a standard light source, such as Illuminant C, is considered to light the objects, then the source SPD can be considered as background information and a color solid can be taken to represent the boundaries of object color perception by humans. Any realistic object spectral reflectance function will map to a point within or on the surface of this solid, and that point can be related to a color name, such as "dark red," "pale blue," or to some appropriate set of three numbers which will predict the object's color appearance. White will appear at the top and black at the bottom. Descriptions of two such color solids, apparently written by Dorothy Nickerson, appear in the American Heritage Dictionary at the entry word "color."[15] The exception that proves the rule with respect to color solids is fluorescent pigments. These violate the restriction that light radiated cannot exceed light incident at each wavelength; and indeed the eye can recognize this, that a fluorescent pigment displays a combination of lightness and saturation which is outside the limits of normal pigments.

A convenient basis for calculations involving pigments is the CIELAB uniform color space[9]. CIELAB maps any object color into three numbers L^*, a^*, and b^*. L^* represents lightness, with $L^* = 100$ representing white. Roughly speaking, a^* represents redness (if > 0) or greenness (if < 0) while b^* represents yellowness (if > 0) or blueness (if < 0). The starting point for computing (L^*,a^*,b^*) is usually $(X,Y,Z)_O$ of the object, plus $(X,Y,Z)_W$ for a reference white similarly lighted. The CIELAB calculation is invertible: given $(X,Y,Z)_W$, $(X,Y,Z)_O$ can readily be recovered from L^*, a^*, b^*.

4.1. Effect of Veiling Reflections on Object Color

The concept of a volume of possible colors provides a general way to discuss lighting effects on color. Brill and Howland advanced the idea of a volume-gamut index[16]; Thornton and Chen have discussed it in a general way[17] and Xu has exploited it[18] for the purpose of describing color-rendering effects, though Xu did not use the term "volume". We now look at the effect of veiling reflections on the limits of perceived object colors. Color rendering, meaning the effects of the source SPD, is NOT a variable in this discussion. While many discussions of color solids are based on the absolute mathematical limits imposed by assuming spectral reflectance always less than one[19], we start with a different definition of the limits of the color solid.

Michael R. Pointer determined the limit of "real" surface colors by making a search for examples of actual pigments displaying high saturation. He started with the commercially available "Munsell Limit Color Cascade," which is a set of 768 saturated color samples[20], and then extended this set with tabulated data and fresh measurements of other colors, for a total of 4089 colors. From these, he mapped the limits of the "real" color solid in CIELAB space (as well as another color space, L* u* v*), reporting the data in both graphical and tabular form[20]. The reference illuminant for all data was Illuminant C. Pointer found it most revealing to deal with CIELAB space in a cylindrical polar co-ordinate version. In this scheme, which is part of the official definition of CIELAB,[9] the axial co-ordinate is L^*, and the radius and hue angle (c^*, h^*) are the polar version of (a^*,b^*). Thus, L^* corresponds to the psychological dimension of lightness; c^*, the radial co-ordinate, corresponds to perceived saturation of colors, and h^* goes around the color circle, from red (about 0°) to yellow (about 90°), green (about 180°), through blue (about 270°). Whites, grays, and blacks of course lie along the L^* axis ($c^* = 0$).

Pointer's data have the merit of realism, and it is actually much easier to type them into a computer file than to write a program which computes points on the theoretical extreme limits of the color solid. It was therefore asked how much a given level of veiling reflections would reduce the volume of Pointer's color solid in CIELAB space, based on the desaturation and lightening that surface reflection will cause. In accord with the data, the veiling light source was taken to be Illuminant C. Veiling luminance was set to 4%, 8%, 12%, and 16% of the reference white. Results are presented in Figure 11 for four of the 36 constant-hue planes. The effect of adding white to a particular color is shown by an arrow, with its tail at the initial saturation (c^*) and lightness (L^*) and arrowhead at the new values. Successive additions of four percent to each limit color result in a chain of arrows. The first 4% represents the veiling effect of spherical illumination. It will be seen that this "small" admixture of white light causes a great loss in the range of dark and saturated colors available, while it does add a smaller amount to the range in the area of light colors of medium saturation.

Two effects are at work here. One is that since the white light is a fixed color on the axis, its addition pulls all other colors toward the middle, reducing their differentness. This effect would show up in virtually any color space, and would always act to shrink the volume of the solid. The other effect is not a purely physical one; it is that the arrows at lower luminance levels are longer, meaning that a fixed increment of radiant power has a greater effect when added to a darker color. This is the non-linearity of human vision which was described above when the effect of white added to black was expressed in terms of Munsell value. It is incorporated into CIELAB in the form of a cube-root transformation.

4.2. Volume of the Color Solid

The net effect of veiling reflection is to reduce the volume of the color solid. The volume of a polyhedron determined by the limiting colors was computed, based on the complete set of Pointer's data as given at ten-degree increments in hue angle. (A slight ambiguity arises in going from the set of points to a set of surfaces, which was resolved by favoring local convexity. This minor technical decision is expected to have little effect on the relative loss of volume as veiling reflection is increased.) At the successive 4% steps in veiling luminance, the volume is reduced to 63%, 46%, 35%, and 28% of its initial value. In other words, spherical illumination reduces the number of different colors that can be seen by 37%. Sixteen percent veiling reflection, corresponding to the image of a luminaire of 30° semi-subtense, will reduce the number of colors by 72%.

As pointed out earlier, giving a colored surface a matte texture is similar to making it shiny and then viewing it under spherical illumination. The surface reflections are spread over a hemisphere. Thus, the 37% reduction in number of colors gives an indication of why colored pictures in particular are often given shiny surfaces. Of course, photographic print papers cannot achieve the full gamut of colors that Pointer spanned with many distinct pigments, so the 37% number does not apply directly. But the fact that the use of three pigments limits the color gamut of photographic papers[20] is all the more reason to conserve

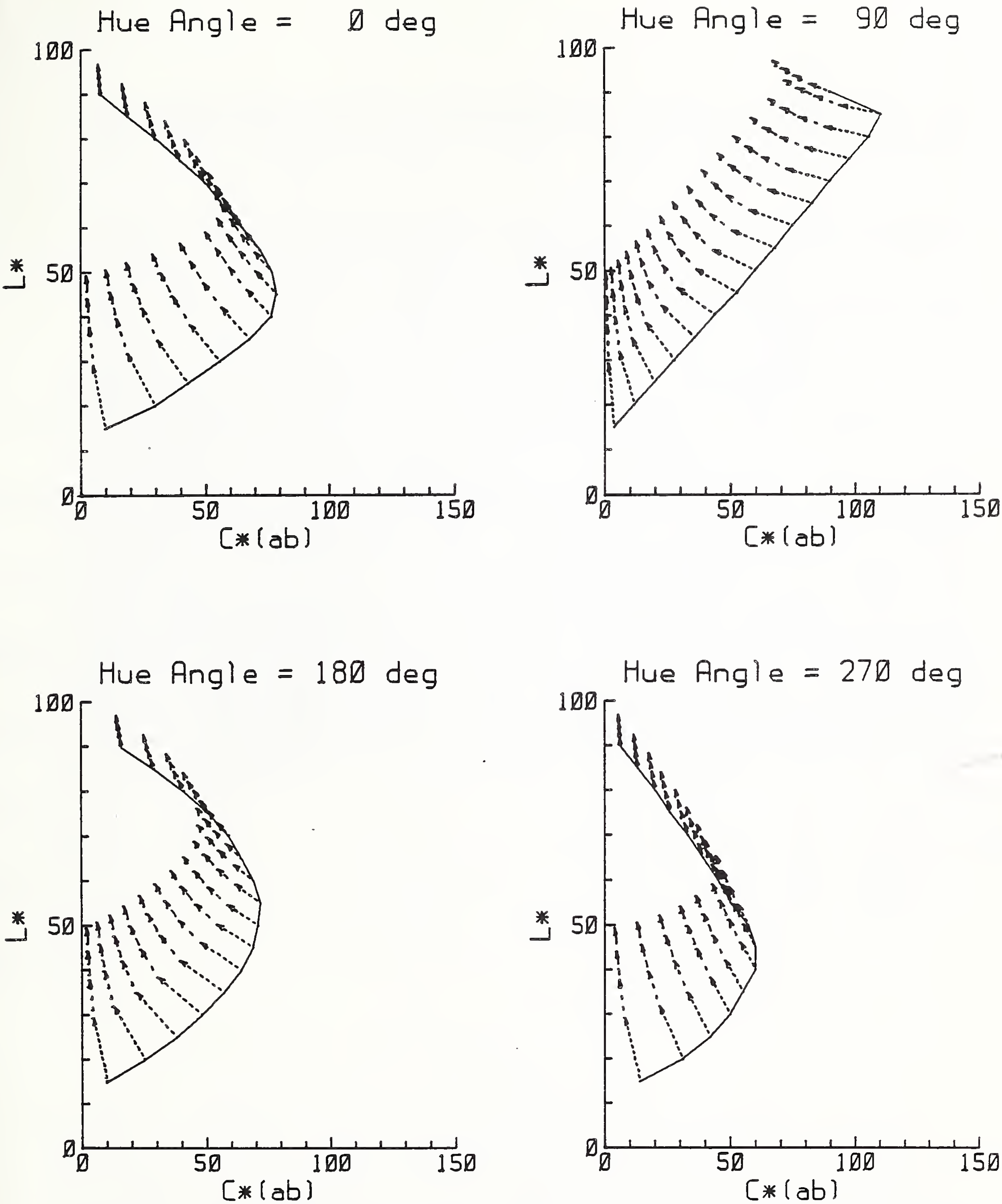

Figure 11. Reduction in the range of lightness and saturation of surface colors due to veiling reflections. Data are plotted in the cylindrical-polar version of the CIELAB uniform color space, at four selected hue angles (h^*). Radial coordinate c^* represents saturation, while axial coordinate L^* is a measure of lightness. The solid lines represent the limits attainable with real pigments, according to Pointer[20]. Chains of arrows show successive shifts as veiling reflection is increased to 4%, 8%, 12%, and 16% of white. At these selected hue angles, the shifts stay in the constant-hue plane, but at other h^* values, they don't. At all hue angles, including those not shown, a similar systematic loss of saturation and of lightness range occurs.

the remaining color solid by control of surface reflections. Best controlof surface reflections comes from giving the surface a high gloss and then viewing the picture with a "light trap"---a very dark surface---at the mirror angle.

The decrease in possible saturation of colors can be seen in the differences between the matte and glossy sets of Munsell papers. Munsell papers are a commercially available[21] set of color-painted papers based on the Munsell uniform color space[12,22]. There are currently about 1600 notations exemplified in the glossy finish collection but only 1300 in the matte finish collection. For numerous technical reasons, these numbers are not a direct measure of the volume of glossy and matte color solids, but do give some clue as to the practical loss of variety in matte colors. Since Munsell notation is inherently a cylindrical system, similar to the cylindrical version of CIELAB, the nature of the matte-glossy difference can be exemplified in diagrams at constant hue, similar to Figure 11. Figure 12 shows two constant-hue slices through the set of available papers, with available glossy papers denoted by rectangles. For instance, the rightmost rectangle in the top row under "10Y" indicates that there is a glossy paper for notation 10Y 9/6. (10Y indicates hue, a yellow; 9/ tells the Munsell value; and 6 indicates chroma or saturation.) The heavy line encloses those rectangles for which a matte paper is available. At hue 10Y, we see that eight hues are lost, but two are gained in going from glossy to matte. At hue 2.5R (a red), nine hues are lost and none are gained. The solid line bisects the rectangle for 2.5R 2/2 to indicate that a chip is sold at 2.5R 2.5/2. Where possible, matte chips are made with value 2.5, since none can be made with value 2. In the neutral series, the pure whites, grays and blacks, the glossy series goes down to value 0.5/, while the matte series stops at 1.75/ on the black end.

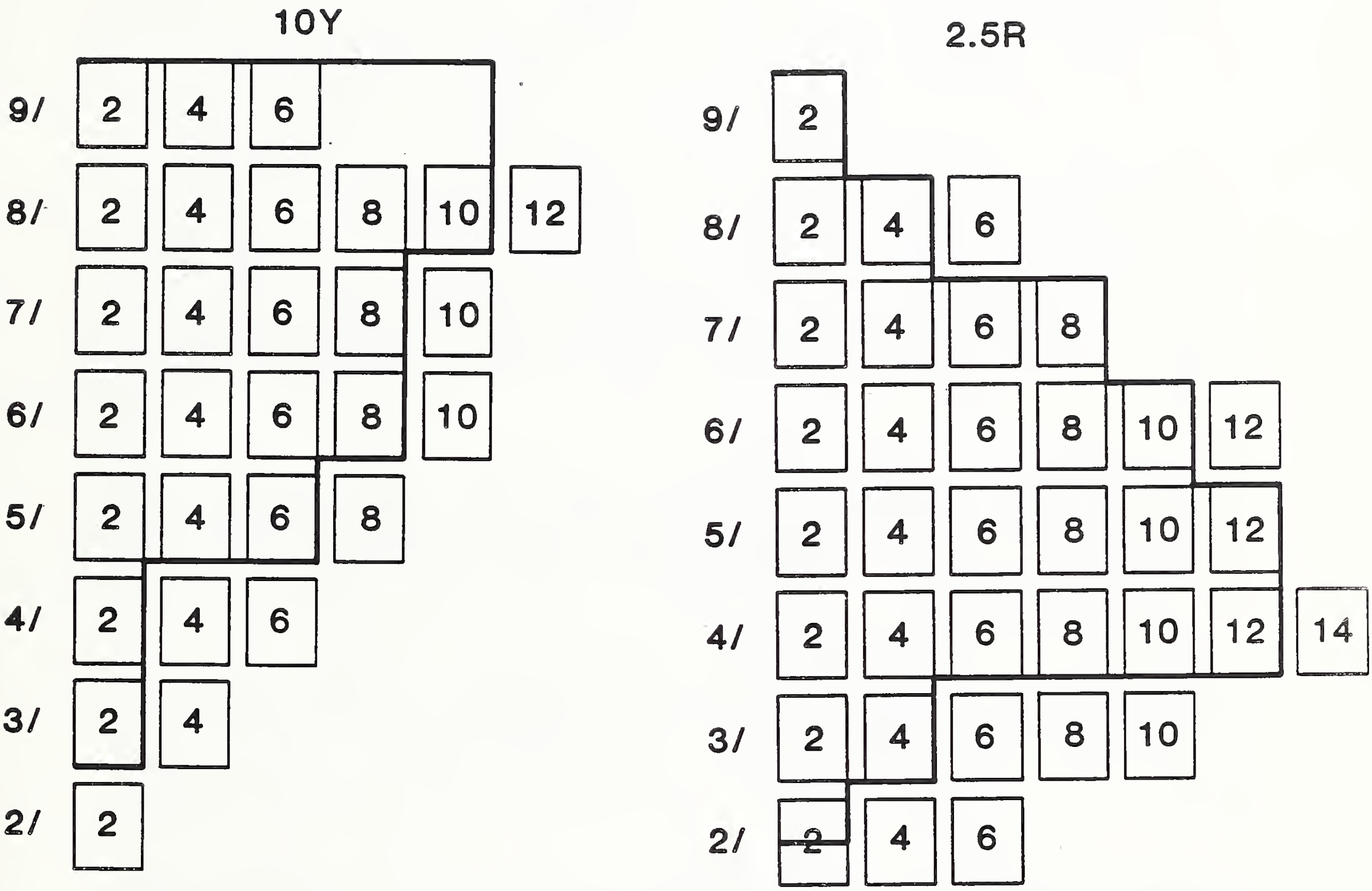

Figure 12. Comparison of the range of Munsell colors available in the glossy and matte sets. Two constant-hue planes (10*Y* and 2.5*R*) are shown, similar to Figure 11. Rectangles with numbers stand for glossy chips that are available. The heavy line indicates the range of matte chips available. For instance matte chips are available, but not glossy ones for notations 10Y9/8 and 10Y9/10. Glossy papers, but not matte, are available for 10Y4/4 and 10Y4/6.

5. Summary and Conclusions

It is characteristic of engineering in general to deal methodically with facts that are basically simple. The man in the street knows that bridges should be strong, that a big beam is stronger than a small one, that water pressure increases with depth. Yet a bridge engineer is distinguished by his ability to deal quantitatively and methodically with these facts (and many others). The present paper has attempted to deal methodically with some of the simple facts that bear on lighting design: You don't want a luminaire at the mirror angle with respect to a flat task. If lighting is by a single small luminaire, you can easily tip the task to move the luminaire image away. As the luminaire gets larger, you have to tip the task farther, until at some point it is inconvenient or impossible to do so. As the luminaire gets larger, its image gets dimmer relative to a white, but it never gets so dim that it's negligible. The eye tends to see grays, blacks, and colored pigments as if it were comparing them to a white object. The eye's response to blacks, grays and whites is non-linear; a small change in the luminance of a black is much more noticeable than a similar change to a light gray or white. Highlights and veiling reflections, the images of a light source that appear on dielectric objects, tend to be white, rather than the color of the object. Shiny surfaces can and often do display blacker blacks and more saturated colors than matte-surface objects (Why do people wax furniture and cars?). But a shiny surface has little effect in a blank environment---spherical lighting conditions.

Any discussion of lighting depends on simplifying assumptions. Our particular discussion of veiling reflections and of the perception of lightness and color started with a simple and extreme model of veiling reflections. That is, the task has a flat, shiny surface and the observer can tip it if necessary. The luminaire has a well-defined edge and beyond that is a dark surface.

To summarize in one recommendation, we may say that your mother was right: you should read with a light over your left shoulder. The light should be fairly compact, and there should be a dark surface near it that can be put at the mirror angle from your book. As to how dark that surface should be, it would be nice if it is darker than the white paper of the book itself.

A second recommendation starts with the observation that the veiling reflections in a flat surface comprise a somewhat artificial case. Even books and papers can be curved, and many other objects certainly are. To provide clear seeing of black and colored objects in general, it would be nice to provide one or more large dark areas somewhere to be imaged in the surfaces of these objects. This will provide the best chance of seeing blacks and colors clearly.

The simplicity of these recommendations brings into focus the fact that no single idea in this paper is entirely new. In a local museum, for instance, oil paintings are lighted from above by spotlights, which puts the luminaire image above the frame for a standing viewer. Further, the walls behind the viewer are painted a medium gray---perhaps Munsell value 5. Here, the non-linearity of lightness perception works to advantage, since value 5 is perceptually a middle lightness, but has only 20% the luminance of a white. The fact that the paintings are lighted more brightly than the walls goes even further to reduce the relative luminance of the wall image in a painting's surface. The use of small sources means that the surface reflection that remains unavoidable, due to the texture of canvas and brushstrokes, takes the form of tiny highlights which reveal that texture

Relative to such successful designs as this museum lighting case, the purpose of this paper has been to show that such designs can be understood in quantitative technical terms. Art and engineering need not be thought of as mutually exclusive.

On a technical level, it is probable that some of the simple calculated results have been presented elsewhere before. The purpose of this paper, however, has been to put the problem of veiling reflections in a proper context of physics and visual science, and to exemplify an approach to lighting based on explicit assumptions and cause-and-effect reasoning. Because the assumptions have been openly stated, the reader may find that it is easier to disagree with some things that have been said than is the case where assumptions are hidden---as they often are in discussions of lighting. Clearly stated disagreements may help clarify technical issues and are to be welcomed.

Finally, I have in this paper made a departure from many other works on lighting by not making reference to observer "performance." Instead, I have talked about perception, and have implicitly taken the view that "clear seeing" should be a major goal of lighting design. We have found that "clear seeing" need not be a nebulous or difficult concept in the context of lighting. The lighting environment controls the range of blacks and colors that are available to an observer. This is, of course, the familiar problem of contrast, but I focus the discussion by observing that in our everyday environment, filled with dielectric solid surfaces, it is the blacks and saturated colors that are in jeopardy, not whites and pastels. Also, I avoid expressing contrasts in terms of ratios at arbitrarily selected borders; instead, I express them in terms of the well-established CIELAB and Munsell schemes, which better describe the way that people see objects. That is, CIELAB and Munsell space model in an approximate way the fact that objects are seen in context as white, gray, and black, and as saturated or desaturated colors; also, they model the non-linearity that governs such perception.

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The problem of veiling reflections in flat reading matter is examined in three theoretical analyses. These assumptions are made: (1) The surface is shiny, so that surface reflections can be treated as creating a mirror image. (2) The light source has a non-zero area. (3) Insofar as it matters, the reading material has non-zero area also. The first analysis assumes that the reader can tilt the reading material. The extent to which a larger luminaire forces him to tilt farther from his line of sight and from the incident light is then computed. The second analysis assumes that the luminaire image is not avoided. Then, the smaller the luminaire is, the brighter its image will be, relative to a diffuse white surface; this effect is expressed in a formula and in graphs. The overall implication of the first two analyses is that while veiling reflections are not negligible with spherical illumination, the worst light sources are those of intermediate size, whose image is hard to avoid, yet brighter than in the spherical case. The final analysis shows that when veiling reflections cannot be avoided, they desaturate colored objects. For instance, spherical illumination reduces the accessible volume in the CIELAB uniform color space by 37%.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

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