LBL-10514

Cost-effective visibility-based design procedures for general office lighting

Robert Clear and Sam Berman

General office lighting visibility specifications were analyzed with respect to optimization of cost effectiveness. Cost effectiveness is a function of visual performance, not visibility per se. It was found that the present procedures which utilize ESI are not readily adaptable to cost optimization calculations. An alternative procedure using log VL is presented which appears suitable for this use. A sample calculation of net benefits versus light level is presented. For the same calculation the net benefits from visibility saturate at lower levels of visibility than are normally prescribed for office environments.

Introduction

The concept of cost benefit analysis leads directly to the use of visual performance (i.e., the speed or accuracy with which a visual task is performed) rather than derived metrics such as ESI or VL as the basic visibility related performance parameter. The 1977 IES Design Committee's recommended specification procedure[1] does not have visual performance in its formulation and hence will not lead to cost-effective general lighting designs. We discuss the direct calculation of average relative visual performance (RVP) and then present a reasonably accurate approximation which has significant advantages in speed and flexibility. Finally, we attempt to assess the conditions under which this procedure will provide useful information.

Cost benefit analysis and visibility

The basic idea of cost-benefit analysis is to treat any decision as an investment decision and then to evaluate its cost effectiveness. Thus, a decision on how a building is to be lighted can be thought of as an investment decision. In a complete analysis the investment must be considered to have both a fixed cost, consisting of the materials and installation costs, and an operation cost, consisting of both maintenance and energy costs. By discounting the yearly operating costs and prorating the fixed costs of the installation over its expected life, a total annual cost figure can be calculated. Balanced against this cost is the discounted value of the benefits in an office or industrial environment. The improved lighting is generally considered to provide benefits in the form of increased productivity. Since productivity has a very high value even small increases would pay for fairly major investments in the lighting.

The actual implementation of a cost benefit analysis is often not as straightforward as the foregoing description might seem to imply. In lighting design it is unfortunately very difficult to *isolate* and measure the effects of the specifiable aspects of a lighting system (e.g., footcandles, ESI, etc.) on productivity. Simple correlations are inadequate because of the lack of control over confounding variables such as work load, age, motivation, temperature, etc. Dealing with this problem has essentially shaped the direction of much of the recent vision research. The approach that has been used to get around this difficulty is to measure "visibility" and visual performance under laboratory conditions where confounding variables can be better controlled.

In these experiments, visibility is defined with respect to the "threshold" detection levels of a reference task and is measured by VL or ESI. The types of tasks that are examined in the visibility experiments have ranged from identifying the correct orientation of Landolt rings[2] to proofreading checks or even performance scores on the Davis Reading Test.[3] Visual performance for these experiments is generally considered to be some combination of speed and accuracy: attributes which determine real productivity for clerical or industrial tasks. The different experiments can be compared in common units by separating the visual and nonvisual components of performance and then normalizing the visual component scores to their maximum values. The resulting relative visual performance (RVP) component can be fit as a function of visibility as measured

---

A paper presented at the Annual IES Conference, August 24 through 28, 1980, Dallas, Texas. AUTHORS: Lawrence Berkeley Laboratory, University of California, Berkeley, California.

by either ESI or VL (see Visual performance and ESI section). If visual performance is the dominant rate limiting process in a real environment, and if the lighting does not influence productivity in any other manner, *then* changes in RVP, calculated from changes in visibility will be approximately proportional to changes in real productivity. Thus, under these assumptions the cost effectiveness of a lighting system can be examined by analyzing the visibility under the lighting.

To determine the most cost effective lighting, the proportionality constant between RVP and actual productivity would have to be known. However, comparative judgments between different lighting systems can be made at a fixed RVP without knowing the proportionality constant. Furthermore, since RVP is a function of visibility, cost effectiveness comparisons can be made at a fixed visibility. Thus, a specification in ESI or VL makes sense in that one can expect that the RVP, and presumably the productivity, will be the same under all lighting systems built to the specification. Choosing the best system is then simplified to choosing the cheapest system (in annual or life cycle dollars) since the benefits are identical for all the systems.

The situation is somewhat different when there is more than one value of visibility or RVP of interest. For instance, if there are several work locations in a room, then the total productivity should be approximately proportional to the sum or average of the RVPs of the locations. If the work locations in the room are unknown, then the expected value of productivity will be approximately proportional to the expected value of RVP, which is just the average of RVP over the working area. However, as we show in the Visual performance and ESI section and Exact and approximate calculations of RVP section, the spatial average values of visibility and visual performance are not as simply related as were the point values. In these sections we evaluate ESI and $\log_{10}$ VL measurements in terms of how well they can be used to approximate the average value of RVP ($\overline{\mathrm{RVP}}$), and thus how well they can be used to judge relative cost effectiveness as a function of visibility.

Visual performance and ESI

There are a number of semi-empirical expressions for the relationship between relative visual performance, RVP, and visibility. The simplest expression for this relationship has the form of the standard error function of statistics:

$$\mathrm{RVP}(x,\alpha) = \frac{1}{\gamma\sqrt{2\pi}} \int_{-\infty}^{x} e^{-((x'-\alpha)/\gamma)^2/2} dx'. \qquad (1)$$

In this equation RVP is the relative visual performance, γ determines the slope of the fit, and is a function of α, a fitted parameter which corrects for the intrinsic visual difficulty of the task:

$$\gamma = .187 + .228\alpha \qquad (2)$$

and finally x is the logarithm of the visibility level:

$$x = \log_{10} \mathrm{VL}. \qquad (3)$$

RVP can be related to ESI via the relationship between VL and ESI[4]:

$$\begin{aligned}\mathrm{VL}(C_{eq},L_b,\mathrm{CRF}) &= \mathrm{VL}(C_{eq},\rho x\mathrm{ESI})\\ &= C_{eq}[a((b/(\rho x\mathrm{ESI}))^{.4} + 1)^{-2.5}]. \qquad (4)\end{aligned}$$

In this equation the first factor C_{eq}, is the "equivalent" contrast, which is the contrast of a reference target of equal visibility to the target of interest. The term in brackets is the contrast sensitivity (the inverse of the threshold contrast) of the reference task at the ESI of interest. In this term a and b are fitted constants (a = 16.847, b = .4784), and ρ is the reflectivity of the task. The ESI is calculated from the background luminance, L_b, and the contrast rendition factor, CRF. A typical relationship between RVP and ESI is shown in Fig. 1 of the Interpretation and conclusions section.

This RVP expression is fairly successful in fitting the results of detection visibility experiments. To extend the fit to more general experiments it is necessary to correct for time spent on non-visual components of a task, such as motor response or cognition. An expression for relative performance, RP, that has been proposed for these more general experiments separates the fraction of the task that is visually related, v, from the nonvisual fraction, (1 − v):

$$\mathrm{RP} = v(\mathrm{RVP}) + (1 - v). \qquad (5)$$

Reference 2 graphs a number of different experiments against this function, and these graphs show that reasonable agreement is possible as long as visibility is not too low.

A more recent and complicated expression for RP presented in CIE 19/2 separates the visual components of the task into visual subprocesses each of which has the form of the RVP expression in Eq. 1:

$$\mathrm{RP} = \sum_{j=1}^{5} w_j(\mathrm{RVP}_j) + \left(1 - \sum_{j=1}^{5} w_j\right). \qquad (6)$$

The w_j are proportions needed for each subprocess and the RVP_j are the relative performance rates for each visual subprocess. CIE 19/2 gives the formulas for the α_j and γ_j for the RVP_j. However it appears unlikely that existing performance data is sufficiently precise to warrant the use or allow the validation of this more complicated expression.[5,6]

The major deviations of the data from Eq. 5 are at low visibilities. However this problem arises because visual and non-visual components are simply added. The non-visual component is a time, but the original experiments for RVP measured accuracies. Since the accuracies are measured for fixed exposure times, RVP also measures speed (inverse time) at fixed accuracy.[7] The two components can be combined in consistent units by adding times. It can be shown[7] that this gives

$$\mathrm{RP} = ((1 - v) + v/\mathrm{RVP})^{-1}. \qquad (7)$$

Here v is the ratio of the minimum time required for the visual fraction of the task to the minimum total time for the task.

Table 1. Characteristics of the ESI distributions.

Case	Direction	Mean ($\bar{x}$)	Standard deviation (σ)	Skewness (s[*])	Kurtosis (k[†])	(75[‡])	Percentiles 75th	85th	95th
Example I									
	North	39.7	18.1	.134	2.05	21.3	23.6	18.7	12.5
	South	42.7	17.6	−.069	2.04	23.6	26.8	19.9	13.1
	East	47.6	23.1	.170	1.87	22.5	28.4	20.9	13.5
	West	55.8	22.1	−.215	1.95	34.3	38.5	29.4	17.9
Example II									
	North-South	86.8	39.8	.070	2.07	—	55.2	41.3	23.1
	East-West	85.3	27.0	−.243	2.31	—	66.9	55.2	36.1
	Total	86.1	34.0	.020	2.71	—	60.6	48.0	29.1
Simulation		77.4	3.89	−.210	2.46	—	74.4	72.8	70.8

[*] Skewness = m_3/σ^3 where m_3 is the 3rd central moment of the distribution.
[†] Kurtosis = m_4/σ^4.
[‡] This column gives the values that are at least above the 75th percentile with a 90 percent confidence limit, given a random sample size which is the same size as the grids actually used.

Equation 7 gives zero performance at zero visibility while Eq. 5 (and 6) give non-zero performance at this limit. The added terms in Eq. 6 allow a better fit near the low visibility limit, but it still retains the inconsistent addition of times and accuracies.

As a practical matter usually only relatively high visibilities and productivities are likely to be of interest to the lighting engineer. At high visibilities Eqs. 5 and 7 (and even 6) give almost the same results. In fact Eq. 5 is the first two terms of the Taylor's expansion of Eq. 7 about RVP = 1. Thus the major determinant of accuracy at high visibility is not the form of the RP Eq., but the specification of visibility and the uncertainty in the relationship between RP and productivity. The effective visibility is affected by viewing angle, tilt angle, orientation of subject and task, age of subject, type of task, glare, polarization, condition of the room, etc.[5,6] It is impractical to measure all these factors, and their effects are often not well understood.[7] Furthermore at high visibilities the assumption that RP is the dominant factor in productivity is likely to be poor. Changes in RP will be small, thus factors such as the fraction of time, F, spent on visual tasks, social pressure, or fatigue and comfort may be the dominant factors in determining productivity. Since in general the influence of these factors is very poorly known, uncertainties in the visibility-RP relationship will be relatively unimportant for realistic environments.

The calculations in this paper are based on Eqs. 1–5. We expect that the results will not be significantly different if Eq. 6 is used. The present calculations are noticeably easier and less time-consuming than calculations with Eq. 6.

Since Eq. 5 is linear in the relationship between RVP and RP we can calculate the average relative performance, $\overline{RP}$, from the average relative visual performance, $\overline{RVP}$ (the bar represents the average). In practice we use the relationship

$$\overline{RVP} = \frac{1}{n} \sum_{i=1}^{n} RVP_i \qquad (8)$$

to estimate $\overline{RVP}$. Here the RVP_i are the RVP values at different locations in the room and n is large. Actually the range of RVP_i was small enough in our sample calculations that $\overline{RVP}$ could be used to calculate $\overline{RP}$ from Eq. 7, which is non-linear, with insignificant error (maximum .2 percent, typical .01 percent). However, the relationship between ESI and RVP is very non-linear and the spread in ESI is large; therefore there is no a priori reason to expect a simple relationship between the average value of RVP and simple parameters (such as the average) of the ESI distribution.

The Design Practice Committee of the IES appears to have partially recognized this problem in that their recommended procedure for ESI specification in general lighting does not use average ESI ($\overline{ESI}$). Instead, the designer specifies a percentage of the work area that has at least the recommended ESI value for the work. A procedure is given for generating a grid of points over which ESI is calculated to determine percentile values of ESI. If this procedure produces an excessive number of points for calculation, a sampling procedure is used to estimate the percentile values for the grid. The report recommends that a percentage work area criteria of at *least* 75 percent be used and gives examples of 85 percent to 95 percent. The higher values are used for "critical" or difficult tasks. Critical tasks are those which have a high economic return. The use of the sampling technique effectively raises the percentile criteria. In order to provide an 85 percent to 99 percent level of confidence that the room as a whole meets the percentile criteria, the sample must meet a higher percentile criteria. Thus, for example, to provide an 85 percent confidence level that 75 percent of the locations in a room meet the criteria value requires that 80 percent of the points in a 100 point sample meet the criteria. Therefore the use of a 100 point sample in this case has effectively raised the percentile criteria level from 75 percent to 80 percent.[1]

Tables 1 through 3 display the results of sample calculations of percentile ESI, and $\overline{RVP}$ values.

Table 2. Values of $\overline{RVP}$ for the example in Table 1.

Case	Direction	Average relative visual performance*		
		$\alpha = .3$	$\alpha = .5$	$\alpha = .7$
Example I				
	North	.986 ± .007	.886 ± .028	.683 ± .042
	South	.987 ± .006	.891 ± .024	.690 ± .038
	East	.987 ± .006	.892 ± .027	.694 ± .043
	West	.989 ± .005	.901 ± .022	.708 ± .035
Example II				
	North-South	.991 ± .004	.914 ± .021	.730 ± .035
	East-West	.992 ± .002	.917 ± .012	.736 ± .021
	Total	.992 ± .004	.916 ± .017	.733 ± .029
Simulation		.992 ± 0	.918 ± .001	.735 ± .003

* Mean and standard deviation of the distribution of RVP values in the room.

These results illustrate some flaws in the percentile specification procedure. These sample results were calculated from the data of examples I and II of the appendix of the Design Committee Report on the specification of ESI.[1] Table 1 gives ESI parameters and percentile ESI values for these distributions. It also lists the results for a simulated almost uniform ESI distribution to show how the percentile criteria procedure favors uniformity. Strictly as a matter of convenience the new almost uniform distribution was calculated by transforming the data x (x = ESI), for the west direction of example I, to give new data $x' = 67.61 + .176x$. This new data gives a nearly uniform distribution that might represent a luminous ceiling.

Table 2 presents the means and standard deviations of the RVP values calculated from the ESI values for the examples in Table 1. There are two notable features of these values. One is the startingly low variation in RVP for easy tasks (α low). The second is the stability of relative $\overline{RVP}$ rankings for different installations with changes in α.

In Table 3 we calculated the ESI levels that correspond to the $\overline{RVP}$ values at different values of α ($ESI(\overline{RVP}_\alpha)$), by substituting $\overline{RVP}$ into Eq. 1 and solving for ESI.[7] $ESI(\overline{RVP}_\alpha)$ is the visibility that corresponds to the average visual performance in the room, and can therefore be used to judge the relative performance of different lighting installations. In the last two columns of the Table we compare these values at $\alpha = .5$ to the 75th and 95th percentile ESI values. At the 75th percentile criteria the two examples from the IES Committee Report have percentile ESI values that are from 15 percent to 34 percent lower than ($ESI(\overline{RVP}_\alpha)$). At the 95th percentile criteria the percentile values are from 113 percent to 194 percent lower than $ESI(\overline{RVP}_\alpha)$. By comparison, the percentile ESI values from the almost uniform distribution are only from 4 percent to 9 percent lower than the actual visibility.

All of the percentile ESI values underestimate visibility, indicating that this specification procedure will result in higher visibility than the IES specification for individual tasks. This is true even at the 75th percentile level which is supposed to be for easy non-critical tasks. For critical tasks (e.g., 95th percentile level) the variability in the ratio of $ESI(\overline{RVP}_\alpha)$ to percentile ESI values (see Table 3) shows that there is little relationship between the percentile ESI level and the actual visibility. Thus the percentile specification is not useful in ensuring good or optimal visibility for these critical tasks and is almost useless as a visibility based specification procedure. To be useful the specification must either give $\overline{RVP}$ directly or be closely related to it. In the next section we briefly discuss the direct calculation of $\overline{RVP}$ as a

Table 3. Comparison of percentile $\overline{ESI}$ values to $\overline{ESI}$ values calculated from $\overline{RVP}$ for the examples in Table 1.

Case	Direction	ESI ($\overline{RVP}$)			Ratio: ESI ($\overline{RVP}$ $\alpha = .5$)	
		$\alpha = .3$	$\alpha = .5$	$\alpha = .7$	ESI (75%)	ESI (95%)
Example I						
	North	29.9	31.7	32.7	1.34	2.54
	South	33.6	35.3	36.2	1.32	2.69
	East	34.5	36.8	38.1	1.20	2.58
	West	43.8	46.1	47.3	1.20	2.58
Example II						
	North-South	63.1	67.7	70.0	1.23	2.93
	East-West	75.2	76.9	77.9	1.15	2.13
	Total	68.8	72.0	73.8	1.19	2.47
Simulation		77.2	77.3	77.3	1.04	1.09

Table 4. Characteristics of the $\log_{10}$VL distributions.

Case	Direction	Mean ($\bar{x}$)	Standard deviation (σ)	Skewness (s)	Kurtosis (k)
Example I					
	North	.8659	.0404	−.8598	2.763
	South	.8729	.0366	−1.092	3.252
	East	.8766	.0414	−.9075	3.078
	West	.8906	.0344	−1.425	4.953
Example II					
	North-South	.9139	.0356	−1.605	5.764
	East-West	.9190	.0217	−1.286	5.676
	Total	.9164	.0296	−1.673	7.468
Simulation		.9182	.0027	61.46	265.4

specification procedure and then present an approximation for $\overline{\mathrm{RVP}}$ which has some advantages over the direct calculation.

Exact and approximate calculations of RVP

At present one method of computing an RVP from the existing computer programs is to use Eqs. 3 and 4 from the section on Visual performance and ESI to convert the ESI values to $\log_{10}$VL values and then use Eq. 1 to calculate RVP values. This involves substantial extra effort and computer time. Further the computation is relatively inflexible in that the whole distribution has to be recalculated for each different value of α or C_{eq}.

We can derive an approximation to $\overline{\mathrm{RVP}}$ by assuming that the distribution of $\log_{10}$VL values in a room is approximately normal.[7] This leads to a double normal integral that can be simplified to the following single integral:

$$\overline{\mathrm{RVP}} \approx \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y} e^{-z^2/2} dz \qquad (9)$$

where

$$y = \bar{x} - \alpha)/\sigma_t, \qquad (10)$$

$\bar{x}$ is the mean of the $\log_{10}$VL distribution, and

$$\sigma_t = (\sigma^2 + \gamma^2)^{1/2} \qquad (11)$$

where σ is the standard deviation of the $\log_{10}$VL distribution, and z is simply the variable of integration. If $\sigma < \gamma$, we get a simpler approximation by assuming that

$$\sigma_t \approx \gamma. \qquad (12)$$

In fact if σ is small both approximations will be fairly good even if the $\log_{10}$VL values are not very well fit by a normal distribution.[7] Equation 9 has the same form as Eq. 1 and is again just the standard error function of statistics. Thus, in this approximation the values $\bar{x} = \overline{\log_{10}\mathrm{VL}}$ and σ are determined and then $\overline{\mathrm{RVP}}$ is determined for any α by substituting the appropriate values into Eqs. 9, 10, and 11. Furthermore, from Eq. 4 we can see that the use of a different task with a different value of $C_{eq}(C'_{eq})$ merely adds a constant K to $\log_{10}$VL, where

$$K = \log_{10}C'_{eq} - \log_{10}C_{eq}. \qquad (14)$$

The computation of $\log_{10}$VL in a computer program such as Lumen II should be no more difficult than the computation of ESI. Both are relatively simple functions of the contrast rendition factor, or CRF, and luminence L, each evaluated at the point of the analysis. Furthermore, it should be easier to compute a mean and standard deviation of $\log_{10}$VL than it is to compute and plot the distribution of ESI values.

As a guide to determining the likely accuracy of the procedure, we again analyzed the examples given by the Design Practice Committee's report on specification procedures. Table 4 lists the parameters of the $\log_{10}$VL distributions for these examples. The parameters of the simulated distribution are also listed although the simulated distribution was not included in the error analysis.

Table 5 presents an error analysis for the approximation given by Eqs. 9, 10, and 11. Columns one and two show that the error in estimating $\overline{\mathrm{RVP}}$ was completely negligible over the range of α's tabulated. Spot checks for higher and lower α's gave similar results.

In order to achieve at least partial consistency with the presentation of the error for the percentile ESI procedure, we show in the third column the percentage error in ESI calculated from the above $\log_{10}$VL approximation (ESI (calc)) relative to ESI calculated from the actual average relative visual performance, (ESI($\overline{\mathrm{RVP}}_\alpha$)). Even though ESI is sensitive to changes in RVP, particularly for α small (RVP → 1) the error was less than 2 percent and the typical error when $\alpha \geq .5$ was .1 percent, which is better precision than the original tabulation of ESI

Table 5. Error analysis for the first approximation.

	Absolute Error	Percentage Errors	
	RVP (calc)- $\overline{\mathrm{RVP}}$	100 (RVP-(calc)-$\overline{\mathrm{RVP}}$) / $\overline{\mathrm{RVP}}$	100(ESI(calc)-ESI($\overline{\mathrm{RVP}}$)) / ESI($\overline{\mathrm{RVP}}$)
α = .3		%	%
Maximum	.00009	.01	1.8
Typical	.00006	.006	1.0
.5 < α < .9			
Maximum	−.00008	−.015	+.2
Typical	−.00006	−.008	−.1

values. For comparison, in Table 3 we displayed the ratios of actual to computed ESI values in place of percentage errors because the errors were so large that the symmetry of the percentage error computed against the calculated and the actual values, respectively, had been lost.

Examination of the values of σ in Table 4 reveals a fairly wide variation in value. However, all of the values of σ are small with respect to γ so the approximation of σ_t by γ (Eq. 12) is fairly good. Table 6 gives the error analysis for the approximation obtained by substituting Eq. 12 for Eq. 11. The error from this approximation in estimating $\overline{\text{RVP}}$ is up to ten to twenty times the error from the first approximation. Nevertheless it is probably still well within the precision of Eq. 1 as a fit of VL to the visual performance data. Again, the percentage error in estimating ESI is substantially larger than the percentage error in $\overline{\text{RVP}}$. Note, however that the maximum error of 13 percent is necessarily found under conditions where variations in ESI are relatively unimportant. For more visually demanding conditions the error of estimation of $\text{ESI}(\overline{\text{RVP}}_\alpha)$ is less than 5 percent. These errors are still substantially smaller than the errors found using the percentile ESI approach.

As an aside, we note one more feature of this type of approximation. The reduction of double Gaussian integrals to single integrals can be applied to simplify distributions in $\log_{10}C_{eq}$ that are approximately normal,[2,7] just as easily as it is applied to $\log_{10}$VL distributions.

Interpretation and conclusions

We assume that RP is directly related to productivity, Pr, by the fraction of work, F, that is visually related:

$$\text{Pr} = \text{F(RP)} + (1 - \text{F}). \tag{13}$$

An example of how RP varies with lighting conditions follows from Table 2 of the section on Visual performance and ESI. For easy tasks ($\alpha = .3$) even major changes (2x) in ESI cause only .5 percent changes in RVP which should cause statistically insignificant changes in RP (< .5 percent). For more difficult tasks ($\alpha \geq 5$ percent), the changes are more significant but the overall level of performance is substantially lower. In a case like this there are greater returns from modifying the task than from improving the lighting.

Table 6. Error analysis for the second approximation.

	Absolute Error	Percentage Errors	
	$\text{RVP(calc)}-\overline{\text{RVP}}$	$\frac{100\text{x}(\text{RVP(calc)}-\overline{\text{RVP}})}{\overline{\text{RVP}}}$	$\frac{100\text{x}(\text{ESI(calc)}-\text{ESI}(\overline{\text{RVP}}))}{\text{ESI}(\overline{\text{RVP}})}$
$\alpha = .3$		%	%
Maximum	.00104	.11	13.1
Typical	.00070	.07	10.
$\alpha = .5$			
Maximum	.00219	.25	5.4
Typical	.00150	.17	4.
$\alpha = .7$			
Maximum	.00120	.17	2.2
Typical	.00090	.12	1.5
$\alpha = .9$			
Maximum	−.00024	−.05	−.3
Typical	−.00010	−.02	−.1

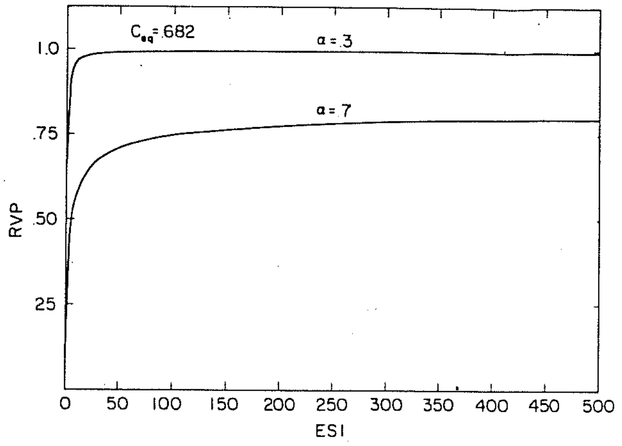

Figure 1. Relative visual performance as a function of visibility (ESI).

Figure 1 shows a plot of how RVP varies with ESI at two levels of task difficulty. This is the same type of information available from Table 2. To get a cost benefit curve requires detailed information on how the costs vary as a function of ESI and the level of the productivity expected at RP = 1. A set of four illustrative curves were derived for Fig. 2 by making assumptions about these parameters. We replaced ESI by footcandles on the horizontal axis by assuming that CRF could be made to equal one for all the systems (note that a CRF of one is higher than usual practice). The costs per resultant footcandle were assumed to be proportional to footcandles. A quick estimating guide[8] was used to estimate installation costs. Operating costs were calculated at the stated cost per kWh by assuming 30 maintained lm/w delivered to the work surface. The costs per kWh essentially span the costs that are likely. Productivity

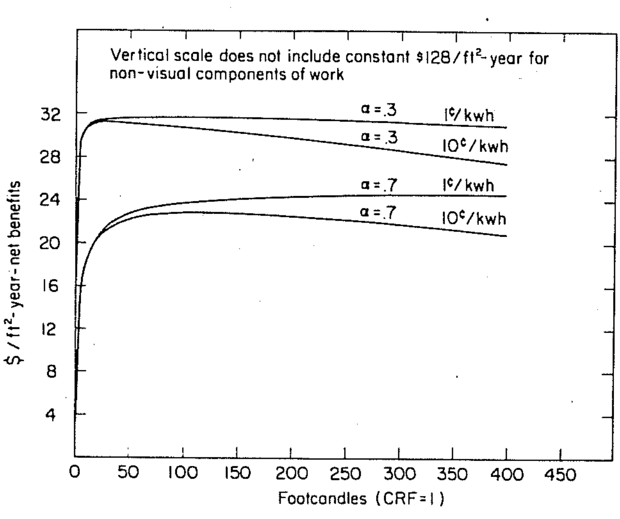

Figure 2. Net economic benefit, under illustrative conditions, as a function of light level.

was calculated by assuming an average of 100 ft^2 per worker, an output of \$16,000 per year and values of $v = .4$ and $F = .5$ (see Eqs. 5 and 13). The resultant curves should be at least illustrative of how the benefits vary with increasing light levels.

These curves confirm the trends shown in Table 2. The most important criteria in productivity are again the intrinsic difficulty α, and the intrinsic contrast C_{eq}, of the task. The most significant feature of these curves with respect to light level is their relative flatness near their maximums (note that there is a suppressed zero in this graph so that relative changes are even smaller than shown). As we noted earlier the relationship between the RP function and actual productivity is subjected to major uncertainities. In addition, the future cost (and even availability) of electricity is very uncertain. When these uncertainties are coupled with the flatness of the net benefit curves near their optima, we find that the actual location of the optima for any installation is very uncertain.

This situation leads to a decision based on minimizing risks. For example, IES recommendations have traditionally been made in the form of minimum levels. This is a rational type of standard for a period characterized by rising productivity and consistently falling electrical costs, since the cost of overlighting tends to be insignificant. However, present electrical costs are rising and thus there is a substantial cost (risk) in overlighting. In this situation maximum and minimum levels, or perhaps target levels, are more appropriate than just a specification of a minimum level. The GSA 10-30-50-70-100 standard is an example of this approach. In terms of the cost benefit curves, rising electrical costs imply that the lighting levels should be set lower than the optimal level as calculated at present electrical costs. The distinct knee of these curves as plotted provides a convenient visual cue as to how low light levels can be reasonably set.

The cost curves in Fig. 2 are as sensitive to the area that is lit per worker as they are to the cost of electricity. Thus another response to rising electrical prices is task lighting.[9] The shape of the net benefit curve at high values of RVP is mostly dependent upon the cost per kWh divided by the area lit per worker. Lighting a 10 ft^2 area on a desk instead of a 100 ft^2 working area per worker is almost equivalent to going from the 10 cents per kWh curve to the 1 cent per kWh curve. Clearly the potential for considerably higher light levels, and thus higher performance levels, are attainable through task lighting. General lighting can then be designed for aesthetics, comfort, or interest, since the visibility of easy tasks is almost guaranteed by meeting these criteria. In fact, as shown in Fig. 2, a level of from 10 to 20 ESI, which at this level is almost equivalent to footcandles, provides adequate visibility for easy tasks. These types of lighting criteria may call upon the designer and architect[10,11] more than the lighting engineer.

These illustrative examples indicate that visibility should perhaps not be the criteria used for general lighting, that instead, visibility constraints can be potentially more cost effective when met by task lighting. The Exact and approximate calculations of RVP section will be useful in helping managers to make intelligent decisions based on their present and predicted costs. The material in this section provides an example of how the RP and RVP functions can be used. It further points to information needed to predict meaningful cost effective lighting designs. In particular, F, the fraction of tasks that are visibility dominated, is a major unknown. Further studies should be undertaken to improve its accuracy.

Acknowledgment

The work described in this paper was funded by the Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Applications of the U.S. Department of Energy, under contract number W-7405-ENG-48.

References

1. Design Practice Committee of the IES, "Recommended practice for the specification of an ESI Rating in interior spaces when specific task locations are unknown," JOURNAL OF THE ILLUMINATING ENGINEERING SOCIETY, Vol. 6, No. 2, January 1977, p. 111.
2. Publication CIE. Preliminary 5th draft, "Implementation procedures for evaluating visual performance aspects of lighting," Technical Committee Report of the Commission Internationale de L'Eclairage, 1976. Available from H. Richard Blackwell, Institute for Research in Vision, The Ohio State University, 1314 Kinnear Road, Columbus, Ohio, 43212, (614) 422-6265.
3. Publication CIE #19/2, Preliminary 8th draft, "An analytic model for describing the influence of lighting parameters upon visual performance," 1979, Technical Committee Report of the Commission Internationale de L'Eclairage, Available from H. Richard Blackwell. (See Ref. 2 for address.)
4. J. E. Flynn and G. J. Subisak, "A procedure for qualitative study of light level variations and system performance," JOURNAL OF THE ILLUMINATING ENGINEERING SOCIETY, Vol. 8, No. 1, October 1978, p. 28.
5. R. W. Richardson and S. M. Berman, 1979, "Equivalent sphere illumination and visibility levels," LBL #9492, Energy and Environment Division, Lawrence Berkeley Laboratory, Berkeley, California 94720.
6. R. Clear and S. Berman, 1980. "Cost effectiveness of visibility based design procedures for general office lighting," LBL #10514, Energy and Environment Division, Lawrence Berkeley Laboratory, Berkeley, California 94720.
7. See Reference 6 for a more complete derivation and discussion.
8. Robert Snow Means Company Inc., 1980, "Building systems cost guide 1980," 100 Constitution Plaza, Kingston, Ma. 02364.
9. N. Florence, "The energy effectiveness of task oriented lighting systems," LIGHTING DESIGN AND APPLICATION, Vol. 9, No. 1, January 1979, p. 28.
10. S. D. Lay, "Brightness patterns and visual fields," *Trans. Illum. Eng. Soc., London*, Vol. 16, No. 7, pp. 172–183, 1951.
11. Lighting Principles Subcommittee, Natl. Ill. Comm. of Britain, "The design of the visual field," *Trans. Illum. Eng. Soc.*, London, Vol. 18, No. 3, pp. 225–242, 1958.

DISCUSSION

B. F. JONES:* Mr. Clear and Mr. Berman are in essence espousing the determination and use of $\overline{\text{ESI}}$, which is the ESI "Rating"

---

* Orange, California.

equivalent to average relative visual performance. This has the merit of giving the designer a figure which is indicative of the visual performance level to be expected in the room.

At first reading, I was of the opinion that this was an excellent idea, since it was directly related to the performance that could be expected. On further thought, however, I came to the conclusion that as it stands it is incomplete in the same manner that average ESI is incomplete—that it does not give any guidance as to the range of values or the uniformity of ESI that can be expected in the room. As a result, two systems could have identical $\overline{\text{ESI}}$ and yet be vastly different in performance, with one having similar performance at any location, and the other varying widely from point to point.

I made some quick checks to see what effect the distribution of ESI values might have on the $\overline{\text{ESI}}$, relating it to the percent work stations with the ESI Rating used in the currently recommended IES System. I found that for a uniform distribution, the $\overline{\text{ESI}}$ value fell at about 67 percent work stations. For two practical distributions, one of narrow range and one of broad range, $\overline{\text{ESI}}$ fell at around 50-55 percent work stations, which is rather close to average ESI. On the other hand, the *midpoint* of the range of RVP's for a typical system comes at about 80 percent to 85 percent work stations, and for a single-figure criterion may be more meaningful, since it insures visual performance equivalent to that ESI Rating over the substantial majority of the room, and does not allow for extremely low levels within the room, as does either average ESI or $\overline{\text{ESI}}$ as defined.

Perhaps a modification of the system which gave RVP as a function of percent work stations, and the ESI equivalents, would be more appropriate. This would still allow the designer to select his system based not only on a one-number criterion but also on knowledge of the variation within the room as a function of area served. Note that in this case any of three number systems—RVP, VL, or ESI—could be used to convey the same information, since they are mutually interconvertible.

I would suggest that this system be conveyed to the Design Practices Committee, as the committee responsible for such recommended practices, to be used in any potential modification or refinement of the existing ESI Rating system.

D. L. DiLaura:[†] The general purpose of this paper is to demonstrate a cost effective design procedure for office lighting. Correctly enough, the authors isolate potential visual performance as an important metric lighting system effectiveness.

Then, as is widely accepted and understood, they use visibility as an important determinant of potential visual performance. Thus, they relate visibility to potential visual performance. The relationship they choose to use is that contained in a model of visual performance given in Reference 3. The model expresses potential visual performance in terms of RVP and uses VL as its principal metric of visibility. Using this model, the authors calculate values of RVP and attempt to make generalizations about office lighting design procedures. It is here, that the paper is seriously flawed. The following difficulties should be mentioned.

1. The model the authors use has *not* been shown to a valid predictor of RVP for visual displays of a practical nature. Performance experiments conducted by Bodman, Smith, and McNelis, give results that are not consistent with this model. The authors' use of this model to generate expected levels is very premature. The difficulty centers on the validity of the model's assumption, that equal visibility levels (produced by possibly *different* values of contrast and luminance) yield the same RVP. The data of Bodman, Smith, and McNelis show that this is not necessarily so.
2. The authors have not considered the consequences of the variance of the data used to construct the model they use. The resulting variance in the RVP values can be large and swamp changes in RVP values the authors wish to attribute to lighting system changes. This difficulty prohibits the application of the authors procedure in the practical lighting design process.
3. It is impossible to determine whether the results and comparisons given in the authors' Table 3 are artifacts of the visual performance model they use, or not. The values of ESI (RVP) shown are very sensitive functions of the specifics of the model.

It can be argued that actual performance in a practical lighting environment is affected by so many powerful nonlighting factors that an analysis based on visual performance is not meaningful. The authors evidently reject this argument on the basis that *comparisons* are being made and such factors will be more or less the same for such compared lighting systems. Unfortunately, the authors use a model of visual performance that is not robust enough to be used in such comparisons. This discusser feels that the procedures proposed and conclusions reached by the authors are too sensitive a function of the visual performance model they use to be considered for general office lighting.

Rebuttal

Authors: From the comments of the discussers, it appears important to reiterate and emphasize the general issues. We hope that in replying to their specific comments we can clear up confusion surrounding the use of $\overline{\text{RVP}}$ as the appropriate visibility related measure of the worth of a lighting system as well as the conditions under which we feel this concept is applicable.

First, in reply to Mr. Jones, the transformation from $\overline{\text{RVP}}$ to ESI ($\overline{\text{RVP}}$) (incorrectly given as $\overline{\text{ESI}}$ in Mr. Jones discussion) is monotonic, thus the latter function can be used for comparisons. We found it useful in illustrating the problems with the percentile ESI concept. However, $\overline{\text{RVP}}$ is more directly related to fundamental cost benefit concepts and is generally more useful. In fact, ESI ($\overline{\text{RVP}}$) is not even defined if more than one task is considered. In short, we are "espousing" the use of cost benefit concepts, not the use of ESI ($\overline{\text{RVP}}$).

It is not clear to us what Mr. Jones means by his statement that "two systems could have identical $\overline{\text{ESI}}$ (sic) and yet be vastly different in performance." If one accepts the validity of a cost-benefit approach, the "performance" of a lighting system has a well-defined meaning in terms of cost effectiveness. Under the assumption that productivity is linearly related to visual performance (RVP) the expected benefit, or performance, is proportional to $\overline{\text{RVP}}$ and is totally independent of the details of the distribution. Thus two systems with the same ESI ($\overline{\text{RVP}}$) and thus the same $\overline{\text{RVP}}$ will have the same performance.

We know of several situations which violate these assumptions. Some of them do in fact, as Mr. Jones suggests, require knowledge of the RVP distribution. $\overline{\text{RVP}}$ is also not an appropriate metric when the productivity at a particular location is dependent upon productivity at other locations. For instance, if output is dependent upon the pace of the slowest worker in a group instead of being a sum, then the output model must attempt to evaluate the average productivity of the slowest worker. This is not given by $\overline{\text{RVP}}$. On the other hand, one can question the linear relationship between RVP and productivity without abandoning the averaging concept. There is essentially no information on how accurately the RVP function correlates to real productivity and it quite obviously does not include the effects of discomfort glare, nor does it attempt to estimate a correlation between visibility and motivation. However, if one is willing to use ESI as an estimate of visibility, which Mr. Jones seems to be willing to do, then it follows that $\overline{\text{RVP}}$, or at worst the average of a function of RVP, (or ESI) is the corresponding best estimate of the relationship between visibility and average productivity.

We feel that the first two examples are recognizably special cases. Their existence is almost irrelevant to the designer of a building for general occupancy. Furthermore, percentile ESI is inappropriate as a metric for any of the above examples.

Mr. Jones calculation that ESI ($\overline{\text{RVP}}$) was approximately equal to $\overline{\text{ESI}}$ for two "practical distributions" is not surprising if these distributions gave generally high visibilities. From Fig. 1 in our paper it can be seen that the RVP (VL) curve is almost flat (linear) at high visibilities (VL). Thus, at high VL $\overline{\text{ESI}}$ will tend toward ESI ($\overline{\text{RVP}}$) and be a reasonably good estimator of it.

We disagree with Mr. Jones' suggestion that midpoint of the range of the RVP values (RVP_{mp}) or a percentile RVP value may

---

[†] Smith, Hinchman & Grylls, Detroit, Michigan.

be more meaningful than $\overline{RVP}$. Percentile RVP is just a generalization of percentile ESI and is in fact, equivalent to it if only one task need be considered (i.e., there is a monotonic relationship between them). Neither percentile RVP or RVP_{mp} is related unambiguously to productivity.

The concern over having a specified fraction of a work area at or above an ESI rating value appears to us to be based on a misconception concerning the relationship between ESI and productivity. Such a special status for a particular ESI value makes sense only if the productivity–visibility relationship is essentially a step function located at the ESI value. Although this type of approach is suitable for a field like structural engineering, it is not useful in office lighting design where one hardly expects catastrophe to strike the worker if visibility is less than the rating value.

In reply to Mr. DiLaura we would first like to make a factual correction to a statement in his discussion. We used the model for visual performance listed in Reference 2, not Reference 3. As noted in the text we felt that the more complicated model presented in Reference 3 was not warranted by the limited data available.

Mr. DiLaura appears not to have considered the logical implications of his claim that visibility levels (VL's) are not predictive of visual performance. ESI and VL are synonomous and related by a mathematical expression. If VL is not predictive of performance then neither is ESI, and there is therefore no valid reason for specifying percentile ESI since it would also lack any relationship to performance or cost effectiveness. In short, even his own premise would lead Mr. DiLaura to agree with our contention (although for a different reason) that percentile ESI standards are not useful.

The existence of any visibility criteria based on ESI, including percentile ESI, is strong evidence that the general lighting community accepts, or at least has in the past accepted, the concept that visibility level is related to performance. To our knowledge the CIE reports (References 2 and 3 of our paper) represent the only attempt using explicit mathematical formulae to relate visibility levels to performance. We feel that it is a rational course to apply the current information on the relationship between visibility and performance for the analysis of visibility based design procedures and standards. Given the current state of knowledge we have shown that percentile ESI specifications are inconsistent with cost effective design practice. In addition we feel that present design practice and recommendations need to be shown to be cost effective. Based on our admittedly limited examples it appears that levels may be set too high. Given the current problems with energy the burden of proof must rest on those who would support the current recommendations.

We have also been concerned about the data problems Mr. DiLaura refers to, but we do not agree with his interpretation of their cause. We feel that the present model is seriously flawed by being both incompletely and incorrectly specified, and we hope to present this argument at the 1981 IES Conference. Although a new model might lead to numerical changes in recommended visibility levels, the qualitative general conclusions presented here should remain valid.

We refer the reader to the Visual performance and ESI and Interpretation and conclusions sections of our paper plus Reference 6 for a discussion of the "consequences of the variance of the data used to construct the model . . ." Mr. DiLaura appears to have misinterpreted our point here. The region of the cost-benefit curve near the optima is relatively flat. Errors in the estimate of the performance (both from variance in the data as Mr. DiLaura notes, and from errors or inaccuracies in the model) make it impossible to accurately estimate the optimal visibility level. This is essentially Mr. DiLaura's first point with regards to variance effects, and which we are in essential agreement. However, we do not agree that the variance prohibits application of our procedure, but rather have a somewhat different view of its application. General lighting recommendations need to be evaluated for cost effectiveness (see in particular Fig. 2) as it is essential for both perspective, and sensible engineering application of visibility criteria.

As an aside we would like to mention that only mean values enter in the calculation of expected net benefits. Consideration of variance typically arises in cost benefits calculations when threshold considerations are relevant, i.e., in the assessment of risk. The important point is to use an unbiased estimator for the means. The function given in Reference 2 was the least biased published estimator that we are aware of.

The comparisons in Table 3 should be sufficient to make the essential point that percentile ESI is not a valid metric for visual performance. Although the detailed numerical comparisons are obviously dependent on the model chosen, it is not difficult to show that the lack of correlation between percentile values and visual performance is not an artifact of the model. Basically, as mentioned in our reply to Mr. Jones, percentile ESI should be a good approximation to mean performance only when the visibility-performance relationship is essentially a step function. Let f(v) be the (unknown) function giving the relationship between visibility, v, and performance. Let p(v) be the distribution of visibility values in a space. The mean performance in the space is given by the expression $\int_0^\infty f(v)p(v)dv$. If v_0 is the target visibility rating then the percentile value (expressed as a fraction) is given by the expression $\int_{v_0}^\infty p(v)dv$. Inspection of these two integrals shows that they will be equal for arbitrary p(v) only when f(v) is a unit step function with the step located at v_0. This appears unlikely, and certainly was not true for the model we examined. In addition it cannot be true in any situation where there are several tasks of different visibilities since then, by definition, the different tasks would have different v_0!

The authors feel that the presence of visibility recommendations in the form of ESI levels is evidence that the IES has rejected the hypothesis "that an analysis based on visual performance is not meaningful." Our intention was to explore the implications of the hypothesis that visibility and visual performance are related and to use the best available information that expresses this connection.

Mr. DiLaura appears to be concerned that we are suggesting a new procedure for making more subtle distinctions over appropriate visibility levels. In such a case the burden of proof would certainly rest on us, and we would be among the first to claim that our model was not robust enough for such a purpose. However, this is not our purpose. Instead, our intention has been to examine the methodology and implications of current practices. Our claims are that: 1) Cost benefit analysis is the appropriate tool for such an examination, 2) percentile ESI specifications by any standard of proof are not related to cost effectiveness, 3) given the rising costs of energy the burden of proof as to the cost effectiveness of current design practices, and visibility recommendations should rest on those who support them, 4) the model we used for these calculations is essentially the only one available, and is therefore the appropriate model to use, and 5) it appears that current visibility levels may, in fact, be too high to be justified.