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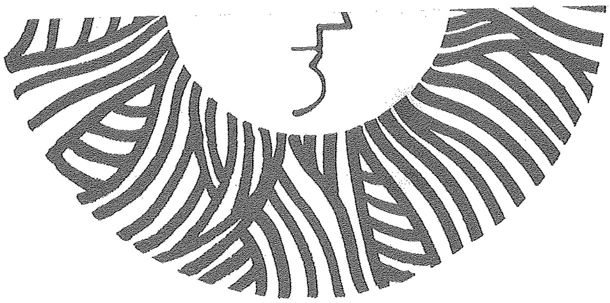

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## I. INTRODUCTION

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.

## II. 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 proof-reading 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 non-visual 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 by either ESI or VL (see section III). 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 judgements 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 sections III and IV, 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 ($\overline{\text{RVP}}$), and thus how well they can be used to judge relative cost effectiveness as a function of visibility.

## III. 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:

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

In this equation. RVP is the relative visual performance, $\gamma$ determines the slope of the fit, and is a function of $\alpha$, 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:

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

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

$$VL(C_{eq},L_b,CRF) = VL(C_{eq},\rho xESI) = C_{eq}[a((b/(\rho xESI))^{.4} + 1)^{-2.5}] . \qquad (4)$$

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 $\rho$ 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 figure 1 of section V.

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 non-visual fraction, (1-v):

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

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:

$$RP = \sum_{j=1}^{5} w_j(RVP_j) + (1 - \sum_{j=1}^{5} w_j) \ . \qquad (6)$$

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 $\alpha_j$ and $\gamma_j$ for the $RVP_j$. However it appears unlikely that existing performance data is sufficiently precise to warrent 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

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

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.

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 visiblity 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

$$\overline{RVP} = \frac{1}{n}\sum_{i=1}^{n} RVP_i \tag{8}$$

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%, typical .01%). 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% be used and gives examples of 85% to 95%. 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% to 99% 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% confidence level that 75% of the locations in a room meet the criteria value requires that 80% 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% to 80%[1].

Tables 1 through 3 display the results of sample calculations of percentile ESI, and $\overline{RVP}$ values. 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 startlingly low variation in RVP for easy tasks ($\alpha$ low). The second is the stability of relative $\overline{RVP}$ rankings for different installations with changes in $\alpha$.

In Table 3 we calculated the ESI levels that correspond to the $\overline{RVP}$ values at different values of $\alpha$ ($ESI(\overline{RVP}_\alpha)$), 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% to 34% lower than

(ESI($\overline{RVP}_\alpha$)). At the 95th percentile criteria the percentile values are from 113% to 194% lower than ESI($\overline{RVP}_\alpha$). By comparison, the percentile ESI values from the almost uniform distribution are only from 4% to 9% 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 specification procedure and then present an approximation for $\overline{RVP}$ which has some advantages over the direct calculation.

Characteristics of the ESI Distributions

Table 1.

| Case | Direction | Mean ($\bar{x}$) | Standard Deviation ($\sigma$) | Skewness ($s^a$) | Kurtosis ($k^b$) | Percentiles | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ($75^c$) | 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 |

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a. Skewness = $m_3/\sigma^3$ where $m_3$ is the 3rd central moment of the distribution.

b. Kurtosis = $m_4/\sigma_4$.

c. This column gives the values that are at least above the 75th percentile with a 90% confidence limit, given a random sample size which is the same size as the grids actually used.

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

Table 2.

| Case | Direction | Average Relative Visual Performance[a] | | |
|---|---|---|---|---|
| | | $\alpha = .3$ | $\alpha = .5$ | $\alpha = .7$ |
| 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 |

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

Comparison of Percentile ESI Values to $\overline{\text{ESI}}$ Values Calculated from $\overline{\text{RVP}}$ for the Examples in Table 1.

Table 3.

| Case | Direction | ESI ($\overline{\text{RVP}}$) | | | Ratio: EST ($\overline{\text{RVP}}$ $\alpha = .5$) to | |
|---|---|---|---|---|---|---|
| | | $\alpha = .3$ | $\alpha = .5$ | $\alpha = .7$ | 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 |

## SECTION IV: EXACT AND APPROXIMATE CALCULATIONS OF RVP

At present one method of computing an RVP from existing computer programs is to use Eqs. 3 and 4 from section III 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 $\alpha$ or $C_{eq}$.

We can derive an approximation to $\overline{\text{RVP}}$ 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:

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

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 $\sigma$ 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

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

In fact if $\sigma$ 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]. Eq. 9 has the same form as Eq. 1 and is again just the standard error function of statistics. Thus, in this approximation the values $x = \log_{10}VL$ and $\sigma$ are determined and then $\overline{\text{RVP}}$ is determined for any $\alpha$ 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 $\overline{RVP}$ was completely negligible over the range of $\alpha$'s tabulated. Spot checks for higher and lower $\alpha$'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, $(ESI(\overline{RVP}_{\alpha}))$. Since $\overline{RVP}$ is relatively insensitive to changes in ESI, particularly for $\alpha$ small ($RVP \rightarrow 1$) the error was less than 2% and the typical error when $\alpha \geq .5$ was .1%, which is better precision than the original tabulation of ESI 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 $\sigma$ in Table 4 reveals a fairly wide variation in value. However, all of the values of $\sigma$ are small with respect to $\gamma$ so the approximation of $\sigma_t$ by $\gamma$ (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 $\overline{RVP}$ 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 $\overline{RVP}$. Note, however that the maximum error of 13% is necessarily found under conditions where variations in ESI are relatively unimportant. For more visually demanding conditions the error of estimation of ESI($\overline{RVP}_\alpha$) is less than 5%. 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.

Characteristics of the $\mathrm{Log}_{10}$ VL Distributions

Table 4.

| Case | Direction | Mean ($\bar{x}$) | Standard Deviation ($\sigma$) | 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 |

Error Analysis for the First Approximation

Table 5.

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

Error Analysis for the Second Approximation

Table 6.

| | Absolute Error | Percentage Errors | |
|---|---|---|---|
| | 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 |

## V. INTERPRETATION AND CONCLUSIONS

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

$$Pr = F(RP) + (1-F) \quad . \qquad (13)$$

An example of how RP varies with lighting conditions follows from Table 2 of section III. For easy tasks ($\alpha = .3$) even major changes (2x) in ESI cause only .5% changes in RVP which should cause statistically insignificant changes in RP ($< .5\%$). For more difficult tasks ($\alpha \geq 5\%$), 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.

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 figure 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 lumens per watt delivered to the work surface. The costs per Kwh essentially span the costs that are likely. Productivity was calculated by assuming an average of 100 square feet 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 $\alpha$, 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 these graphs so that relative changes are even smaller than shown). As we noted earlier the relationship between the RP function and actual productivity is subject to major uncertainties. 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 figure 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 ten square foot area on a desk instead of a 100 square foot 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 figure 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. Section IV 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.

## ACKNOWLEDGEMENT

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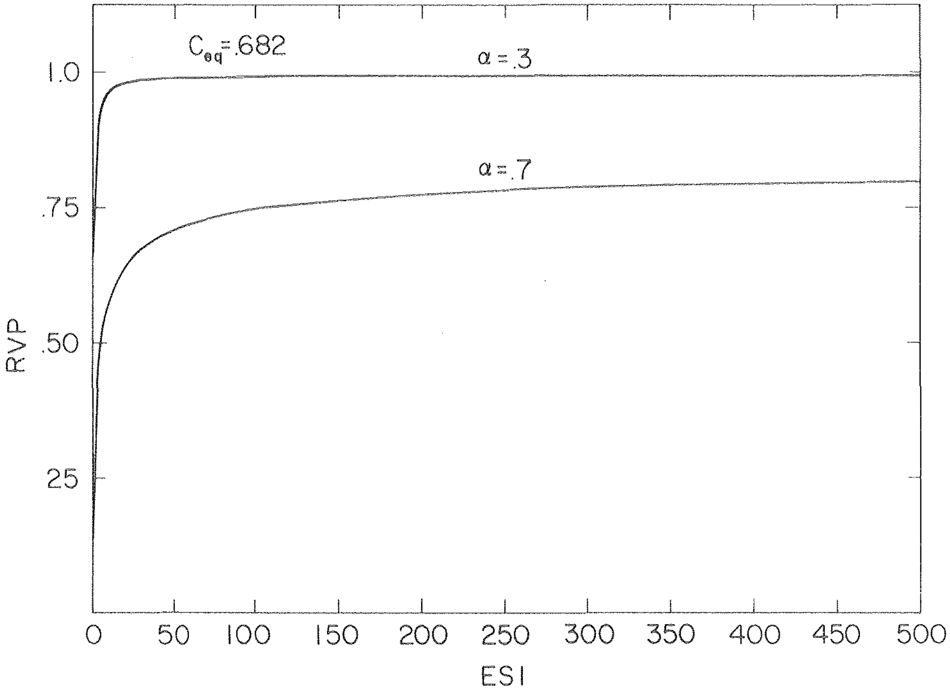

Figure 1. Relative Visual Performance as a Function of Visibility (ESI)

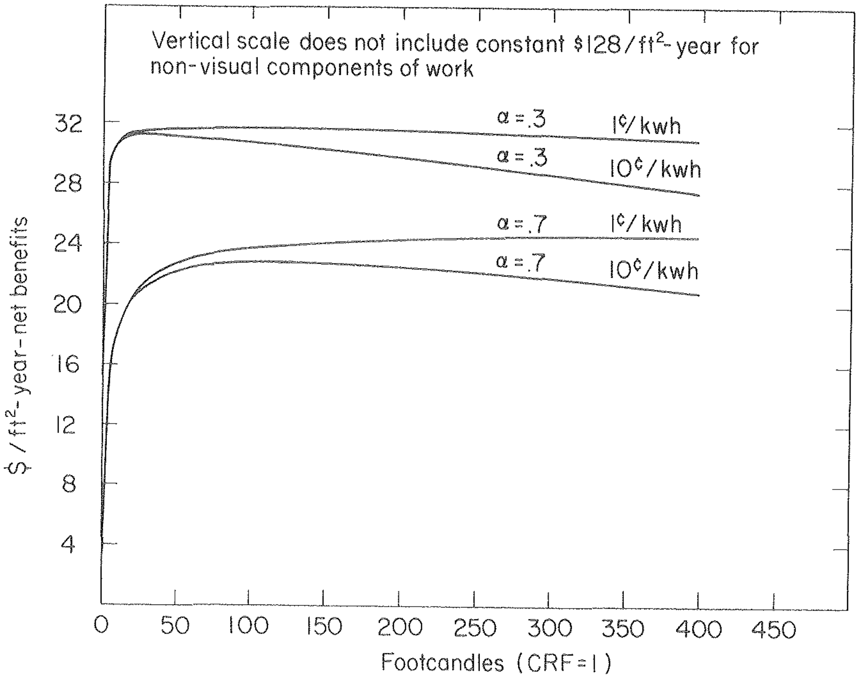

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Figure 2. Net Economic Benefit, under Illustrative Conditions, as a Function of Light Level

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