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RELATING PRODUCTIVITY TO VISIBILITY AND LIGHTING

Robert Clear and Samuel Berman

Lighting Systems Research
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

The problem of determining the appropriate light levels for visual tasks is a cost-benefit problem. Existing light level recommendations seriously underweight the importance of economic factors. Furthermore, the relative importance of the visibility factors in determining the optimal light levels appears inconsistent with the importance of these factors in determining visibility and visual performance.

We show that calculations based on acuities give a lower limit of 100-200 lux for cost-effective light levels for office tasks. Upper limits are calculated from correlations of task performance to visibility levels. Visibility levels become progressively insensitive to luminance as luminance increases. Average power densities above 100 watts/m^2 are cost-effective only when visibility is very low. However, there is a 3-to-10 times larger increase in benefits from improving contrast or contrast sensitivity than from using more than 10 watts/m^2. Contrast or contrast sensitivity can be improved by using forms with larger print, using xerographic copy instead of carbon or mimeo, making sure office workers have the right eyeglasses, or even by transferring workers with visual problems to less visually demanding tasks. Once these changes are made it is no longer cost-effective to use more than 10 watts/m^2. This conclusion raises serious questions about recommendations that lead to greater than about 10 watts/m^2 of installed lighting for general office work.

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I. Lighting Criteria as an Economic Problem

In trying to develop a logical method of integrating visual performance criteria into the design, specification, and evaluation of interior lighting systems, it is helpful to realize that this is a problem of both visual science and economics. Economics enters into the problem because the interest of the user is in the benefits that are derived from the lighting, not in the lighting itself. The user does not have a direct interest in visibility and visual performance. Instead, the user is interested in these attributes of the lighting system because of the belief that they are correlated to productivity, safety, and freedom from visual fatigue. Since these benefits have economic value, the determination of visual performance criteria can be stated as an economic problem.

The lighting levels required for adequate productivity will usually be more than adequate for safety and freedom from visual fatigue. In addition, many of the safety-related issues involve different visual tasks than those affecting productivity. We assume that the issues of safety and visual fatigue can be dealt with separately and will not generally affect the visual performance criteria for tasks that affect productivity. There seems to be no reason why other attributes of lighting, such as discomfort glare or the subtle cues involved in subjective evaluations of a space, should be functions of, or be correlated to, the visual performance potential of the tasks that affect productivity. We therefore assume that these attributes, too, can be evaluated and dealt with without affecting visual performance criteria. We will therefore concentrate on just the productivity/visual performance/visibility relationships.

Expressed in economic terms, the problem of integrating visual performance criteria into the design process becomes a problem in determining the cost-effectiveness of achieving a given level of visual performance. A net benefit can be calculated by subtracting the costs (the fixture installation cost, the opportunity cost of money, and the operation and maintenance costs of supplying a level of visual performance) from the value of productivity, where both are calculated as functions of visual performance. The optimal level of visual performance is the level with the highest net benefit.[1,2]

Cost-benefit calculations do not appear to have been explicitly used in setting past recommendations. Nonetheless, there has been a close historical correlation between lighting costs and practices.[3] It is evident, therefore, that explicit cost-benefit analysis should be germane to the problem of determining lighting recommendations.

One reason that the cost-benefit approach may not have been used explicitly is that the productivity/lighting relationship is not accurately known. Nonetheless, it only makes sense that any lighting recommendation based on visual performance should be consistent, in terms of cost-effectiveness, with the current state of knowledge. General information and even the lack of knowledge are important in determining the best form for lighting recommendations.

Consider, for example, the 1959 and 1972 IES recommendations of minimum footcandles or ESI for specific tasks. A simple minimum is adequate to describe the region of maximum net benefit only if: 1) productivity falls rapidly when the lighting is below the target value and is essentially constant at light levels above the target value; 2) the recommended value can be accurately identified; and 3) the cost of lighting is negligible so that there is no net cost for light levels above the minimum. None of these conditions appear realistic for tasks of moderate difficulty.

These recommendations were founded on the work that led to the present CIE system of estimating visual performance (CIE 19/2).[4] This system relates the fraction given by the actual contrast over the threshold contrast to visual performance. The reference contrast sensitivity

(RCS) function increases very rapidly at low light levels and becomes relatively flat at high light levels. This shape implies that a task which requires little light will have a fairly identifiable light level below which productivity drops rapidly.[5] Conversely, for more difficult tasks productivity should be a gentle function of the lighting near the net benefit maximum. In addition, the net benefit curve may be strongly affected by electrical costs at these higher levels. At 10¢/kwh these costs can be 10% of the rental value of a space at lighting levels as low as 500 lux.* These very general arguments indicate that the optimal light levels should be sensitive functions of both cost and task difficulty for the moderately difficult tasks, and it is therefore dubious that a minimum target value can be specified that has any significance in terms of cost-effectiveness.

II. Visual Performance and Productivity

Before we proceed further, it is useful to review the current state of information on visibility/visual performance/productivity. Public Works Canada has suggested in its invitation to the symposium that the publication CIE 19/2 serve as a basis for discussion of the visual performance problem. This publication presents a model for the visibility/visual performance relationship. The section on cost-benefit analysis assumes that visual performance is linearly related to overall performance (productivity).[6] However, the report offers no evidence to show that this is the actual relationship. In fact, a little thought reveals a number of likely ways in which visual performance and productivity can be related.

Consider, for example, a situation where the visual and nonvisual components of a task or job are done in parallel. If performance is measured in terms of speed, then the total time for the task is the longer of the times for the visual and nonvisual components. Walking is

* We are assuming 30 maintained lumens/watt delivered to the working space for 3000 hours/year. This gives 50 kwh/m^2-year or \$5/m^2-year. Office space rental in the San Francisco Bay Area (1/82) ranged from \$50-150/m^2-year. The lower end of the range gives the 10% value. Since Bay Area rentals are high, the cost of lighting may be relatively higher elsewhere.

an example of this. At high visibilities you walk at whatever speed is comfortable, while at low visibilities you must slow down to avoid bumping into things. Reading for comprehension may be another, more pertinent example.

We get a similar visual performance/productivity relationship if motivation instead of ability determines overall performance. Workers may only exert themselves to produce a "fair" day's work and no more.[7] In fact, productivity may even be subject to contract bargaining.[8] A more benign reason for limiting output arises from the natural desire to finish the task, or some discrete portion of the task, before taking a break. If the increase in the potential visual performance is not sufficient to allow the worker to get to the next natural ending point on the task, there may be no change in output.[7]

In all of the above cases there is a level of visual performance above which there are no further increases in productivity. This will tend to be the most cost-effective level. In practice this single visual performance level will translate to a range of visibilities due to the differences in visual sensitivity among individuals.

Now let us assume that the job consists of tasks linked in series. In this case the times for the visual and nonvisual components of the task will add. Let W_t be the fraction of total time it takes to do the visual tasks as visibility approaches infinity, RTP the relative performance on the visual components of the task, and RP the overall relative performance (productivity). Then RP is:

$$RP = (W_t \; / \; RTP \; + \; (1-W_t))^{-1} \qquad (1)$$

The first order Taylor's expansion of this equation around RTP = 1 is equivalent to the linear model proposed in CIE 19/2.[1,4]

The manner in which tasks can combine is more varied when performance is measured in terms of accuracy. For instance, the visual and nonvisual components of a job may be totally separate so that performance on one does not affect performance on the other. If overall performance is just the sum of the performances on the individual tasks, then we get the linear or "dilution" model proposed in CIE 19/2:[6]

$$RP = W_t RTP + (1-W_t) \qquad (2)$$

where W_t is now the fraction of time spent on, or value of, the visual tasks.

If instead the nonvisual components of a task contribute directly to final accuracy, then final accuracy will be a product instead of a sum. For instance, the probability of neither the visual nor nonvisual components of a task contributing an error is given by:

$$RP = (P_{nv}^{n_1} RTP^{n_2}) \qquad (3)$$

where P_{nv} is the accuracy on the nonvisual components of the task and n_1 and n_2 are the number of nonvisual and visual steps, respectively, needed to complete the task.

High values of the n_i make it very difficult to get high productivity. It therefore seems unlikely that tasks for which this relationship applies are common if the n_i are high.

A common practice is to introduce redundancy into the task if it is not already naturally present. Redundancy provides multiple chances to correct errors. Some assembly tasks and simple tasks like answering the phone can be performed without any light. For these types of tasks, accuracy is given by the probability that at least one of the (redundant) visual or nonvisual steps is correct:

$$RP = 1 - (1-P_{nv})^{n_1} (1-RTP)^{n_2} \qquad (4)$$

where the n_i are now the number of redundant steps involved in the completion of the task. For office tasks which do require vision, redundancy will affect the visual and nonvisual components separately:

$$RP = (1 - (1-P_{nv})^{n_1}) \, (1-(1-RTP)^{n_2}). \qquad (5)$$

A high value of n_2 will make these types of relationships very insensitive to variations in visual performance.

This discussion barely serves as an introduction to the number of relationships which are possible and even likely. For instance, we have not analyzed situations where the accuracy on one subtask is dependent on the accuracy of another task. We have not analyzed cases where performance is determined by both speed and accuracy. We have not explored many of the possible influences of motivation. Finally, we have not analyzed situations where different relationships apply to different parts of the job. Until studies empirically identify the most common relationships, it is only possible to examine "case" studies.

The easiest case to calculate is a lower limit on visual performance. We expect that acuity limits (free viewing) for the visual tasks are a lower limit on how low visual performance can drop before there is an effect on productivity. In this case we are defining the acuity limit as 100% probability of detection or identification, instead of the 50% criterion that is more common. We feel that the former definition is as low a level of performance as is likely to be acceptable.

The next-easiest model to evaluate is the simple "dilution" model, which, as we have noted before, is the model suggested in CIE 19/2, and is very similar to the series model (Eq. 1). This model probably overestimates the effect of visual performance on productivity. In particular, note that the parallel processing, the redundancy modified (Eqs. 4 and 5), and the motivationally fixed productivity models all give lower estimates than the dilution model. Furthermore, the motivationally fixed productivity models are essentially the only models for which there is concrete evidence.[7,8]

The two cases we have listed are useful in that they appear to provide limits to what the real relationships might be. They therefore provide bounds that can be used to evaluate the importance of visual performance.

III. Problems in CIE 19/2

In the discussion of the visual performance/productivity relationships we found that it was important to specify whether productivity was determined by speed, by accuracy, or by a combination of the two. The CIE visual performance model does not distinguish between these different types of performance. A detailed analysis of the problems that this creates has been presented in an earlier paper by the authors.[2] In this paper we briefly present the results of that analysis.

The CIE 19/2 model uses a weighted sum to describe how the subcomponents of visual performance -- detection, saccadic motion, fixation, and identification -- combine to give visual performance. This is not self-consistent, as different types of performance require different relationships. For example, if performance is measured by speed, then we expect the times for each subcomponent to add to give an overall time, which is the inverse of overall performance (see Eq. 1). If instead we are concerned with accuracy, then the weighted sum implies that each visual subprocess is independently responsible for a fraction of the overall accuracy. This interpretation cannot be reconciled with the physical description of the subprocesses. Finally, if performance depends upon both accuracy and speed, then the criterion the subject uses to allocate time to the task enters the visual performance function either as an independent variable or as a constraint. Neither is consistent with the CIE model. Consider, for example, the case where the subject maximizes his performance. This condition makes the subject's allocation of time dependent upon the form of the performance function.[2] This in turn implies that performance and even relative performance depend upon the form of the performance function. This is not consistent with the CIE visual performance model, which assumes complete independence from the form of the performance function.

The fact that the terms of the CIE model cannot be identified with the physical processes in a self-consistent manner indicates that the functional form provides at best an empirical fit to performance data. This means that the free parameters of the model, D, W_{123}, and P_{max}, have no intrinsic physical significance and therefore in general cannot be estimated in advance. This means that the CIE model is not useful for predicting the results of new experiments under different conditions than the old ones.

A second problem that arises from the failure of the CIE model to distinguish between different types of performance measures is that it can make it difficult or impossible to relate the CIE estimate of visual performance to productivity. Productivity on a job in general will be a fairly specific combination of speed and accuracy. On the other hand the visual performance-data fit by the CIE model can be any combination of speed and accuracy the experimentor chooses to use. If the performance functions in the laboratory and the field are not the same, then the subject's allocation of time may be different in the two situations. This makes it hard to relate the visual performance data to productivity.

The use of arbitrarily chosen performance relationships can distort the visual performance/productivity relationship in other ways, too. For instance, some of the score functions that were used in experiments that were analyzed in CIE 19/2 introduce an arbitrary constant into the fit. The constant is fit by the W_{123} parameter in the CIE model. The introduction of arbitrary change in W_{123} biases the fit, and by extension the estimate of productivity that one would make from the fit.

The only ways to avoid the above problems are to make sure the performance and productivity measures are similar, or to use a model which explicitly fits the variations in both speed and accuracy.

In addition to the above modeling problems in CIE 19/2, there are also problems in determining the statistical significance of both the visual performance fits and the parameters of the model itself. Consider first the question of the statistical significance of the visual performance fits.

One problem in doing any statistical analysis of the visual performance fits is that in half of them no error bars were calculated. Another problem is that most of the fits do not have enough data points to provide very much information on the shape of the visual performance/visibility curve. In one fit there are actually twice as many unknowns as there are data points, giving an underdetermined, not overdetermined, system of equations. In another fit the number of unknowns and data points is equal, and in half of the remaining fits there is only one degree of freedom. Only two of the 20 fits have six or more degrees of freedom.

A related problem with some of the fits is the excessive number of unknowns. The two worst cases have 12 and 13 unknowns respectively. No statistical tests were presented to show that it is signal, not noise, that is being fit while going to such a large number of unknowns.

There is not one visual performance/visibility fit in CIE 19/2 that is completely free of statistical problems. The statistical significance of the fits is therefore unclear and questionable. In the interests of parsimony, a simpler model should be used until it can be verified that more complicated models actually provide more information.

Statistical problems similar to those above appeared when we examined the fits to the data used to determine the relationships between fixed parameters in the CIE model (e.g. the dependance of m on age, of γ and X on task demand D, of α_3 on X, and so forth). Most of this work is in a set of six support documents. In the first of these documents we found what appears to be another serious statistical problem.[9]

The error bars in this first paper appear to be larger than is reasonable. The data points that are plotted are corrected probabilities that range from -.25 to +1. The distribution of points with the largest standard deviation, σ, is the one with half of the points = 1 and half = -.25 so that $\sigma = .625$. The standard deviation of a measurement of the mean of a distribution, σ_m, is $\sigma/\sqrt{N}$ where N is the number of points measured. The data sets consisted of observations on 45-49 subjects so $\sigma_m \leq .09$ $(.625/\sqrt{49.})$ The plotted error bars (after correction from probable error to σ) range from $\pm .05$ to $\pm .1$. It seems unlikely that individual scores would cluster closely at both ends of the maximum range with an average exactly in the middle. We therefore suspect that the error bars have been incorrectly calculated, and we feel that the conclusions drawn from the fits are not well supported. This first support paper proposed a weak linear relationship between γ and α. We suggest that this relationship will have to be reevaluated.

We want to emphasize that our criticisms apply fairly specifically to the mathematical model presented in CIE 19/2. We are not questioning the more robust trends, such as the improvement in visual performance with increases in visibility, or the relative importance of contrast, size, disability glare, and task difficulty as compared to luminance in the calculation of visibility. There is also some evidence in the data for saturation of performance at high and low visibilities, and in addition this trend seems inherently reasonable. What we are disputing is the claim that the CIE 19/2 model can be used to accurately predict performance as a function of visibility.

IV. The Consensus Approach to Lighting Level Recommendations

There are two options available to Public Works Canada at this time. One can use only the information that seems very robust in CIE 19/2, or one can seek an alternative approach. An alternative that has been used very recently is the consensus approach adopted in the RQQ No. 6 illumination selection recommendations.[10]

Unfortunately, this approach is not without shortcomings. The consensus approach tends to lead to confirmation of past practice. The designers and engineers who are active now learned their trade under the old IES recommendations. The new RQQ No. 6 recommendations differ from the previous ones in that there is less emphasis on CRF and in that they provide illumination levels a factor of two lower if age, reflectance, or the relative unimportance of accuracy or speed on the task justifies it. These differences are not very significant.

As we showed earlier, the previous IES recommendation did not explicitly consider cost-effectiveness. The RQQ No. 6 recommendations still do not consider costs at all, and they appear to badly underestimate the importance of CRF, age, reflectance, and the significance of the need for speed or accuracy. Finally, the actual illumination ranges appear to be essentially arbitrary in terms of their being cost-effective.

The RQQ No. 6 recommendations attempt to reach a consensus of what constitutes "good practice" without providing any guidelines as to what is meant by it. The concept of cost-effectiveness has been treated only superficially in IES publications, and in fact was not really important until after 1972. It is not possible to get an informed consensus on what constitutes cost-effective lighting until there has been much more experience with the concept.

Ideally, it would be best to determine cost-effectiveness directly from the effect of visibility on productivity. In practice it has been hard to even establish a lower limit on visibility this way because of the extreme difficulty in controlling external variables and in measuring the small but potentially significant changes in performance that are related to visibility alone.[1,7] We feel that presently the best that can be done is to estimate upper and lower bounds from the "dilution" model and the acuity limit respectively, as we mentioned earlier. We propose to use whatever information that does appear robust from CIE 19/2 in these estimates.

V. A Lower Limit for Light Level Requirements for Office Tasks

To calculate the lower visual performance or visibility limit we use Kaneko's fit of Ito's acuity data,[11] and Henderson's measurements of the equivalent contrasts (C_{eq}'s) of a number of office tasks.[12,13] Kaneko fit acuity, A (minutes^{-1}), to contrast, C, and luminance, L (cd/m^2):

$$A = .7284\ L^{.2131} C^{.53158} \tag{6}$$

The equivalent contrast is defined as the contrast of a four-minute disk with the same visiblity as the actual target when viewed under the same light level in matched 1/5-second pulses. We assume that to first order the visibility match would be the same for binocular free viewing. Eq. 6 can then be rewritten in terms of the equivalent contrast of the four-minute disk to give:

$$L = .00661\ C_{eq}^{2.41} \tag{7}$$

The measured range of C_{eq} for office environments was from .2 to 2.

Inserted into Eq. 7 these values yield a lower limit on luminance of .001 to .3 cd/m^2 The lower figure is substantially below the range of applicability of Eq. 6 and is probably incorrect.

Equation 6 was derived from the average results of young subjects' just being able to just detect a gap in a Landolt ring. Blackwell has shown that the criteria for detectability under free viewing conditions yields a visibility level that allows close to 100% success under forced choice conditions.[14] However, the use of the average results for young subjects in our calculation is clearly restrictive in that it excludes the bulk of the working population. Estimates in CIE 19/2 set the decrease in contrast sensitivity in going from 20 to 65 years of age as about a factor of 2 and give a further factor of ~ $\sqrt{2}$ decrease for each 1 standard deviation from the mean. Inserting these factors into Eq. 7 yields an upper limit of 1.5 cd/m^2 for the average, normally sighted individual at 65, and upper limits of 3.5, 8.5 and 19 cd/m^2, respectively, for 1, 2, and 3 standard deviations from the mean at 65. The last value provides a healthy safety margin for most tasks for most people. However, it still may be insufficient for people who need eyeglass corrections, or who have eye diseases, or who have some forms of visual handicaps. These latter cases are recognizably special, and should be dealt with accordingly.

A luminance of 19 cd/m^2 can be provided by 150 lux when reflectances are 40% or greater. If this value seems startingly low, it may help to note that 1) it is a lower limit, 2) we have not included the effects of poor contrast renderings or disability glare, and 3) the tasks were restricted to office tasks, not general industrial tasks.

From Eq. 7 we see that a reduction by a factor of r in contrast requires an increase by a factor of $r^{2.41}$ in luminance to maintain visibility. Thus we can trade a 10% reduction in contrast for a 25% increase in luminance, or a factor of 2 reduction in contrast with a factor of 5 increase in luminance, and so on. Experiences with installations which have poor contrast rendering or problems with disability glare may give one the mistaken impression that very high light levels are necessary to even see certain office visual tasks. These contrast factors both depend upon lighting design. A cost-effective design has to be optimized over these factors. Conceivably, this could result in a lower limit of 200-250 lux, but it is hard to see how the level could be much higher in a design that is still cost-effective.

Experience with industrial tasks may also lead to the impression of a need for high levels that is based on conditions that are not relevant to office lighting. If, for instance, a job is done on an assembly line at a fixed speed, then our assumption that free viewing is nonlimiting may be grossly wrong. In addition, some industrial tasks may have lower C_{eq}´s than the office tasks measured by Henderson. These factors do not reflect upon the illuminance needs in offices.

Note that even for very low C_{eq}´s the most cost-effective solution is not always more light. Magnification, for example, may be the only way to see a very small task detail, and, if speed is not the limiting constraint on performance, may even be advantageous for bigger, more visible tasks. From Eq. 6 it can be shown that at moderate luminances a factor of 2 magnification is almost equivalent to a factor of 5 increase in light level. To provide truly cost-effective designs, the illuminating engineer must be willing to advise the client on visibility, not just lighting.

VI. An Upper Limit Estimate for Cost-Effective Lighting in Offices

To obtain an upper limit estimate of how productivity varies with lighting, we use a simplified version of the CIE 19/2 model.[1] Specifically, we use the reference contrast sensitivity function to calculate VL, and relate relative visual performance (RVP) to VL by the empirical relation:

$$RVP = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Z} e^{-(z^2/2)} dz \qquad (8a)$$

$$Z = (\log_{10}(VL) - \alpha) / \sigma \qquad (8b)$$

where α and σ are empirically determined parameters. The relative visual performance is then "diluted" (e.g. Eq. 2) to give RTP, which in turn is "diluted" to give productivity, P:

$$P = P_v \times RVP + (P - P_v) \tag{9}$$

where P_v is the value of the visual work times the dilution constant from RVP to RTP.

Our expression for RTP preserves the basic trends in CIE 19/2 and in many earlier works. It also has a form similar to that of the CIE expression at moderate to high visibilities. The range of values of α and σ that fit the data in the CIE model should therefore be a reasonable guide to the range of the corresponding variables in Eq. 8b. The advantage of this RTP expression over the form given in CIE 19/2 is that it does not include the complex detail that is not justified on theoretical grounds and that is of dubious usefulness on practical grounds. We are not claiming theoretical validity for our expression; in fact, it is clearly incorrect at low visibilities since it does not tend towards zero.

The idea behind Eqs. 8 through 9 is to provide a rough guide to how visibility affects productivity, and to what variables are important. To calculate net benefits we go one step further and include estimates of costs. We use a simple linear model for costs, B:[15]

$$B = (.02 \times a_1 + .036 \times a_2 + 10^{-5} \times n \times a_3) \times W \tag{10}$$

Here .02 and .036 are base case values for maintenance and annualized fixture costs, a_1 and a_2 are multipliers so that we can examine the sensitivity of the net benefit to changes in these costs, 10^{-5} is a constant, n is the number of hours lights are on, a_3 is the cost of electricity in ¢/kwh, and W is the installed wattage.

A computer program was written to evaluate the net benefit (Eq. 9 minus Eq. 10) as a function of the installed watts/m^2 and the cost of electricity. To compute VL from W we used the relation:

$$VL = C_4 \times b_1((b_2/W \times \epsilon \times \rho)^{.4} + 1)^{-2.5} \tag{11}$$

Here C_4 is the product of the contrast factors; C_{eq}, disability glare factor (DGF), contrast rendition factor (CRF), and the age correction to contrast sensitivity ($1/m_1$). The b_i are derived from the RCS constants, and ϵ and ρ are the delivered lumens/watt (efficacy times coefficient of utilization times the maintenance factor) and the reflectivity, respectively. We also evaluated net benefits for task lighting. We assumed that ϵ for task lighting was one-half that of general lighting and varied the costs, the ratio between task and general light levels, and the area lit by the task lamp.

In our preliminary evaluations of the computer runs, we were primarily interested in the determination of optimum light levels, or, alternatively, power densities. In rough order the most important variables affecting lighting levels were P_v, the degree of task lighting (area and light level ratios), the task visibility and difficulty variables (C_4 and α), the cost of electricity, the area per employee, ϵ, and finally ρ. A short summary of the sensitivity of the optimal light level to these variables is presented in Table 1. Note that options such as daylighting and lighting controls have not been evaluated and therefore are not listed in the table. This does not mean that they are unimportant! Note further that our rough-order ranking might change if the possible range of the independent variable is substantially different from the range we examined.

The variable P_v is essentially a measure of the importance of speed and/or accuracy. It is the product of three factors, all of which are quite variable. The three factors are the total value of the employee's work, the fraction of the work devoted to visual tasks, and, finally, the dilution constant from RVP to RTP. The variability in the office work should be reflected in the salary range. In private industry this range can be enormous; for governmental employees the range is probably closer to 4:1 or slightly more. The second factor should be more variable. Intuitively, it looks as if there could be a 10:1 difference in the fraction of time spent on visual tasks between people-oriented jobs - sales, reception, and management - and clerical or keypunch jobs. The third factor is sometimes related to the variable W_{123} in CIE 19/2.[2,4] There is over a 10:1 range in this variable. There may be an even larger variation in this variable in field rather than laboratory situations because of the wider range of motivation that should be found in the field.

The potential range of P_v from these arguments is around 3-4 log units. The actual range will depend on whether the factors are correlated and will be smaller.

There may also be questions about the degree of task lighting listed in Table 1. Basically we assumed that the area on a table or desk in which a person actually does his more difficult visual work can be very small. In addition, we have assumed that by controlling the field of view via privacy panels or walls, it should be possible to attain high light level ratios without degradation of the contrast factors DGF and CRF. Although small variations in these factors do not affect the optimal light level, they do affect the overall net benefit level and therefore the desirability of using task lighting in the first place. There may also be equipment availability or discomfort problems at very high light levels that reduce the degree of task lighting that is practical. We suspect that the degree of task lighting could easily be .6 log units more or less than what we evaluated.

The contrast factors C_4 and α are fairly well understood. In our discussion of acuity we quoted values of 1 log unit variation for C_{eq}, a .3 log unit variation from m_1, and possibly a .3 log unit variation from DGF and CRF for a total range of 1.6. The variable α is already a log value and, from CIE 19/2, should vary by about .4. Th sum of C_4 and α is thus about 2 log units. The range we evaluated was biased towards the more difficult tasks. For these tasks it will generally not be cost-effective to have poor values of DGF and CRF, so the expected overall variability should be slightly smaller. At high values of P_v the range of C_4 and α should substantially increase their potential effect. We argue later that our choices of P_v were too high, so that our estimate of the importance of the contrast factors should be less of an underestimate than it appears.

The remaining variables in Table 1 are fairly self-explanatory. Note, however, that we have used a positive log factor to indicate an increased optimal light level with increases in P_v, task lighting, and ϵ and decreases in $C_{eq} + \alpha$, ¢/kwh, area, and reflectivity.

It is interesting to compare the variations in Table 1 with those given in RQQ No. 6. In RQQ No. 6 the factor for the importance of speed and accuracy (P_v in Table 1) only changes the recommended light levels by .2 log units. Task lighting is assumed for all lighting above 200 lux, and is therefore not a source of variability in the optimal light level. Note, however, that the degree of task lighting is not evaluated. RQQ No. 6 treats the contrast factors separately. The parameters CRF and DGF are assumed to be high for any task requiring more than 200 lux and are therefore a negligible source of variability in the recommended light levels. The parameter α is not discussed. The parameter C_{eq}, either as used explicitly in Fig. 2.3 or via its correlation to the task categories in Fig. 2.2, is the dominant factor in determining light levels in RQQ No. 6. A .7 log unit decrease in C_{eq} gives a 2 log unit increase in the recommended illuminance. By comparison, the age effect, which can decrease the overall contrast fact (C_4) by .3, only increases the recommended light level by .2 log units. The cost factors, ¢/kwh, area per employee, and delivered lumens per watt, are not explicitly considered in the RQQ No. 6 recommendations. Finally, a .4 log unit change in reflectivity gives a .2 log unit change in light level. This last recommendation is the only one that is consistent with the values in Table 1.

The major problem with the RQQ No. 6 recommendations is that they underestimate the importance of the value placed on speed and/or accuracy. This factor determines the whole balance between the expected benefits from lighting and its costs. This balance sharply limits the importance of the other variables.

Some of the results in Table 1 may seem counterintuitive, but are quite reasonable when viewed in the context of cost-effectiveness. For example, the drop in optimal light levels at low values of the contrast factor occurs because increased light levels do not improve performance much when the intrinsic visibility is poor. When the task is moderately difficult, increasing the light level produces large changes in productivity, and, therefore, high light levels become worthwhile. Finally, for easy tasks the performance saturates at low light levels, and once again the increases in performance at high light levels are no longer worthwhile.

In Table 2 we list the cost-effective light and power density levels for a base case lighting problem. This example shows how important P_v is in determining the optimal levels. It also shows how relatively unimportant the contrast factors are in determining these levels. However, this type of presentation hides the fact that the contrast factors are critical in achieving cost-effective lighting.

In Table 3 we list calculated net benefits at several luminance and contrast factor levels. The results should be staggering. A change of the contrast factor by .4 log units is essentially equal to the difference between a normal young adult and a 65-year-old adult whose vision is less than 1 standard deviation below normal. The difference between a Xerox copy and a fourth carbon copy is .5 log units or greater.[12] Clearly, if P_v = $32,000 it would make sense to have a minimum requirement on visual sensitivity as a condition of employment, and fourth carbons would simply not exist.

We feel that this result shows that such large values of P_v either do not occur in office tasks, or they only occur for very visible tasks. Even with more moderate values of P_v, such as P_v = $4000, this effect results in differences of several hundred to a few thousand dollars. These differences are still large enough to be noticeable. We suspect that few tasks have values of P_v even as high as $4000. If such tasks do exist, we strongly recommend that the task be simplified as much as possible, and that the employees at the very least have their vision tested frequently.

VII. Conclusion

We feel that in general the results we are getting indicate that optimal power densities for cost-effective visual performance are in the range of 10 watts/m^2 or less. At this level the ambient lighting can be at about 150 lux. From our earlier arguments about acuity, this light level should be sufficient for employees to perform difficult tasks away from the work station if necessary, although not necessarily efficiently. At the work station light levels of 1500 lux should provide cost-effective lighting even if P_v is as high as a few thousand dollars. In addition, if the task lighting is provided by a local fixture, then higher light levels can be obtained if necessary, by bringing the task close to the fixture (or vice versa).

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TABLE 1
Relative Importance of Severable Variables
To The Optimum Light Level

Variables	Range of Variables Tested (log units)	Optimal Light Level Varies in Log Units Between a Minimum of and Maximum of:
P_v	1.8	.9, 1.8
Task Lighting	2.3*	.3, .8
Contrast Factors $(C_4\alpha)$	1.0	-.3, .8
¢/kwh	.9	.1, .5
Area	.3	0, .3
Lumens/Watt Delivered	.2	-.1, .4
Reflectivity	.6	-.1, .3

*Ratio of task light level to general light level divided by fraction of area that is lit by task lighting.

TABLE 2

Cost-Effective Lighting

P_v	¢/kwh	Light Level (lux)	Power Density (watts/m^2)
500	2.5-10	300-1500	2-10
4000	2.5	1200-6000	8-40
4000	5	900-4500	6-30
4000	10	600-3000	4-19
32000	2.5-10	2100->15000	13->95

General assumptions: ρ = 80%, ϵ (general) = 30 lumens/watt, ϵ (task) = 15 lumens/watt, area/employee = 20m^2, 10:1 ratio for task to ambient light level, task area = 5% of total area, and a 1 log unit variation in the contrast factors. Note that averaging over age and task difficulty reduces the spread in the levels.

TABLE 3

Net Benefit as a Function of Contrast and Light Level

$\underline{Log}(C_4) - \alpha$	Light Level (lux)	Net Benefit ($)
-1.4	15000	7000
-1.0	75	11110
-1.0	1500	20600
-1.0	15000	22800
-0.8	225	23700
-0.8	1500	27200
-0.8	15000	28500
-0.4	75	30300
-0.4	1500	31680
-0.4	3000	31700

Calculated at P_v = $32000, $(P-P_v)$ = 0 and base case conditions as in Table 2.

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