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ECONOMICS AND LIGHTING LEVEL RECOMMENDATIONS

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Economics and Lighting Level Recommendations

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Abstract

The Illuminating Engineering Society of North America develops light level recommendations for tasks where visual performance is important. The 1959 and 1972 recommendations for illumination levels were based on the principle of delivering a fixed level of performance as predicted by the visual performance models of the time. This same principle is being considered for future revisions to the recommendations. There is currently no explicit method for determining whether a given fixed performance level is in any sense optimal or best.

Visual performance increases with lighting levels, but so do economic and environmental costs. These costs lessen the economic benefits of the improved visual performance. A formal method for including these factors in light level recommendations is to restate the problem in terms of net benefits (benefits minus costs). The resulting equations have well defined optima versus light level, and thus give an explicit estimate of what the best lighting levels are in terms of current visual performance models, and current economic conditions.

A simple net-benefit procedure is described, and sample calculations are shown for two current visual performance models. Fixed performance levels do not provide economically optimal recommendations with either model. There are also differences between models, but they are less significant than the large differences between the principles of fixed performance levels and economic optimization.

Introduction

Since 1952 there have been three revisions of the Illuminating Engineering Society of North America's (IESNA) lighting level recommendations for offices, and a new revision is in progress. The illuminance selection procedure is "intended for use in interior environments where visual performance is an important consideration."[1] Illuminance is only one of many variables in a lighting design, but once the other variables are fixed, the designer needs to know how much light to provide.

Although measures such as equal apparent contrast contours may have a maximum with respect to luminance, this does not appear true for visual performance at any practically obtainable level, and there is thus no obvious performance level which is best.[2] The 1959 and 1972 recommendations were instead designed to provide a fixed level of performance, as calculated by a model developed by Blackwell.[3-5] Blackwell selected the 99 percent accuracy level as a compromise between the ideal of 100 percent accuracy and what was practically attainable. Problems with validating and using the associated ESI visibility calculations, questions about the model, and finally pressures for energy conservation, led to the abandonment of the Blackwell model in favor of consensus based recommendations in 1981. The consensus levels were set at what experts judged to be "appropriate" levels for the task at hand. Currently, the IESNA's RQQ committee is again considering the determination of illumination levels based on a visual performance model, and again has to wrestle with the question: what is the practical balance between desired and attainable performance - i.e. what is the appropriate level of performance on which to base lighting recommendations?

The question of what is practical, or appropriate, is an economic question.[6] For the applications considered here, lighting is installed so people can work more efficiently. The increased productivity pays for the cost of the lighting. A calculation of the most economic (appropriate) light level can be accomplished via cost-benefit analysis.

Cost-benefit analysis provides a basis for understanding the economic consequences of under or over-lighting, and shows what information is needed to make sensible lighting recommendations. It also provides an explicit procedure for averaging over various tasks and ages to get the most economic light levels when there is variability in these parameters. When there is more than one visual performance model available it provides a method for determining whether the differences between models are important economically. If the differences are significant cost-benefit analysis provides an explicit procedure to average over model predictions. Perhaps most important of all, applying cost-benefit analysis reveals the assumptions used in determining a recommendation.

In this paper we describe the basic cost-benefit methodology. We calculate luminances and illuminances with two visual performance models over a range of economic inputs. The results illustrate the difference obtained between economic optimization and the principle of a fixed performance level.[7-10] The use of recommendations based on fixed RTP values is not supported.

Cost-Benefit Modeling

Background

In a cost-benefit analysis all the consequences of a given action are assigned a monetary value. A net benefit, NB, can then be computed as the difference between the costs and the benefits of the action:

$$\text{NB} = \text{Benefits} - \text{Costs} \qquad (1).$$

The benefits and costs for office lighting are:

Benefits = Productivity + Comfort + Satisfaction (2)

and,

Costs = Installation + Maintenance + Energy (3).

We define the most economic action as that which maximizes the net benefit. Optimal illuminances are determined by writing each of the terms in equations 2 and 3 as functions of illuminance.

We assume that the value of the productivity of a worker is approximately equal to their total compensation, S. This should be fairly accurate for clerical and other repetitive jobs where productivity can be measured reasonably easily. It will be subject to larger errors where productivity is harder to determine.

Work commonly consists of a mix of visual tasks, such as reading or inspection, and tasks that are primarily non-visual, such as conversation, moving, and thinking. The time to complete some simple reading tasks has been modeled as a function of the visibility of the task and the age of the subject.

Relating Illumination to performance

For the visibility dependent portion of a job, define relative visual task performance, or RTP, as the speed (as measured in units of inverse time) of task performance under any given visibility condition, $1/t_v$, divided by its speed under a reference visibility condition, $1/t_{vR}$ (RTP =

$[t_{vR}/t_v]$). Let F be the fraction of time spent on the primarily visual tasks under the reference condition, $(F=t_v/t_{nv}+t_v)$ where t_{nv} is the time for the non-visual portion of the job. Productivity, P, is defined here as compensation (i.e. value of work) that is achieved under a given visibility condition. In terms of the visual (F/RTP) and non-visual ((1-F) components, Productivity is given by:

$$P = S/[F/RTP + (1-F)] \qquad (4).$$

Equation 4 relates productivity to visibility and hence illuminance via the RTP function, and thus makes it possible to do a cost-benefit analysis.

The visual task performance (RTP) functions considered here are dependent upon worker age, task angular size, contrast, adaptation luminance, and glare. Glare is treated in terms of its effects on adaptation and effective contrast. The adaptation luminance depends on the reflectance of the background, and the illuminance at the task.

The other three parameters do not appear to strongly depend on the illuminance level. For instance, the work of both Rubinstein and Slater shows that changing light levels by varying fixture spacing or output normally has very little effect on the spatial average of the contrast of the standard pencil task.[11,12] Similarly, angular size is determined by the physical size of the task and the viewing distance. Unless the task is extremely difficult, viewing distance is relatively fixed, so angular size becomes a fixed constant for a given task. Worker age is fixed externally, and is not varied as part of the optimization. Thus, visual performance for a given task, with a given type of illumination system, becomes a function of illuminance alone.

If video display units or daylighting are present, the assumption that glare and contrast are independent of illuminance fails. In this case contrast and glare changes must be determined as a function of illuminance. The worst case is when these parameters, and even visual performance itself, ceases to be a single-valued function of illuminance. Maximization of the cost-benefit equation then requires a case-by-case analysis. In this paper we analyze only the case where contrast is assumed to be fixed.

The RQQ illuminance level recommendations are meant for situations where visual performance is important, and do not explicitly consider comfort or satisfaction. Our analysis does not include comfort or satisfaction terms, because we assume that they are not related to light level as long as the latter is in the range from about 20 to 20,000 lux. At light levels below 20 - 50 lux, satisfaction may begin to drop because the surroundings may look noticeably dim or even dingy. At light levels above 10,000 - 20,000 lux comfort is likely to drop because of the difficulty in controlling glare. Our cost-benefit analysis is only valid when the predicted optimum light levels are within these limits.

Estimating costs

The cost terms for any given job vary with the light level in an approximately linear fashion. Installation costs are the sum of the capital and labor costs for the fixtures and wiring, plus a debit for any increase in needed cooling capacity, and minus a credit for any decrease in needed heating capacity. The unit costs for these terms tend to be fairly constant for a given job, although there are often big differences between jobs due to volume discounts and other economies of scale. We assume that the type and efficiency of the lighting equipment is determined either by direct economic analysis, or by some other constraint. Once the lighting equipment is chosen light level is increased by simply installing more units. To the extent that unit costs are constant, costs will vary linearly with light level.

Maintenance costs are similar to installation costs. Lamp replacement and cleaning involve capital and labor costs, both of which are essentially proportional to the number of fixtures.

Energy costs are related to the installed wattage multiplied by the average frequency of use and the cost of power. For the purpose of policy recommendations the cost of power should include an environmental cost in addition to the direct utility cost. Environmental costs depend upon how the power is generated, and have been estimated to range up to 8¢ per kilowatt-hour.[13]

For any individual building there may also be a charge or credit because of cooling or heating interactions with lighting. Efficient cooling or heating takes only one unit of energy for every three to four units removed or added, so the maximum imbalance is on the order of 25 percent. Whether a building has a net cooling debit or heating credit due to lighting depends upon its size, operation, and location. For any individual building an imbalance of heating and cooling loads adds an additional linear term to the lighting energy cost. Our sample calculations assume that on average heating benefits and cooling costs cancel.

Finding the economic optimum

Since all the costs are approximately linear with respect to illuminance, E, we can gather them into a single coefficient, C, and write the net-benefit equation as follows:

$$NB = S/[F/RTP + (1-F)] - C \times E \qquad (5).$$

Since RTP is a function of luminance, L, we write E as $E = \pi L/\rho$, where ρ is the reflectivity of task's background, and do the optimization in terms of luminances. The luminance that gives the maximum net-benefit is the luminance that makes the partial derivative of equation 5 equal to zero:

$$\partial NB/\partial L = S \times F \times (\partial RTP/\partial L)/[RTP^2\{F/RTP + (1-F)\}^2] - \pi \times C/\rho = 0 \qquad (6).$$

Putting most of the economic parameters on the right side of equation 6, and leaving the task performance estimation on the left side as a weighted slope, makes it easier to analyze and plot.

$$(\partial\, RTP/\partial\, L)/\{F + (1-F) \times RTP\}^2 = \pi \times C/(F \times S \times \rho) \qquad (7).$$

The right side of equation 7 is much more sensitive to the value of F than the left side when RTP is greater than about 0.5. Lower values of RTP are not realistic, as a worker would almost certainly try to find some way to make the task more easily visible.

General features of equation 7

Table 1 lists the range of values for the various inputs to the coefficients of equation 7 for an office lit with 40 watt fluorescent lamps. These values are used in the next section for sample calculations. Before continuing with these calculations it is worthwhile to note some general features of equation 7 and table 1. First consider the practice of adjusting the light level to maintain a fixed level of performance (RTP) for different conditions of visual difficulty (age, size, or contrast). For fixed values of the economic parameters (C, S, and F) the right side of equation 7 is a constant. Equation 7 will have a solution under these conditions only if the slope of the visual task performance function (∂ RTP/∂ L) depends solely on RTP, and does not have explicit additional dependencies on the values of age, luminance, contrast or size. This was not true for the Blackwell visual performance models, and it is not true for any of the current visual performance models. Thus, setting light level recommendations to meet a fixed performance level is not economical.

The second point follows from table 1 which shows that the economic variables vary widely. The right side of equation 7 can vary by almost a factor of 100 to 1 for two offices with different costs and compensation levels. Past recommendations have either ignored economics or have treated them as a small correction to the recommended illuminances. Equation 7 shows that this procedure will give the most economical recommendations only if the weighted <u>slope</u> on the left side of equation 7 varies rapidly near the most economic luminance level.

The third point is that equation 7 is written as if the task, the average worker age, the economic parameters, and for that matter, a correct visual performance model, are known. If there is variability or uncertainty in any of these parameters the largest expected net-benefit over the long-term is obtained by averaging. For example, uncertainties in RTP due to age or differences in RTP models can be handled by computing an average relative visual task performance, RTP_a, where $RTP_a = \sum p_i RTP_i$, with $\sum$ indicating a sum over the different models or ages indicated by the index i, and p_i being the probability of each RTP_i. Equation 7 has to be generalized to a sum if there is a range of tasks each of which takes a minimum fraction of time, F_i:

$$[\ \sum F_i(\partial RTP_i/\ \partial L)/RTP_i^2\ ]\ /\{\sum(F_i/RTP_i) + (1-\sum F_i)\}^2 = \pi \times C/(S \times \rho) \qquad (8)$$

where again RTP_i is the relative task performances for task i. Equation 8 is also valid if there is more than one worker, but their work is interdependent. If workers work independently of each other, so that performance on one task does not affect performance on the second, then the net-benefit optimization consists of a sum of terms of the form shown above.

In many cases complicated averaging will not be needed, because, as we show later, task performance does not vary linearly with respect to light level, and tends to have a sudden steep drop-off as luminance is lowered. This means that there is a much larger economic cost for underestimating the required illuminance level than there is to overestimating by the same amount. Thus, optimal light levels in a multi-task environment will generally be close to the optimal level for the typical difficult task.

Sample Calculations

This section presents the results of cost-benefit calculations with equation 7 over a number of conditions representative of office situations. The example office task that we examined was the reading of print of different sizes and contrasts. The weighted slope given by the left side of equation 7 was calculated for 3 contrast-size combinations covering a wide range of visibilities, and 2 ages at a value of $F = 0.5$. As noted earlier, calculations of the left side of equation 7 are relatively insensitive to the value of F. The optimal illuminance are given as the values where the weighted slopes from the left side of equation 7 equal the right side of equation 7. We examined 3 values of the economic parameters, and 3 reflectances. We first describe calculations done with Rea's RTP model, which is currently being considered for use by the RQQ committee.[7,8] We then describe calculations based on a RTP model developed by the authors.[10] Both models show that using fixed RTPs to determine illuminance levels leads to uneconomic choices. The calculations also show that there are still significant differences between models. Table 2 gives the contrast, size, reflectance, and age conditions conditions studied.

Results with Rea Model

The equation for RTP recommended by Rea is (after collecting terms and multiplying through):[8]

$$RTP(Rea) = 1.4198 \times (1 - 0.0009047 \times RT) \qquad (9)$$

RT is a function of luminance, contrast, and size, that fits the reaction time data measured by Rea.[7] The functional form for RT is quite complex, and the reader is referred to the references for further information.[7,8] Equation 9 relates these reaction times to the relative performance measured in a numerical verification experiment.[14] Rea has suggested that the results from this later task be used to estimate performance in situations ranging from the classroom to the roadway.[8]

To apply the Rea model to our sample task we have assumed a viewing distance of 40 cm, and used Rea's value for the average visual area of 8 point type, which at this viewing distance is equal to 4.8 μ-steradians. Note that the visual area scales as the square of the print point size.

Figure 1 shows RTP(Rea) as a function of illuminance for the 6 visibility conditions of table 2. The small kinks in the curves are plotting artifacts. The reference condition chosen by Rea is not the maximum performance condition, and the maximum RTP on the figure turns out to be 1.04, not 1.0. Figure 1 shows that in this model estimated performance at high luminances is insensitive to age. It is also insensitive to task difficulty, except for the very most difficult tasks. At lower luminances age becomes an important factor even for the relatively easy tasks.

Figure 2 shows the weighted slopes defined by the left side of equation 7 as calculated with the Rea model. At the higher luminances there is surprisingly little difference between the various conditions. Figure 3 shows a graphical construction of how the optimal luminances for different values of the economic parameters are found for a given slope curve.

Table 3 shows a comparison, based on calculations with the Rea model, between luminances determined by choosing fixed performance levels versus those determined by the cost-benefit procedure. The two fixed RTP levels chosen, 0.91 and 0.99, span the range that has been suggested for consideration in the next round of standards by the RQQ committee. These luminance recommendations do not depend on reflectance. In the cost-benefit model the importance of visual work is given by the economic parameters on the right side of equation 7. Reflectance does affect the economic calculations. The calculations in table 3 are based on a reflectance of 0.6, and the extreme values of task importance from table 2, so as to be consistent with the fixed RTP values listed.

The values in table 3 show that the two procedures give recommendations that in some cases differ by more than a factor of 100. This occurs both as a function of size and contrast (task difficulty) for a given value of task importance, and as a function of task importance for a given value of task difficulty.

Actual recommendations are done as illuminances, not luminances. The differences between the fixed RTP and cost-benefit procedures is even larger for illuminances than for luminances. Recommendations based on a fixed RTP level illuminances are simply inversely proportional to the reflectance. This is not true when the recommendations are based on net-benefits, because the optimal luminances then depend on reflectance (see the right side of equation 7). Table 4a shows illuminance recommendations using the cost-benefit procedure are relatively insensitive to reflectance. Table 4b shows how much more sensitive recommendations based on fixed RTPs are to reflectance than recommendations based on net-benefits. The entries in the table are the recommendations normalized against the recommendations for 0.9 reflectance. The last column is for the fixed RTP procedure, while the other columns are for the cost-benefit procedure.

Tables 3 and 4 show that the proposed fixed RTP procedure gives recommendations that are far more sensitive to visibility and task importance than is justified by economic calculations.

Results with VL Model

The Rea model has actually only been validated at one print size. We have recently tested a VL-based model on a study of the speed at which young adults read print of a variety of sizes.[9,10] Two questions arise: 1) Are the two models significantly different? and 2) If they are different, do the fixed RTP and net-benefit procedures still give significantly different recommendations?

Converted to compute RTP instead of reading times, our simple VL fit can be written as follows:

$$RTP(VL) = 1/[\ 1 + 0.667/(1.15VL - 1)] \tag{10}$$

An explicit formula for VL as a function of size, luminance and contrast can be found in Bailey et. al..[10] RTP is assumed to be zero when $VL \leq 1/1.15$, and approaches a maximum value of 1.0 as VL goes to infinity.

We again assumed a viewing distance of 40 cm. The VL model depends upon the identification of a "critical detail" size. We use a value of 1/5 letter height, as this is the common assumption, and it fit quite well in the analysis of our experimental data. For 8 point type this gives an angular size of 2.4 minutes of arc. The critical detail size varies linearly with point size. The VL model work was based on experiments with young adults. For consistency, we use the age correction factors from Rea's model for the calculations here.

Figures 4 and 5 show RTP and the weighted slope of RTP as calculated by the VL model and can be compared to figures 1 and 2. Both RTP and its slope are more sensitive to age and visibility conditions when calculated with the VL model instead of the Rea model.

Tables 5, and 6a and 6b show the luminance and illuminance recommendations calculated with the VL model, in the same fashion that they were shown in tables 3 and 4a and 4b as calculated by the Rea model. The fixed RTP values are lower in table 5 than in table 3, because the maximum value of RTP was defined to be 1 with the VL model, while with the Rea model it reached a value of about 1.04 for the conditions studied. The VL model produces recommendations that range from two times lower to five times higher than those of the Rea model. Despite this large difference between the two models, the results in tables 5 and 6b again show little relation between the fixed RTP method and the cost-benefit method.

Results with Rea Model when Fit to the Reading Speed Data

The Rea model (equation 9) was fit to a numerical verification experiment, while the VL model was fit to reading speed data. It is therefore unclear whether the differences shown above are due to intrinsic differences in these two models, or simply differences in the tasks to which they were fit.

A fit of Rea's model to the results of our study of reading speeds is described in Bailey et. al..[10] For the Bailey reading speed data the values of the parameters of equation 9 become 1.7876 and 0.00153. For the conditions examined here, these parameter values give a maximum RTP value of 1. Figures 6 and 7 show the RTPs and weighted slopes calculated with the above parameters. Comparison of these figures with figures 1 and 2 shows that there is a task effect, while a comparison to figures 4 and 5 shows that there is also a significant difference between the Rea and VL models.

The results of modifying Rea's model to fit the reading experiment data primarily results in lower predicted RTPs at any given visibility than with the original model, but does not substantially change the shape of the predicted curve versus visibility. As a result, the pattern of economically optimal luminances remains almost the same, but the absolute values shift up to 1.8 to 2.5 times the levels shown in tables 3 and 4.

The Rea and VL models show very different patterns in slopes and absolute RTPs, even when fit to the same data. Table 7 shows a comparison of the economically optimal luminances for the two models when both are fit to the reading speed data. Over the range of conditions examined, the ratio of recommendations from one model to the next ranges from about 3:1 to 1/3:1.

Discussion

The fixed RTP procedure leads to illuminance recommendations that are very sensitive to differences in contrast, size, reflectance or visual sensitivity (age). This should not be a surprise, because generally performance is not strongly related to luminance. In some cases there is no luminance that can give the required RTP value, with the result that one has to choose an "appropriate" upper bound. The cost-benefit approach rarely gives impractically high recommendations, because a measure of what is "appropriate" is built into the procedure.

The RQQ #6 consensus recommendations were at least in part a response to the need to include economics.[1] This consensus procedure actually produced age and reflectance adjustments that are closer to the trends shown in our economics calculations than those calculated with the fixed RTP procedure. However neither RQQ #6 nor the proposed fixed RTP procedure appears to properly account for variations in task importance.

The cost-benefit approach requires an explicit estimate of the value, or "importance" of visual work through the computation of the slope term of equation 7; C/(F x S). In RQQ #6 the illuminance recommendations only vary by a factor of 1.5:1 over the entire range of task importances. The calculated economically optimal illuminance range for changes in task importance is about 12:1 to 40:1. The exact range determined by the cost-benefit procedure obviously depends upon the accuracy of the values listed in table 1, but the range will almost certainly be substantially larger than that specified by RQQ #6. With the fixed RTP procedure the magnitude of the illuminance variations with task importance depends upon the ad. hoc. RTP levels chosen, as well as the visibility conditions. The adjustments can be larger, smaller, or simply different than those determined by the cost-benefit calculations.

The magnitude of the predicted differences between tasks and models was neither a predicted, nor particularly welcome outcome of our analysis. The tasks differ in their maximum performance level, and thus presumably the amount of non-visual work required. The models appear superficially similar in form, but treat accuracy and luminance very differently. More work is needed to understand these differences.

Figure 8 shows an expanded view of two sample relative net-benefit curves calculated by the Rea and VL procedures. Picking the optimal luminance for the Rea model results in a large drop in net-benefit if the VL model is correct, and visa-versa. Averaging, over models, in this case, or other variables in other cases, leads to the smallest losses in net-benefit versus the given condition or model that is correct, and thus gives the highest expected net-benefit.

Conclusion

Our main conclusion is that the procedure of basing illuminance recommendations on a fixed (calculated) performance level does not lead to economically optimal recommendations. Difference of more than a factor of 100 occur between the economic optimum illuminances and the fixed RTP illuminances. Our calculations also showed that there are still economically significant disagreements in the predictions of different visual performance models. The consequences of these disagreements can be minimized by applying the cost-benefit approach and averaging appropriately.

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Table 1

Item	Range	Notes
Productivity (F x S per unit area)	\$50 - \$1000/m^2-year	1
1) Worker Compensation (S)	\$15,000-\$200,000/year	2
2) Fraction visual work (F)	5 - 50%	3
3) Area/worker	10-20 m^2	4
4) Visual Performance		
a) Task size	6 - 12 point. type => 1.8 - 3.6 minutes arc, or 2.7 - 10.8 μSR	5
b) Contrast	0.3 - 0.95	6
c) Reflectance	0.3 - 0.9	7
d) Worker Age	20 - 70	
Costs (C)	\$5.4 - \$39x10^{-3}/lumen-year	
Maintained lumens/lamp	1240 -1650	8
Installation	\$1.1 - \$8.1x10^{-3}/lumen-year	
1) Installation cost/lamp	\$35 - \$120	9
2) Annualized cost factor	0.06 - 0.09	10
Maintenance	\$1.15 - \$3.7x10^{-3}/lumen-year	11
1) lamp replacement cost	\$2.20 - \$4.20	9,12
2) lamp replacement interval	3 - 5 years	13
3) ballast replacement cost	\$25.00 - \$36.00	14
4) ballast replacement interval	12 years	15
5) group cleaning cost	\$0.75 - \$2.40/lamp	16
6) cleaning interval	1 - 3 years	17
Electrical	\$3.3 - \$27x10^{-3}/lumen-year	
1) hours of operation	2500 -3500 hours/year	4
2) watts/lamp + ballast	43 watts/lamp	18
3) electrical costs	5.0 - 23 ¢/kwh	19
C/(F x S)	8 - 600x10^{-6}/lux	20

Notes:

1) Compensation rates and visual fraction are assumed to be correlated.
2) Highly compensated executives are assumed to have amenity lighting.

3) The lower limit is a guess to what can be legitimately called lighting for visual performance. The upper limit is a guess as to the minimum fraction of the non-visual time for thinking, talking, and motion in a work environment.

4) Estimated from "Characteristics of Commercial Buildings". DOE/EIA-0246(86). Available Superintendent of Documents, Washington, DC 20402.

5) Estimated for office work. The area of the print for a given print size was estimated from reference 7 (main text). The angular subtense is 1/5 the letter height. Both estimates assume a 40 cm. viewing distance. The lower limit is close to the limit of applicability of these detection models to resolution tasks.

6) Estimated range: print on colored paper to black on white.

7) Reference 1, main text.

8) 40 watt fluorescent lamp - lumens 3150 -3350, CU = 0.69-.73, RSDD = .96, BF = .94, LLD = .79-.85 (spot relamp to 3 year group relamp), LDD = .8-.88 (1-3 year cleaning cycle). References: GE lamp catalog, and J. Lindsey, "Applied Illumination Engineering". Fairburn Press, Lilburn, GA. 1991.

9) R. S. Means 1992 Building Construction Cost Data. Installation estimates include wiring and panel costs. The range reflects both differences in nominal fixture costs per lamp ($25-$50) and differences in material and labor costs with respect to nominal costs for Colorado Springs and Charleston at the low end, and San Francisco at the high end (0.8-1.16, and 0.54-1.65 respectively). Values include contractor overhead and profit.

10) Assumes a discount rate, i, of about 4 - 6 percent (after inflation) and a hardware life, N, of 20 -25 years. Annual cost factor = $i/[1-(1+i)^{-N}]$.

11) High costs for cleaning and lamps give higher efficiencies - this limits the range per lumen.

12) Lamp costs from Lindsey (note. 8). Nominal labor charge including overhead & profit $26/hour. Range computed from city differences (note 9).

13) Group to spot relamping.

14) Electronic ballast @ $20. Labor costs $5 - $16 (Charleston to San Francisco; Lindsey note 8 and Means note 9).

15) Nominal value.

16) 0.15 hours/lamp (Lindsey note 8) and from $5-$16/hour labor charge (Lindsey's values adjusted by Means' city labor rates - note 9).

17) Group cleaning assumed.

18) See Lindsey note 8. Heating and cooling effects are assumed to cancel.

19) DOE/EIA-0348(86). Electric Power Annual, 1986, table 40. See note 4 for availability. Environmental costs assumed to be in the range of 2 - 8 ¢/kwh.

20) Compensation and costs are assumed to be correlated - this limits the range.

Table 2

Conditions used in Sample Calculations

Visibility and Age Parameters

Visibility and Age Condition #	Size* Minutes	Steradians	Contrast	Age
1)	1.8	2.7×10^{-6}	0.3	20
2)	2.7	6.1×10^{-6}	0.6	20
3)	3.6	10.8×10^{-6}	0.9	20
4)	1.8	2.7×10^{-6}	0.3	64
5)	2.7	6.1×10^{-6}	0.6	64
6)	3.6	10.8×10^{-6}	0.9	64

Weighted Slopes ($\pi C/FS\rho$) units = $(cd/m^2)^{-1}$

Task Importance (C/FS)		Reflectance (ρ) 0.9	0.6	0.3
High	$= 8\times10^{-6}$	2.8×10^{-5}	4.2×10^{-5}	8.4×10^{-5}
Medium	$= 7\times10^{-5}$	2.4×10^{-4}	3.7×10^{-4}	7.3×10^{-4}
Low	$= 6\times10^{-4}$	2.1×10^{-3}	3.1×10^{-3}	6.3×10^{-3}

* Note: Size in minutes is 1/5 the letter height, while size in steradians is the angular area of the stroke portion of the average letter.

Table 3

Recommended Luminances (cd/m^2) with the Rea visual performance model: Fixed RTP versus cost-benefit procedure of equation 7 for two values of task importance

	Task Importance			
	Low		High	
Visibility	Procedure		Procedure	
Condition	Fixed RTP	Net-benefit	Fixed RTP	Net-benefit
(see table 2)	(0.91)	(3.1×10^{-3})	(0.99)	(4.2×10^{-5})
1)	570	9	> 5,000	360
2)	< 1	5	140	230
3)	< 1	4	17	210
4)	3,000	20	> 5,000	430
5)	4.5	9	700	260
6)	1.5	6	80	230

Table 4a

Illumination Recommendations for Rea model (lux) - From Equation 7

	Condition 3			Condition 4		
	Task Importance					
Reflectance	low	medium	high	low	medium	high
0.3	29	151	1160	143	475	2430
0.6	23	142	1120	103	370	2250
0.9	21	139	1110	87	330	2170

Table 4b

Illumination relative to value at 0.9 reflectance

	Condition 3			Condition 4			
	Task Importance						Fixed
Reflectance	low	medium	high	low	medium	high	RTP
0.3	1.40	1.09	1.05	1.64	1.45	1.12	3.0
0.6	1.12	1.02	1.01	1.19	1.12	1.04	1.5
0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 5

Recommended Luminances (cd/m^2) with the VL visual performance model: Fixed RTP versus cost-benefit procedure of equation 7 for two values of task importance

	Task Importance			
	Low		High	
Visibility Condition (see table 2)	Procedure Fixed RTP (0.86)	Procedure Net-benefit ($3.1x10^{-3}$)	Procedure Fixed RTP (0.935)	Procedure Net-benefit ($4.2x10^{-5}$)
1)	2,400	48	> 5,000	720
2)	7	14	71	235
3)	1	8	6	125
4)	> 5,000	100	> 5,000	1,250
5)	37	27	450	400
6)	5.5	14	30	210

Note: Fixed RTP values scaled down by a factor of 1.06 from those listed with Rea model to adjust the maximum RTP values for the conditions studied to the same value (0.98).

Table 6a

Illumination Recommendations for VL model (lux)

	Condition 3			Condition 4		
	Task Importance					
Reflectance	low	medium	high	low	medium	high
0.3	52	200	825	750	2300	8500
0.6	40	155	655	520	1720	6600
0.9	33	135	575	435	1460	5700

Table 6b

Illumination relative to value at 0.9 reflectance

	Condition 3			Condition 4			
	Task Importance						Fixed
Reflectance	low	medium	high	low	medium	high	RTP
0.3	1.57	1.47	1.43	1.73	1.58	1.48	3.0
0.6	1.20	1.15	1.14	1.19	1.18	1.15	1.5
0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 7

Comparison of economically optimal luminances (cd/m^2) as predicted by the Rea and VL models, with both models fit to the results of the reading speed study. (reference 10)

	Task Importance			
	Low ($\pi C/FS\rho = 3.1\times10^{-3}$)		High ($\pi C/FS\rho = 4.2\times10^{-5}$)	
Visibility Condition		Procedure		
(see table 2)	Rea	VL	Rea	VL
1)	20	48	890	720
2)	10	14	530	235
3)	9	8	480	125
4)	37	100	1,050	1,250
5)	17	27	590	400
6)	13	4	520	210

Figure 1: RTP calculated by Rea's model

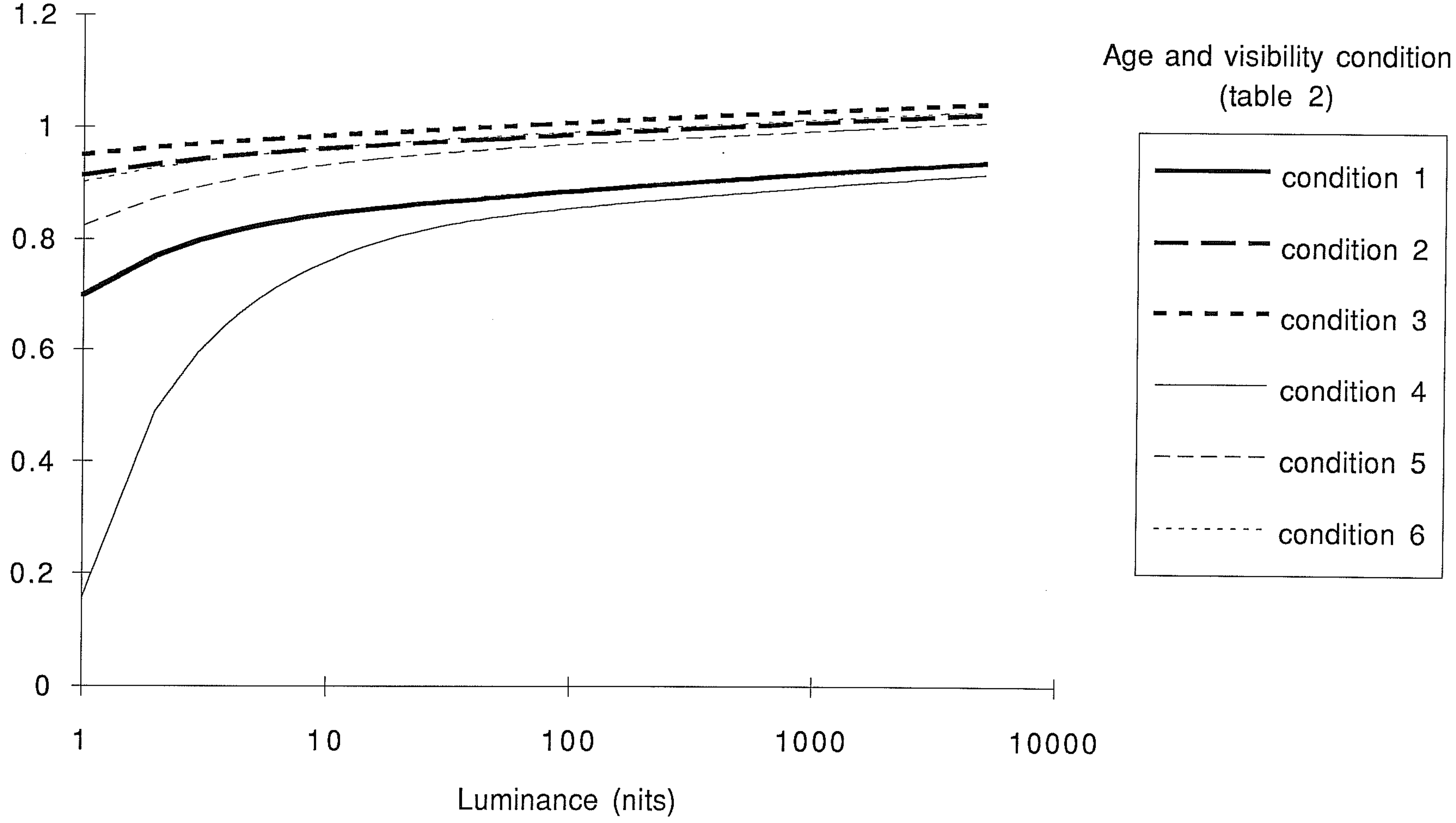

Figure 2: Weighted slopes (equation 7) calculated by Rea's model

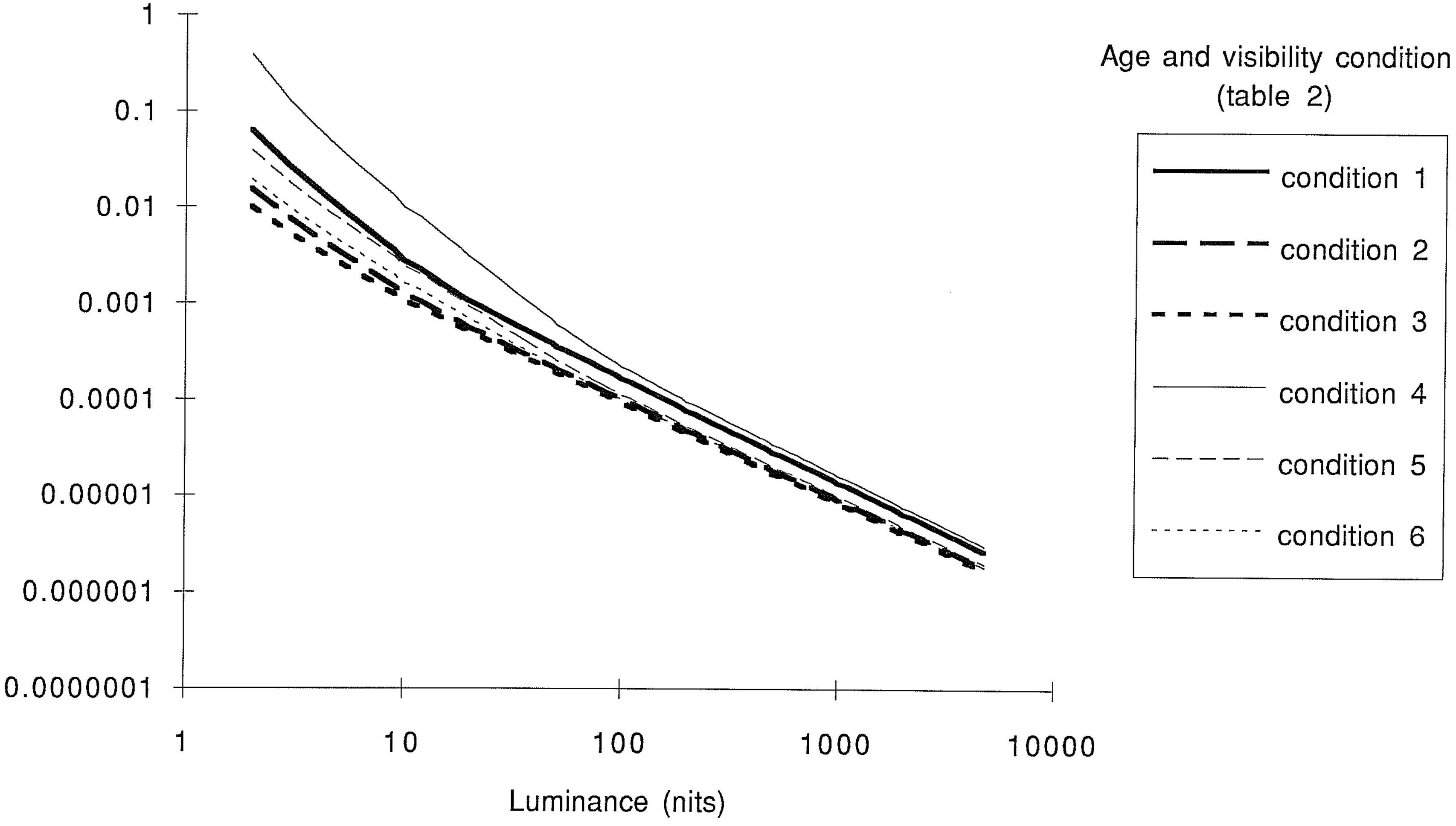

Figure 3: Calculation of Optimal luminances from slope values

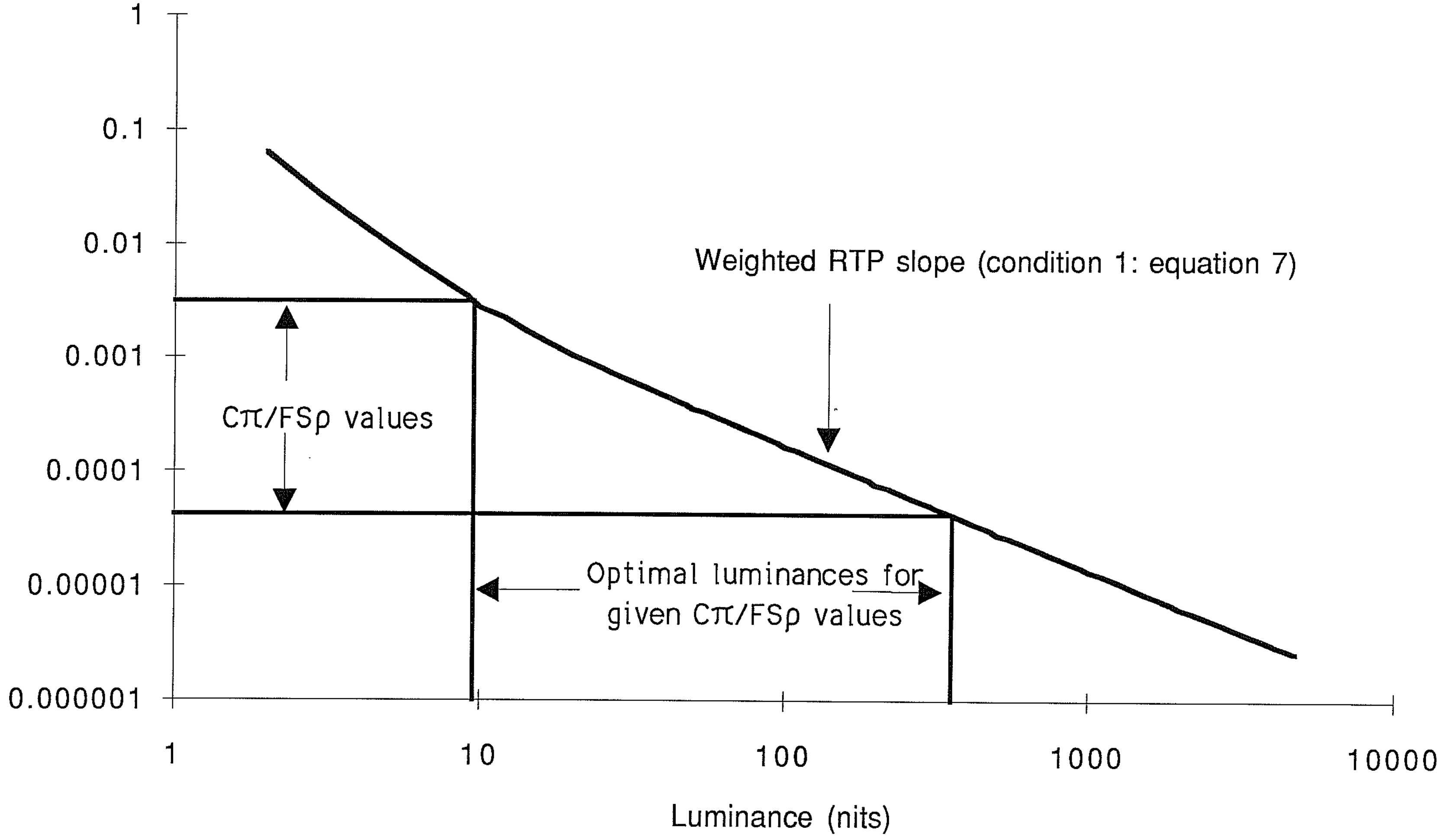

Figure 4: RTP calculated with VL model
(critical detail = 1/5 letter height)

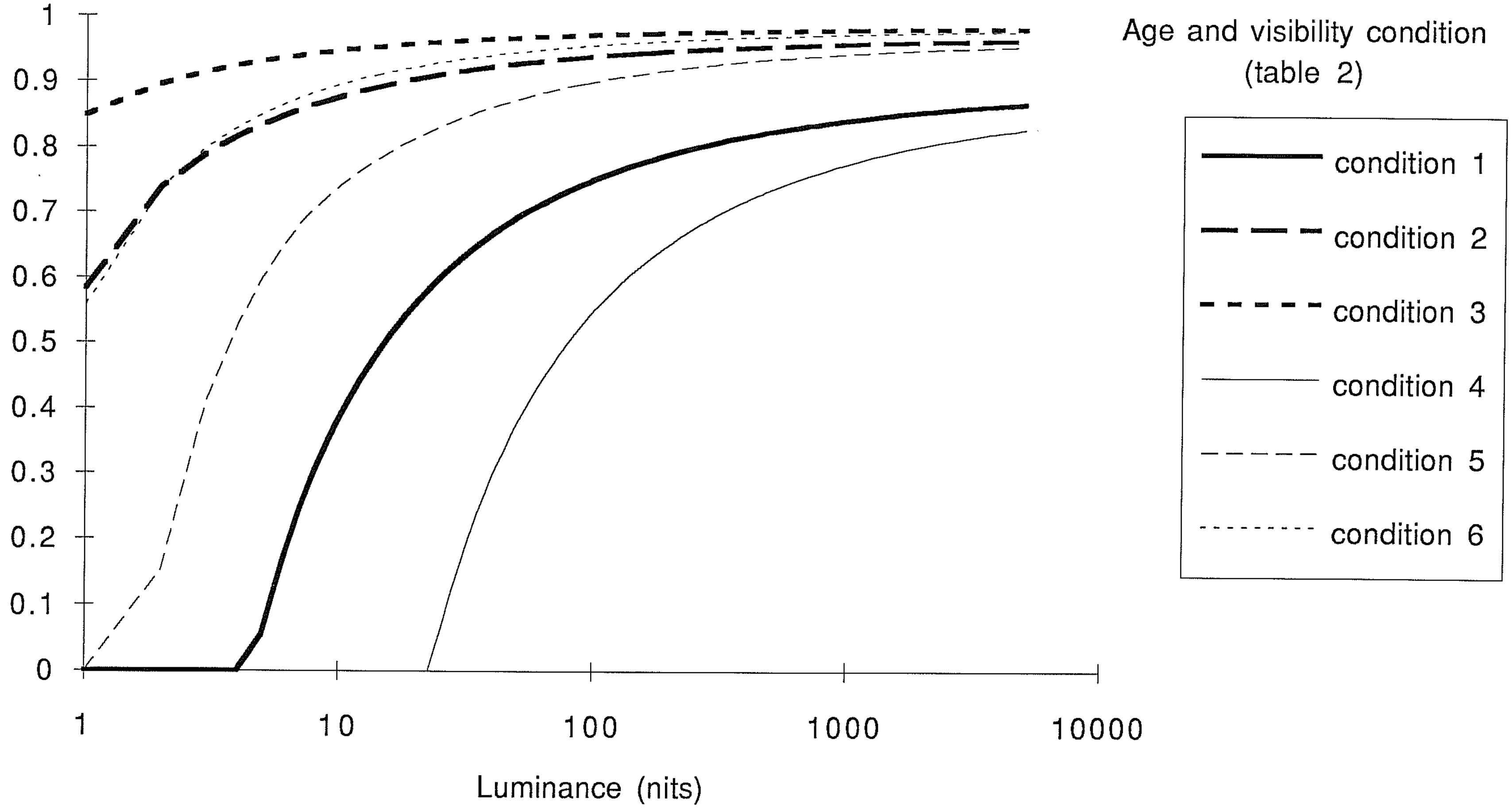

Figure 5: Weighted slopes (equation 7) calculated by VL model (critical detail = 1/5 letter height)

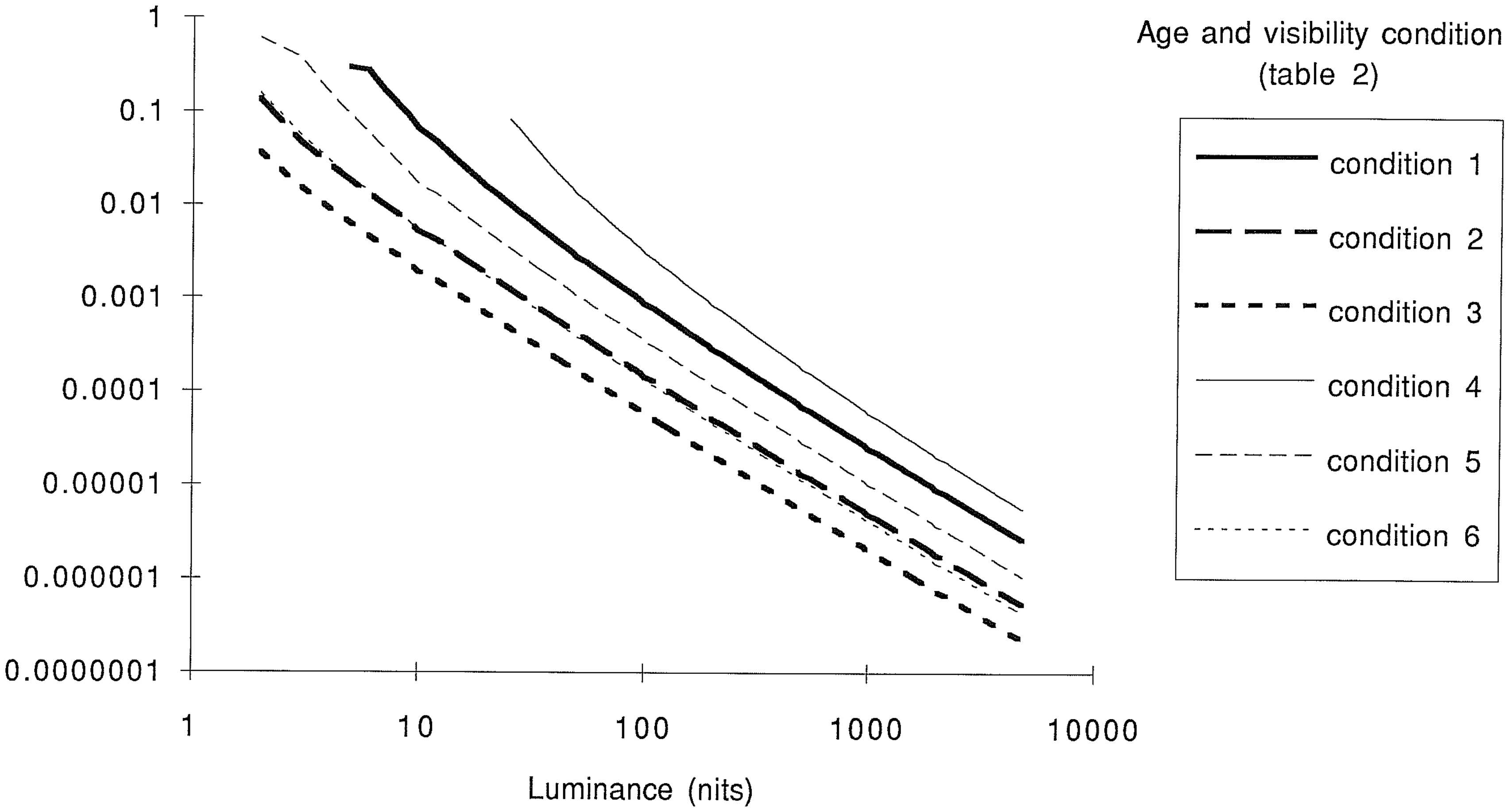

Figure 6: RTP calculated by Rea's model
(as adapted to Bailey reading experiment)

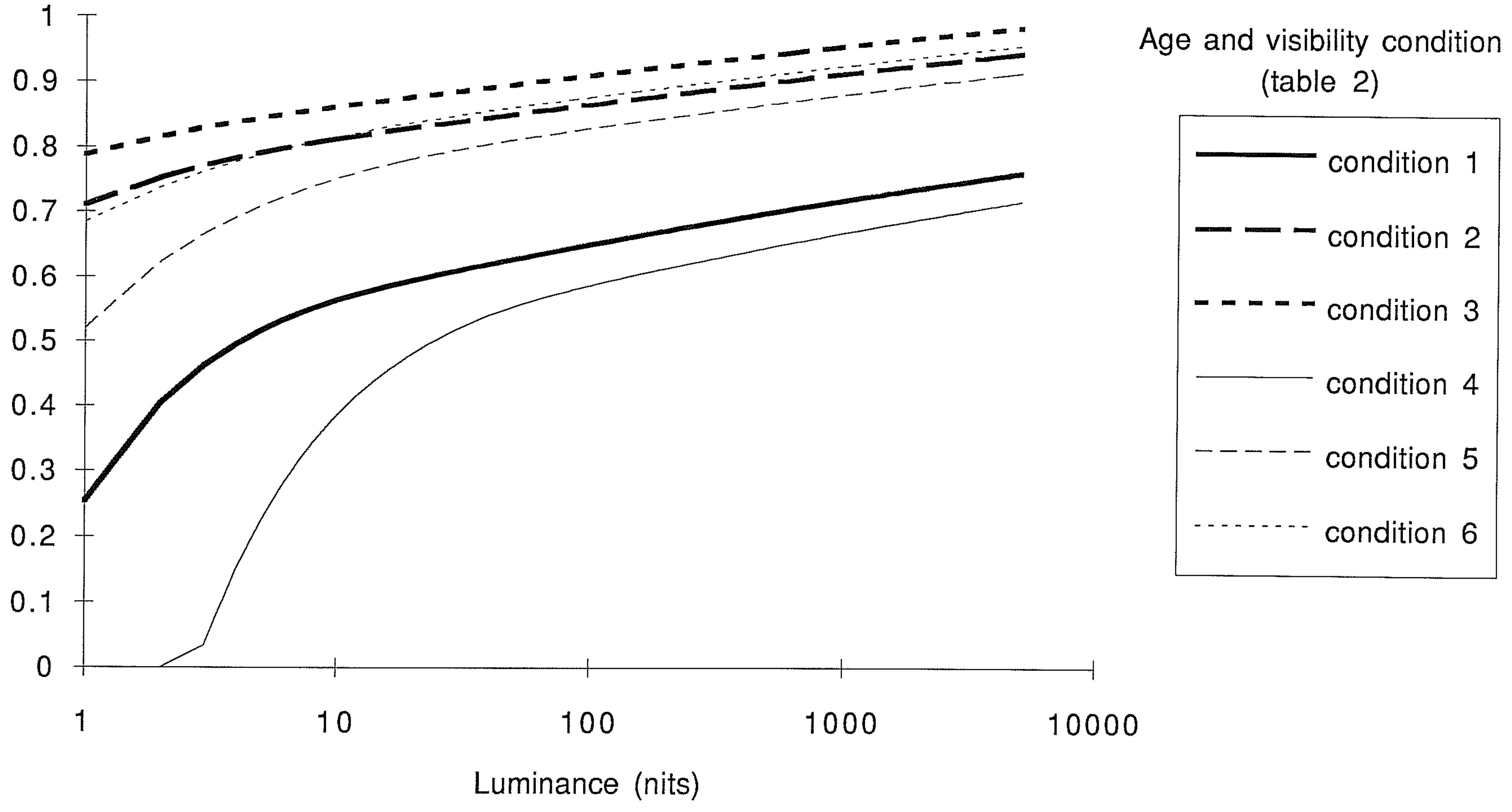

Figure 7: Weighted slopes (equation 7) calculated by Rea's model (as adapted to Bailey reading experiment)

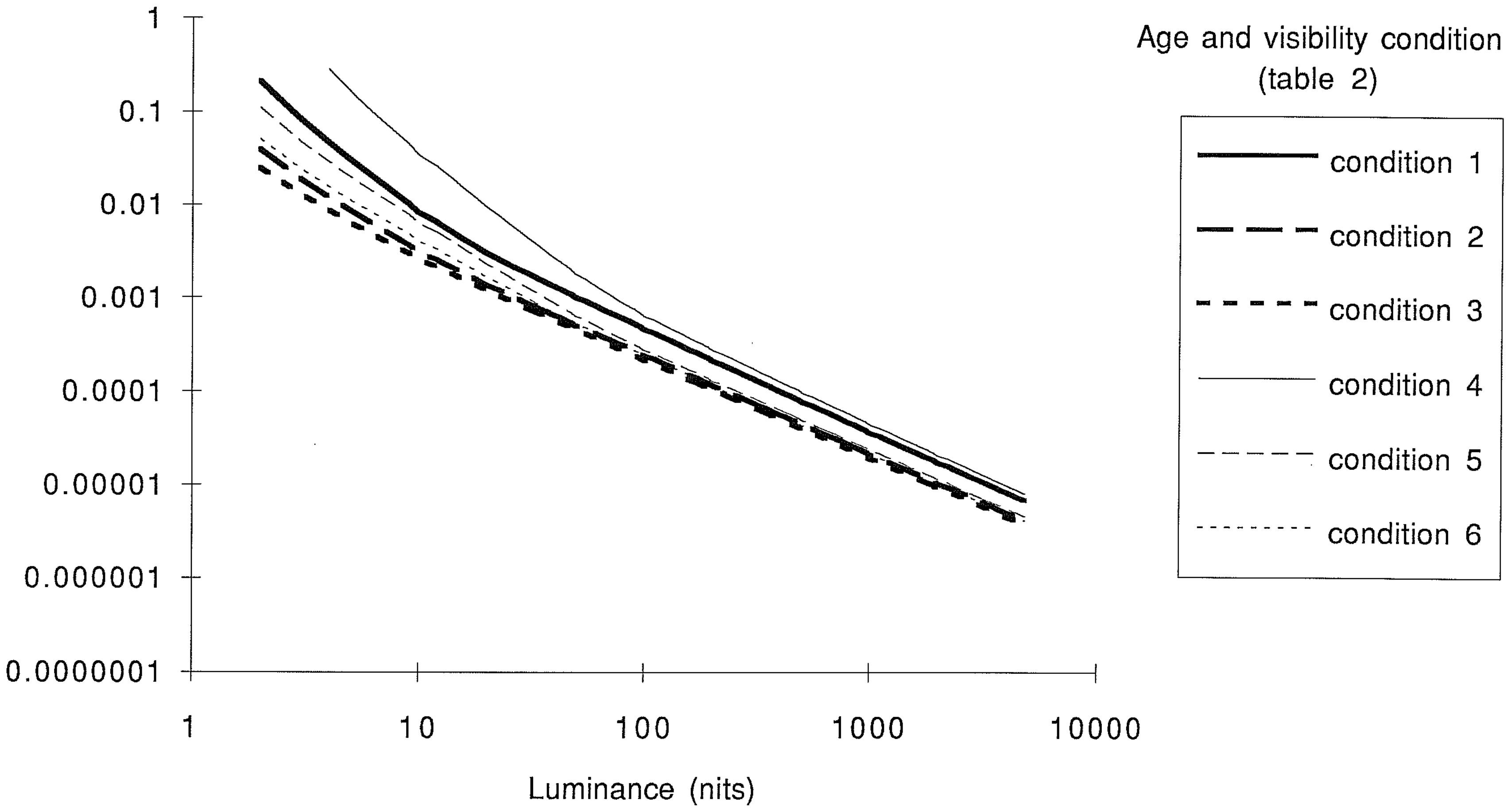

Figure 8: Relative Net-Benefit using the Rea & VL visual performance models with moderately important task & visibility condition 4 of Table 2