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Relative Visual Performance: A Basis for Application

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Summary Visual performance is defined in terms of the speed and accuracy of processing visual information. To evaluate illuminated tasks in terms of visual performance, it is necessary to have a valid computational model that relates measurable, salient aspects of the visual environment (e.g. target contrast) to measurable human responses (e.g. visual response time). A model of visual performance should be independent of the influence of non-visual factors as they influence speed and accuracy. It is also important to have practical application tools that can measure the salient aspects of the visual environment and compute (predict) visual performance for real tasks. This paper describes the basis for a visual performance model and how it can be applied using a computer imaging device.

Relative visual performance: A basis for application

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1 Introduction

Visual performance has traditionally been defined in terms of speed and accuracy of processing visual information. In fact, inferred changes in speed and accuracy for different adaptation levels underlie the rationale for different illuminance levels recommended by national technical societies such as the Illuminating Engineering Society of North America and the Chartered Institution of Building Services Engineers. Consistent with this tradition, visual performance in this report is defined in terms of how quickly and accurately people can process visual stimuli that are defined in terms of adaptation luminance, target contrast and target size. One goal of lighting and vision research has been to develop a general technique for assessing visual performance in actual environments such as offices, schools and roadways. Such a technique would permit the evaluation of real environments by criteria relevant to the visual system, rather than by intermediary criteria such as illumination levels.

To reach this goal, knowledge is required in two areas. First, a *psychophysical model* must be established that relates the salient physical features of the visual environment, such as contrast or size, to measurable responses of human observers such as time or errors. Second, a practical procedure must be developed that can specify accurately the environmental stimuli that are important to visual performance. In other words, a *measurement technique* must be developed to quantify the salient physical features of the visual environment.

Considerable effort has been devoted to reaching this goal over the past sixty years. Luckiesh and Moss[1,2] and Blackwell[3–6] in particular, have pursued both psychophysical research and measurement procedures. Extensive psychophysical data have been obtained on threshold visibility (the limits of visibility) for targets of different size and shape, targets presented off the visual axis, and for observers of different ages. Blackwell used these threshold data, obtained from parametric manipulation along several stimulus dimensions, to develop a computation model of visual performance. This computational model was published by the Commission Internationale de l'Éclairage[7] and a technical review of this model was published by Public Works Canada[8].

Consistent with the psychophysical approach based upon threshold, instruments were also developed by Luckiesh and Moss, Blackwell and others for assessing the threshold visibility of actual tasks. These instruments, known generally as visibility meters, require an observer to view an actual task through an optical device that could gradually make the task invisible, that is, reduce its visibility to threshold. The Luckiesh and Moss[1] visibility meter reduces targets to threshold by reducing adaptation luminance. Most other visibility meters, including those designed by Blackwell[5], attempt to reduce targets to threshold by modulating their apparent contrast. It is also possible to design a visibility meter that would modulate the spatial frequencies of targets to reach threshold, but this approach has not been pursued. Given an empirical measurement of target threshold, a computational psychophysical model can be used to predict the suprathreshold level of visual performance for that target[7].

Difficulties with both the theoretical and practical aspects of the threshold approach have been discussed by several authors in a symposium on the subject[8]. Theoretically, it is impossible to extrapolate suprathreshold visibility directly from threshold visibility, primarily because different levels of maximum visual performance are found at different adaptation luminances[9,10]. To overcome this problem a variety of arbitrary, *post hoc* terms must be introduced to accurately characterise suprathreshold visual performance from threshold measurements[9].

Practically, visibility meters have inherent limitations that prevent adequate characterisation of the visual stimulus for determination of visual performance[11]. For example, all visibility meters introduce optical infidelities. These include instrument-specific changes in contrast (such as losses in high spatial frequencies), size (such as optical magnification) and adaptation luminance (such as transmission losses or colour differences) that cannot be overcome without supplemental measurements and computations. The number of 'correction factors' that are needed to account for the differences between free-viewing and viewing through a visibility meter is large and task specific[11].

Weston[12,13], Boyce[14], Tinker[15–18] and Rea and his colleagues[10,19,20–25], for example, have pursued a different approach to psychophysical research. Rather than assess the absolute limits of visibility and then extrapolate to suprathreshold visual performance, their studies were designed to assess suprathreshold visual response directly in terms of time and errors (alternatively, speed and accuracy). Until recently, only a qualitative understanding of suprathreshold visual performance was possible. As pointed out by Rea[26], there are many subtle yet important experimental controls that must be considered when trying to extract visual performance from task performance, which includes motor skills, motivation and intelligence as well as visual performance. However, by experimental control and simple transformation of the data, the impact of target contrast, target size, adaptation luminance and observer age on visual response time and errors was obtained. From those data a computational psychophysical model of suprathreshold visual response was developed[10,24,27,28].

Rea and his colleagues have also developed a measurement procedure that is consistent with their psychophysical approach that relates measurable, salient values of the visual stimulus to measurable suprathreshold responses in terms of time and errors[29,30,31,32]. Two approaches were pursued. One approach utilised physical measurements of size and adaptation luminance as well as a 'contrast matching' technique, whereby the brightness of one of a large number of achromatic reflectance cards was matched to the actual target. Not only was this approach tedious to perform, but the contrast matching technique produced systematic errors when targets of different colour were compared with the achromatic reflectance cards[31]. A more sophisticated but simpler approach employs modern computer image processing techniques[32]. From a calibrated video image of the task, the salient visual features (such as adaptation luminance, target contrast and target size) are measured and then used as input parameters for the suprathreshold psychophysical model of visual performance which, conveniently, resides in the computer.

The basics of both the psychophysical model and the computer imaging system (CapCalc, which stands for *cap*ture and *calc*ulate) have been described in detail elsewhere[10,24,32]. This report serves two purposes. Primarily, links between two independent experiments are presented for the first time and these links provide the basis for a valid set of visual performance equations. Further, equations are presented that document the presumed age-dependent changes in visual performance from twenty to sixty-five years. Secondarily, the report documents the visual performance equations resident in the current CapCalc software. Thus, this paper describes the basis for relative visual performance and how it can be applied using CapCalc.

2 The numerical verification task

The numerical verification task was developed by Smith and Rea[20] to assess the impact of task luminance and target contrast on the speed and accuracy of processing visual information at a controlled, simulated realistic task. The numerical verification task was used subsequently in a variety of other experiments[23,33], including one reported by Rea[10], which resulted in a computational model of suprathreshold visual performance (Figure 1), known as the relative visual performance (RVP) model.

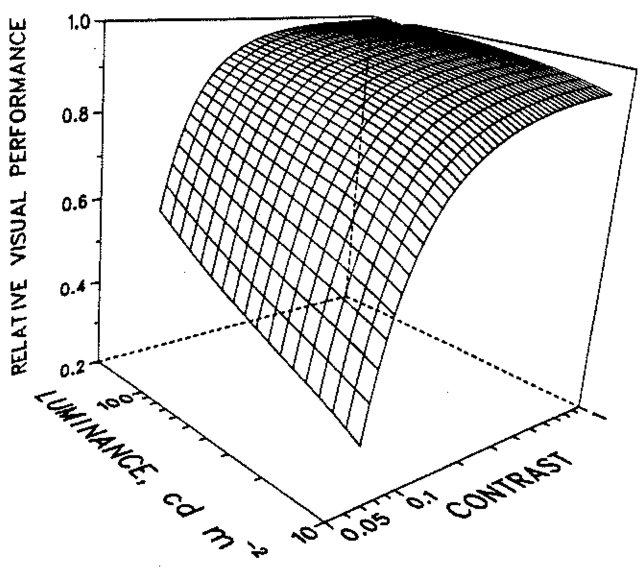

Figure 1 Three-dimensional representation of relative visual performance (RVP) as a function of target contrast and background luminance, based upon the numerical verification task (from Rea[10])

The RVP model presented in Rea[10] was based upon the visual time† for young adult subjects (mean age of twenty-two years) to compare two lists of twenty pairs of five-digit numerals, relative to the computed time to make a comparison under arbitrary, highly visible reference conditions. The time needed to perform nonvisual task-related activities such as placing tick marks to discrepant digits was excluded from the model. Adaptation luminance, from 12 to 169 cd m^{-2}, was changed by varying illumination level; the contrast of the targets (numerals) was modulated, from 0.092 to 0.894, by parametric variations in ink pigment density, ink gloss and lighting geometry. The viewing distance to the centre of the number lists was a constant 50 cm throughout the experiment.

3 Determination of relative visual performance

The RVP model is an attempt to represent the efficiency of visual processing, and is, in principle, independent of the nature of the visual task. RVP ranges from 0 at 'readability threshold'‡ to 1; RVP = 1 corresponds to an arbitrary minimum time computed from data obtained in the 1986 numerical verification task experiment[10]. RVP can assume values greater than 1 for better visual conditions than those associated with the arbitrary reference conditions such as large targets seen at higher background luminances. As shown in Figure 1, above contrast threshold, at a given background luminance, RVP improves rapidly as target contrast increases, until a point where RVP begins to saturate, that is, when further increases in task contrast have little effect. As background luminance increases, contrast threshold is reduced and RVP saturates at a higher level.

Steps 3(*a*) through 3(*f*) document Rea's procedure for calculating RVP[10]. Strictly speaking, the model is applicable to young adults reading negative contrast (dark ink on bright background) letters or numbers, each character subtending

† It was argued that time and errors likely provided the same information about visual performance, but that the time data were more complete and thereby provided a more accurate representation of visual performance.

‡ Contrast threshold values for the printed numerals used in this experiment were based upon a subjective criterion of 'readability.' To reach this criterion more target contrast is required than is required to reach a 'detection' criterion.

an average solid visual angle of 4.8×10^{-6} steradians. Character size is defined by the area of the ink, viewed at a specified distance, that is, the solid visual angle of the character. With the CapCalc system this value is obtained easily by integrating the areas of the size-calibrated pixels which define the character. The range of background luminances in the model is between 12 and 169 cd m^{-2}. The reciprocal of visual time necessary to read the alphanumeric stimuli 'as quickly and accurately as possible' is the measure of visual performance.

3(*a*) Select task background luminance L_B with the range of $12 \leq L_B \leq 169$ cd m^{-2}.

3(*b*) Calculate *readability* contrast threshold $C_{t,r}$ at the selected L_B, where

$$C_{t,r} = 0.0418[(0.308/L_B)^{0.4} + 1.0]^{2.5}.$$

3(*c*) Select task luminance contrast C_v, where L_B is greater than the target luminance L_T, and

$$C_v = \frac{L_B - L_T}{L_B}$$

3(*d*) Calculate the parameters n, k and VP_{max}, where

$$n = 0.882 + 4.38\theta_1 - 6.05\theta_1^2 \text{ and}$$

$$\theta_1 = \log_{10}[\log_{10}(L_B)]$$

$$\log_{10}k = -2.25 + 1.77\theta_2 - 0.217\theta_2^2 \text{ and}$$

$$\theta_2 = \log_{10}(L_B),$$

$$\text{VP}_{max} = 0.0628 + 0.0120\theta_2 - 0.00268\theta_2^2.$$

3(*e*) Calculate the predicted level of performance VP, where

$$\text{VP} = \{\Delta C_r^n/[\Delta C_r^n + (k/L_B)^n]\}\text{VP}_{max}$$

where $\Delta C_r = C_v - C_{t,r}$.

for values of $\Delta C_r < 0$, VP = 0.

3(*f*) Determine RVP, where

$$\text{RVP} = \text{VP}/f, \text{ and}$$

$$f = 0.0760 = \text{VP}_{max} \text{ at } L_B = 169 \text{ cd m}^{-2}.$$

For the numerical verification task experiment, RVP ranges from 0 to 1.

Comparisons between the RVP model predictions and data from other experiments were performed by Rea[26] who argued that, except for a single study by McNelis[34], the studies reviewed had a variety of inherent experimental difficulties that prevented a quantitative validation of the RVP model. Although predictions from the RVP model agreed remarkably well with the data from McNelis, it was deemed prudent to perform another, independent experiment to validate and extend the RVP model.

4 The reaction time experiment for psychophysical model

Rea and Ouellette[24] completed a study of simple reaction times. Square targets of different contrast, both positive and negative, and size, from 2×10^{-6} to 2.8×10^{-3} steradians, were flashed on a video screen of variable luminance. Young adults viewed the display through a circular 2 mm diameter artificial pupil that controlled retinal illuminance, from 0.53 to 801 trolands (T). Detection threshold values and reaction times were determined for the young adult subjects who had a median age of twenty-one years.

Data from the reaction time experiment were similar in form to those from the numerical verification task. Equations similar to those used in the RVP formulation were used to model the visual response times from detection threshold to saturation for the conditions used in the experiment. The parameter ΔT_{vis} is the difference in visual response time for a given set of stimulus conditions, relative to an arbitrary, reference set of suprathreshold stimulus conditions. In keeping with the philosophy expressed in developing the RVP metric, the reference set of stimulus conditions was a target of high contrast and large size, which was presented on the highest background luminance used in the experiment. It was assumed that nonvisual processing time was constant and independent of visual processing time for all conditions in the simple reaction time experiment. Thus, the procedure leading to ΔT_{vis} was designed to isolate the incremental, visual processing time (Figure 2).

5 Determination of ΔT_{vis}

Steps 5(*a*) through 5(*e*) detail the algorithm from Rea and Ouellette[24] for calculating predicted performance R and incremental visual performance time ΔT_{vis} from measurements of retinal illuminance (I_R in trolands from 0.53 to 801), target size (ω in steradians from 2×10^{-6} to 2.8×10^{-3}) and contrast (C_v).

5(*a*) Calculate *detection* contrast threshold $C_{t,d}$ where

$$A = \log_{10}\tanh(20\,000\omega)$$

$$L = \log_{10}\log_{10}(10I_R/\pi)$$

I_R = Retinal illuminance, from 0.53 to 801 T, $= L_A\pi r^2$

r = Pupil radius (mm)

L_A = Photopic adaptation luminance (cd/m^{-2})

ω = Area of target (steradians) from 2.0×10^{-6} to 2.8×10^{-3}

$$\log_{10}C_{t,d} = -1.36 - 0.179A - 0.813L + 0.226A^2 - 0.0772L^2 + 0.169AL.$$

5(*b*) Calculate the half-saturation constant K, where

$$A^\star = \log_{10}\tanh(5{,}000\omega)$$

$$L^\star = \log_{10}\tanh(0.04I_R/\pi)$$

$$\log_{10}K = -1.76 - 0.175A^\star - 0.0310L^\star + 0.112A^{\star 2} + 0.171L^{\star 2} + 0.0622A^\star L^\star$$

5(*c*) Calculate maximum response R_{max}, where

$$R_{max} = 0.000196\log_{10}I_R + 0.00270$$

5(*d*) Calculate performance R and predicted reaction time RT, where

$$\Delta C_d = C_v - C_{t,d};\ \Delta C_d > 0$$

$$R = \frac{\Delta C_d^{0.97}}{\Delta C_d^{0.97} + K^{0.97}} R_{max}$$

$$\text{RT} = 1/R$$

5(*e*) Calculate the change in visual performance ΔT_{vis} relative to a reference condition, where

$$\Delta T_{vis} = \text{RT}_{ref} - \text{RT}$$

RT_{ref} is the arbitrary response time associated with the following stimulus conditions: $\omega > 13 \times 10^{-5}$ ster-

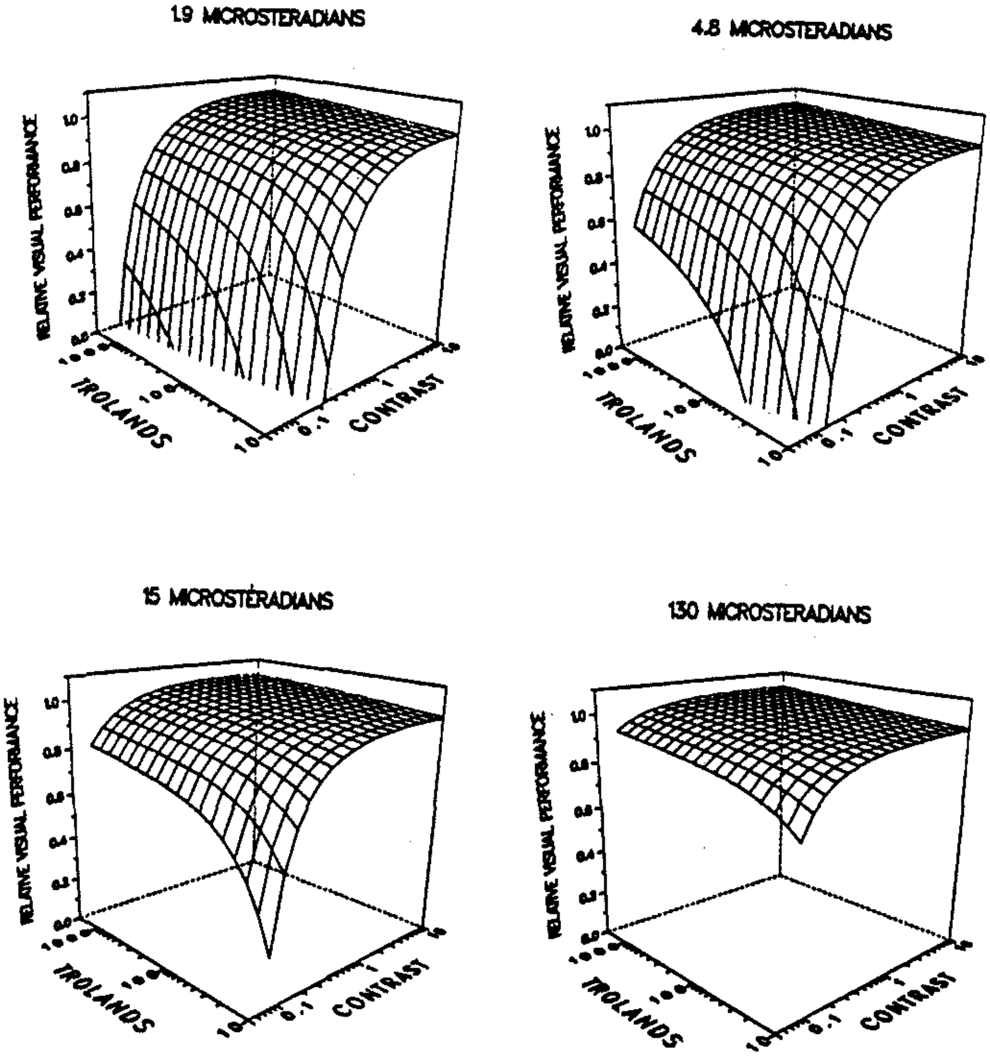

Figure 2 Three-dimensional views of relative visual performance (RVP_{RT}) plotted as a function of retinal illuminance (trolands) and contrast, based upon the reaction time experiment by Rea and Ouellette[24]. Each panel represents a different target size measured in microsteradians (solid angle, in microsteradians). The second panel, labeled 4.8 microsteradians, represents the average target size of the digits in the numerical verification task by Rea[10] and is comparable to Figure 1.

adians, $I_R = 801\ T$, and $C \rightarrow \infty$. Then $\text{RT}_{\text{ref}} = 305$ ms. For the reaction time experiment, ΔT_{vis} ranges from $-\infty$ to 0.

6 Relating RVP and ΔT_{vis}

The purpose of this section is to compare the visual performance predictions from the RVP and ΔT_{vis} models developed, respectively, by Rea[10] for the numerical verification task experiment and by Rea and Ouellette[24] for the reaction time experiment. Subsection 6.1 defines a common set of stimulus conditions for the two experiments. Subsection 6.2 presents a simple, linear transformation procedure relating units of RVP to units of ΔT_{vis}. Finally, a graphic comparison of the two model predictions is offered for the range of stimulus conditions common to both experiments.

6.1 Establishing a set of equal stimulus conditions

6.1(a) Subject age

In both experiments young adults of approximately the same age were used as subjects. Age-dependent reductions in retinal illuminance or retinal contrast should be equivalent for the two subject populations. Therefore, direct comparisons between the performance levels of the two groups should be feasible. Typically, it is only possible to compare the *relative* performance levels of the two subject populations. As discussed by Rea[26] absolute levels of performance can depend upon a variety of non-visual factors. Motivation, fatigue, motor skill and intelligence can all affect task performance, but as long as these non-visual factors do not vary systematically with the stimulus variables (or are constant within subject groups), the relative performance of the two groups can be compared.

6.1(b) Target contrast

Target contrast was controlled and measured in both experiments. Thus, target contrasts in the two experiments can be directly compared.

6.1(c) Target size

Target size was manipulated systematically in the reaction time experiment, but not in the numerical verification task experiment. To compare the results of the two experiments an argument must be developed to relate the square targets in the reaction time experiment to the printed numerals in the numerical verification task experiment. Although not a complete specification, research supports the hypothesis that the visual area of a target is a very robust method of characterising target size for both threshold and suprathreshold performance. Kristofferson[35] showed that detection thresholds for targets of different shape (square, discs, triangles, etc.), but of the same solid angle, were nearly identical. Of the various shapes, discs had the lowest associated detection threshold for a given solid angle, implying that target 'details' (corners and lines) were relatively less effective at producing a visual response. (See Dember[36], pp 117–122, for a summary of this work). Consistent results were obtained by Campbell and Robson[37] using square and sine wave gratings as targets for detection threshold. They found that the contrast sensitivity functions for these gratings were nearly identical, implying, again, that target 'details', or high spatial frequencies were relatively unimportant for detection. Legge *et al.*[38] examined suprathreshold performance at a reading task and found that high spatial frequency information had little effect on reading. This again demonstrates that spatial details are relatively unimportant for typical reading tasks involving speed and accuracy. Rubin and Siegel showed very similar results for letter recognition[39]. Finally, an unpublished study by Rea and Kambich showed that reaction times were effectively the same to flashed rectangular targets of equal solid angle, but of different aspect ratios. Thus, the visual area of a target, measured in terms of steradians (solid angle), appears to be a good first-order approximation of target size as it affects visual performance. This is not to say that target details, i.e. high spatial frequency information, are unimportant. Clearly, high spatial frequency information is important to vision, otherwise it would be impossible to discriminate between letters of different fonts but of equal visual area. Remarkably, however, these higher spatial frequencies can be expected to play a relatively minor role in visual performance as measured in these two experiments. Future work will develop a more detailed model of visual performance using more complete spatial information (e.g. Kambich[40]). Using visual area as a measure of target size is also attractive because it is convenient to measure. The CapCalc video photometer[32], described briefly below, can be used to measure the solid angle of a target. Essentially, each pixel in the video image is calibrated in terms of its visual area for any given distance. Thus, knowing the visual area of every pixel representing a target in the video image, it was possible to determine the solid angle subtended by each digit in the numerical verification task. At the viewing distance and angle used in the numerical verification task experiment, the average solid angle for each of the 10 digits (0 through 9) was 4.8×10^{-6} steradians at the centre of the numerical verification task list.

6.1(*d*) *Retinal illuminance*

Although background luminance was controlled in both experiments, pupil size was not controlled in the numerical verification task experiment. As background luminance increased in the numerical verification task experiment, pupil size would be expected to systematically decrease, and *vice versa*[25]. Several estimates of pupil size for different adaptation luminance have been published. Wyszecki and Stiles[36] use the equation published by De Groot and Gebhard[37] as the best representation of published data on adult sizes as a function of adaptation luminance (Figure 3). The authors' review shows, however, that at high adaptation luminances, computed pupil size goes to zero using the De Groot and Gebhard equation; this is an impossibility. Therefore the authors have modified the equation of De Groot and Gebhard for high adaptation luminances. Equation 1 accurately represents the De Groot–Gebhard equation over the range of adaptation luminances for which

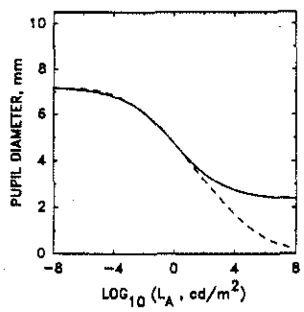

Figure 3 Predicted pupil diameter as a function of photopic adaptation luminance L_A. The dashed line represents De Groot and Gebhard's equation[42] $d = 10^{(0.8558 - 0.000401\{\log_{10}(B) + 8.1\}^3)}$; solid line $d = 4.77 - \{2.44 \tanh[0.3 [\log_{10}(L_A)]\}$ conforms to the dashed line over the range of luminance values where published data were available to De Groot and Gebhard, but does not allow the pupil size estimate to become zero at high adaptation luminances. B is the adaptation luminance in millilamberts ($B = 0.3142\ L_A$).

there are published data, but does not allow pupil area to go to zero.

$$D = 4.77 - [2.44 \tanh(0.3 \log_{10} L_A)] \quad (1)$$

where $D = 2r$ is the pupil diameter (mm) and L_A is the photopic adaptation luminance (cd m^{-2}). From equation 2, retinal illuminances I_R (troland) were calculated for the luminance values used in the numerical verification task experiment:

$$I_R = L_A \pi r^2 \quad (2)$$

6.1(*e*) *Contrast threshold*

Threshold is a useful, but statistical, concept to describe the breakpoint between seeing and not seeing a target. As discussed in some detail by Rea[9,10], different subjective criteria can be adopted by observers when evaluating contrast threshold. For alphanumeric symbols both 'readability' and 'detection' are meaningful criteria to subjects; both criteria can be used to evaluate threshold visibility[9]. Step 3(*b*) describes contrast threshold $C_{t,r}$ for the RVP formulation and is based upon subjective judgments of 'readability' threshold. In other words, determinations were made of the contrast values at which the numerical verification task digits could 'just be read.' Detection contrast threshold $C_{t,d}$ in the ΔT_{vis} formulation from step 5(*a*), determined directly from the reaction time data, was based upon the fifty percent probability of detecting a square target of a given size for each adaptation luminance. It is not possible to compare directly the predictions of contrast threshold in the two experiments because each was obtained from subjects using different threshold criteria. Qualitatively, however, the threshold data from these two experiments are consistent with the discussion by Rea[9]. The contrast values required to reach detection threshold in the reaction time experiment were always lower than those required to reach readability threshold in the numerical verification task experiment for targets of equal solid angle that were presented at the same retinal illuminance.

6.1(*f*) *The set of equal stimulus conditions*

Based upon the rationale developed in sections 6.1(*a*)–(*e*), it is now possible to generate predictions of RVP and ΔT_{vis} for a common set of stimulus conditions. The following set of common stimulus conditions provides values of ΔT_{vis} and RVP of −23 ms and 0.998, respectively. These two special values are designated $\Delta T'_{vis}$ and RVP′ and are used, below, in developing a linear transform between units of ΔT_{vis} and units of RVP. Retinal illuminance $I_R = 801$ trolands. This is the highest value of retinal illuminance in the reaction time experiment and therefore the highest common to both experiments. Target size $\omega = 4.8 \times 10^{-6}$ steradians. This is the average apparent digit size in the numerical verification task experiment and therefore the only one common to both experiments. Contrast $C_v = 1.0$. This is the highest possible contrast for targets darker than their background. Although not used in either experiment, this value is a convenient high-contrast reference value.

6.2 *Relating units of* RVP *to units of* ΔT_{vis}

If, in fact, two independent metrics are scaling the same physical attribute of an object (e.g. temperature), then it should be possible to linearly transform the units of one metric into units of the other (e.g. the Fahrenheit scale to the Celsius scale). Similarly, if the reaction time experiment and the numerical verification task experiment are both scaling visual performance, it should be possible (indeed, required) that the two scales be related to one another by a linear scale transformation.

Equation 3 can be used to linearly transform ΔT_{vis} into units of RVP. ΔT_{vis} values transformed in this way are designated $\mathrm{RVP_{RT}}$.

$$\mathrm{RVP_{RT}} = \mathrm{RVP}' \left(\frac{\Delta T_{vis} - \Delta T_{vis,r}}{\Delta T'_{vis} - \Delta T_{vis,r}} \right) \quad (3)$$

ΔT_{vis} is defined in steps 5(*a*)–(*e*) above, and $\Delta T_{vis,r}$ is the estimated value of ΔT_{vis} at readability contrast threshold. Thus $\mathrm{RVP_{RT}} = 0$ when $\Delta T_{vis} = \Delta T_{vis,r}$ and $\mathrm{RVP_{RT}} = 0.998$ when $\Delta T_{vis} = \Delta T'_{vis}$.

Since readability threshold was not a meaningful criterion in the reaction time experiment, $\Delta T_{vis,r}$ was treated as a free parameter and estimated, by regression analysis, as -800 ± 29 ms in a manner that simultaneously minimised the sums of squared deviations from the three dashed lines in Figure 4, chosen to represent retinal illuminances common to both experiments. This assumes that a value of ΔT_{vis} equal to -800 ms is comparable to a value of RVP equal to zero, readability threshold.

6.3 *Summary*

The data from two experiments of visual performance, one using reaction times and the other timed response in a simulated realistic task, were independently modelled (Rea and Ouellette[24]; Rea[10]). A common set of stimulus conditions was determined and a linear transformation method was developed to relate the units of one experiment to the other.

Considering (*a*) the two very different and independent experiments, (*b*) the estimates leading to a common set of stimulus conditions, and (*c*) the single constant used to relate one scale to the other, the predictions from the two experiments are graphically very similar (Figure 4). It should also be noted that McNelis' visual performance data, based on measured accuracy[34], are also well described by these two sets of functions[26]. The agreement between these three independent visual performance data sets validates, to a first approximation at least, the $\mathrm{RVP_{RT}}$ (or RVP) formulation of visual performance for young adult subjects.

7 Age

To generalise the $\mathrm{RVP_{RT}}$ predictions for older subjects it was necessary to estimate the age-dependent reductions in retinal illuminance and retinal contrast.

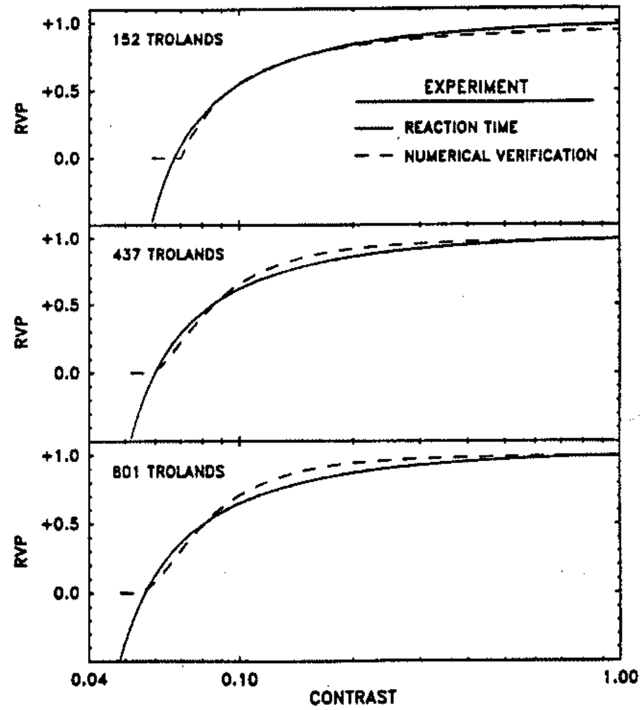

Figure 4 Comparison of the predictions of visual performance as a function of contrast using the RVP (numerical verification), dashed lines, and $\mathrm{RVP_{RT}}$ (reaction time), solid lines. RVP predictions are based upon the numerical verification task experiment[10,27]; $\mathrm{RVP_{RT}}$ predictions are based upon the reaction time experiment[24]. Three adaptation luminances, representing the range of retinal illuminance values common to both experiments, are presented in trolands. Zero on the RVP scale represents *readability* threshold.

7.1 *Retinal illuminance*

Smith and Rea[20] used the numerical verification task with two subject populations of different ages: twenty to twenty-five and sixty to sixty-five years. Task performance for the older subjects was lower than that for the younger subjects. Wright and Rea[28] showed, however, that *relative* values of task performance obtained from the older subjects in the Smith and Rea study could be transformed to be very similar or identical to those of the younger subjects simply by taking into account published estimates of the losses in retinal illuminance and, to a smaller extent, retinal contrast with age.

Weale[43,44] developed an estimate of age-dependent reductions in retinal illuminance (Figure 5). This reduction is based upon Weale's estimates of the thickening of the crystalline lens and reductions in pupil area with age. Combined, these two effects produce retinal illuminance reductions P due both to reduced transmission and to increased scatter, that can be approximated by the following simple linear equation[45]:

$$P = 1 - 0.017(a - 20) \quad (4)$$

where a is the age, in years, between twenty and sixty-five.

Equation 4 modifies the retinal illuminance values I_R in

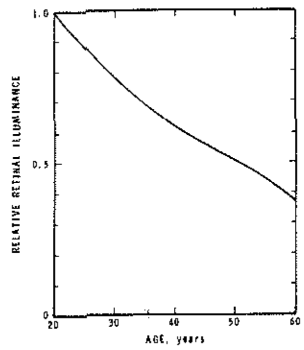

Figure 5 Weale's[43] estimate of the relative decline in retinal illuminance with age (from Wright and Rea[28])

equation 2 and in 5(a) above, thus:

$$I_{R'} = PL_A \pi r^2. \tag{5}$$

7.2 Retinal contrast

Equation 6 provides an estimate of the age-dependent losses ε in retinal contrast between the ages of twenty and sixty-five years:

$$\varepsilon = 1 + [(0.113/45)(a - 20)] \tag{6}$$

This equation is based upon the work of Wright and Rea[28] described above and in Rea[27]. Explicit in the equation is the largely unsubstantiated assumption that the age-dependent losses in retinal contrast that arise from changes in the crystalline lens can be described with a linear equation similar to that which describes the age-dependent losses in retinal illuminance. Consistent with the analysis by Wright and Rea[28], it has also been assumed that the nonlinear, suprathreshold response produced by neural activity remains the same up to age sixty-five years. Imperfections anterior to the retina, mostly in the crystalline lens[44], serve to scatter light, and thus they reduce retinal contrast, effectively elevating contrast threshold. Equation 6 modifies the detection contrast threshold values in 5(a) above, thus:

$$C'_{t,d} = \varepsilon 10^{(-1.36-0.179A-0.813L+0.226A^2-0.0772L^2+0.169AL)}. \tag{7}$$

Equation 6, and therefore equation 7, should be considered highly tentative. Not only are there few reliable estimates of age-dependent light scatter in the crystalline lens, but also the impact of that scatter on visual performance will be highly dependent upon the spatial characteristics of the target. The visibility of large targets will be less affected by entopic scatter than it will for small targets[46].

8 Measurement procedure

To utilise the visual performance model described above for field applications it is necessary to measure the visual stimuli to be used as input parameters in the $\mathrm{RVP_{RT}}$ equations. Thus, the salient features of the spatial luminance distribution in a visual scene must be captured and quantified, ideally using a practical method. The physical characteristics of the visual environment that drive the $\mathrm{RVP_{RT}}$ algorithm are target area (steradians), target luminance (cd m^{-2}), and background luminance (cd m^{-2}). The latter two give target contrast and adaptation luminance (cd m^{-2}). Observer age in years is a mediating variable that modifies the measured target contrast and adaptation luminance values.

The CapCalc video photometric imaging system (Figure 6) is a recent innovation for obtaining the $\mathrm{RVP_{RT}}$ input parameters[32]. Basically, the CapCalc system is comprised of a photoptic sensitive charge-coupled device (CCD) video camera, imaging board and personal computer. It produces a 512 by 480 array of picture elements (pixels) and has an 8-bit brightness resolution (256 levels of luminance). The system is calibrated both in terms of photopic luminance (cd m^{-2}) and solid visual angle (steradians). Images captured with the CapCalc system are stored in terms of the luminance and the subtended angle of every pixel in the captured image.

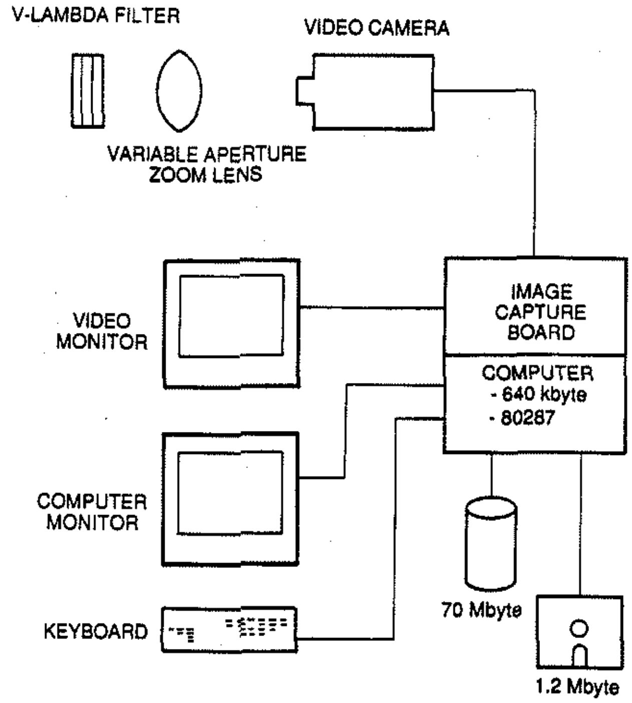

Figure 6 The CapCalc photometric imaging system (from Rea and Jeffrey[32])

Any portion of the 245 760 pixel array captured by the CCD video camera and imaging board can be isolated and then manipulated by the user to identify the input parameters for the $\mathrm{RVP_{RT}}$ calculation. The software permits the user to place a rectangle around the image of the target to be evaluated (Figure 7). A target could be, for example, a letter on a page, a muffler lying in a roadway or, in the case of Figure 7, the directional arrow on an exit sign. Often the target is comprised of several luminance values. The user can 'average' these luminance values using one of the software options and store this value in the computer. The background luminance is similarly obtained and stored.

Adaptation luminance is defined and stored in CapCalc as the unweighted, average luminance of the entire captured image. Based upon the user-defined observer age, adaptation luminance is modified according to equation 5. Since the target luminance averaging procedure defines those pixels that the user has called 'target' and since every pixel has a known solid angle, the areas of the target pixels are summed and then the total visual area of the target is automatically stored in the computer.

Different values for the input parameters (target contrast, target area, and adaptation luminance) can be substituted by the user into the system's memory. $\mathrm{RVP_{RT}}$ can then be

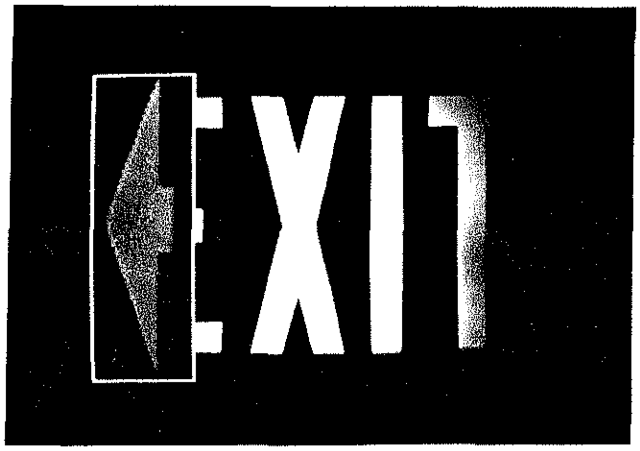

Figure 7 Video image of an exit sign produced by the CapCalc photometric imaging system. The direction arrow has been isolated and enlarged for better analysis of its spatial-luminance characteristics.

recomputed using the new values. For example, the user may want to know what the effects would be on RVP$_{\mathrm{RT}}$ if the adaptation luminance (illumination level) were reduced by fifty percent. By substituting the new value into the system memory the consequences of reduced illumination levels on RVP$_{\mathrm{RT}}$ can be determined. Thus, a variety of 'what if' questions about RVP$_{\mathrm{RT}}$ can be answered.

Like all optical systems, the present CapCalc system does not have unlimited spatial resolution. Using calibrated close-up lenses, however, targets as small as 0.16 by 0.22 mm can be measured without losses in image contrast.

The sensitivity limit of the present CapCalc system is approximately 0.4 cd m^{-2}. This is not a severe limitation for working in the phototopic range, approximately above 3.0 cd m^{-2}[36]. Naturally, as with all photometric instruments having a photopic spectral response, it cannot be used correctly at mesopic or scotopic levels.

9 Discussion

Recommended levels of illumination published by the Chartered Institution of Building Services Engineers (CIBSE) or the Illuminating Engineering Society of North America (IES), for example for offices, schools, and hospitals[47], are predicated on the notion that speed and accuracy of processing visual information can be improved by increasing the level of visual adaptation, that is, by more illumination on a task. It is also formally recognised that tasks having visual targets of lower contrast or smaller size demand higher levels of illumination to maintain the same level of visual performance. It is further acknowledged by the IES that older people need more light than younger people to see equally well.

It has been assumed for some time that if a valid psychophysical model were used in conjunction with a practical field instrument for measuring the visual stimulus, recommended illumination levels could be replaced by more precise recommended levels of visual performance. Certainly this was the belief behind the Commission Internationale de l'Éclairage (CIE) system[7] developed by Blackwell. Although there is considerable research to support the qualitative application of these ideas, it has proven difficult to provide quantitative assessments of realistic targets in terms of visual performance, even using the CIE system. Therefore, despite a long history of research into visual performance and its measurement, recommended illumination levels remain a central part of lighting design and application.

A preliminary model of suprathreshold visual performance, known as *relative visual performance,* was published by Rea[10]. Consistent with earlier studies performed by a number of researchers, RVP was found to vary systematically with background luminance and target contrast. As discussed in the present report, earlier research by McNelis[34] and subsequent research by Rea and Ouellette[24] corroborated and expanded the scope of the preliminary RVP model. This validation provides support for using the RVP$_{\mathrm{RT}}$ formulation, developed in this report, to assess visual performance. Technological advances in CCD cameras and image processing make it possible to apply RVP$_{\mathrm{RT}}$ in the field. Together then, these developments have led to a new, practical method for determining visual performance from spatial luminance data obtained from a calibrated video image. For example, the RVP$_{\mathrm{RT}}$ model and the CapCalc video photometric imaging system can be used to answer a wide range of practical questions[48] such as the following:

* How quickly and accurately can postal workers process mail under a particular lighting system?
* Will a sixty-five-year-old driver travelling at 100 km h^{-1} have time to avoid an obstacle in the roadway?
* What would be the impact on the visual performance of school children if the illumination levels in classrooms were reduced by fifty percent or increased by thirty percent?

These and other practical questions can be answered with a quantitative model of visual performance and a measurement system that can capture and analyse that information in the field. They cannot be adequately resolved by referring to a table of recommended levels of illumination. It is perhaps premature to expect sanctioning bodies such as the Illuminating Engineering Society of North America or the Chartered Institution of Building Services Engineers to abandon recommended levels of illumination for recommended levels of visual performance, but the developments discussed in this report provide another step in that direction.

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Appendix

To calculate RVP$_{\mathrm{RT}}$ follow steps A1 through A7 below. Note that steps 3 and 5 in Appendix C of Rea and Ouellette[24] had typographical errors that have been corrected here. This formulation is exactly that which is presently used in the CapCalc imaging photometric system.

(A1) Calculate the retinal illuminance $I_{R'}$(T). In the range 0.5–801 T:

$$I_{R'} = PL_A\pi r^2$$

where L_A is the phototopic adaptation luminance ($cd\,m^{-2}$).

Pupil radius r(mm) is given by

$$r = 2.3859 - [1.2204 \tanh(0.3 \log_{10} L_A)]$$

$$P = 1 - 0.017(a - 20)$$

where a is the age of observer from twenty to sixty-five, in years.

(A2) Calculate detection threshold contrast $C'_{t,d}$.

$$C'_{t,d} = \varepsilon 10^{(-1.36415 - 0.178589A - 0.812850L + 0.225998A^2 - 0.077169L^2 + 0.169252AL)}.$$

$$A = \log_{10} \tanh(20\,000\omega)$$

$$L = \log_{10}\log_{10}(10 I_{R'}/\pi)$$

ω is the area of the target in steradians from 1.8×10^{-6} to 2.8×10^{-3}

$$\varepsilon = 1 + [(0.113/45)(a - 20)].$$

(A3) Calculate the half-saturation constant K.

$$K = 10^{(-1.763006 - 0.175369A^* - 0.030967L^* + 0.112027A^{*2} + 0.170583L^{*2} + 0.062194A^*L^*)}$$

$$A^* = \log_{10}\tanh(5000\omega)$$

$$L^* = \log_{10}\tanh(0.04\, I_{R'}/\pi).$$

(A4) Calculate maximum response R_{max}.

$$R_{max} = 0.000196 \log_{10} I_{R'} + 0.00270.$$

(A5) Calculate performance R and predicted reaction time RT.

$$R = \frac{\Delta C_d^{0.97} R_{max}}{\Delta C_d^{0.97} + K^{0.97}}$$

$$\Delta C_d = C_v - C'_{t,d};\ \Delta C_d > 0$$

$$C_v = \frac{|L_B - L_T|}{L_B}, \text{ where}$$

L_B is the luminance of background ($cd\,m^{-2}$)

L_T is the luminance of target ($cd\,m^{-2}$)

$$RT = 1/R.$$

(A6) Calculate the change in visual performance ΔT_{vis} relative to the reference condition.

$$\Delta T_{vis} = RT_{ref} - RT$$

$$RT_{ref} = 305.38324 \text{ ms}.$$

(A7) Calculate relative visual performance based upon the reaction time experiment RVP_{RT}.

$$RVP_{RT} = RVP' \left(\frac{\Delta T_{vis} - \Delta T_{vis,r}}{\Delta T'_{vis} - \Delta T_{vis,r}}\right)$$

$$\Delta T'_{vis} = -22.992718 \text{ ms}$$

$$RVP' = 0.998$$

$$\Delta T_{vis,r} = -800 \text{ ms}.$$

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