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Toward a Model of Visual Performance: Foundations and Data

by M.S. Rea

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ABSTRACT

A model of visual performance is proposed that predicts the speed and accuracy with which young adults can read printed letters and numbers of different contrast under illuminance levels commonly used for interior lighting. It is consistent with a variety of psychophysical and electrophysiological suprathreshold contrast response data. The model goes beyond these data, however, by defining the changes in the contrast response functions at different adaptation luminances. Although the model should be useful to illuminating engineers interested in predicting visual performance, it should be expanded to cover a larger range of visual stimuli and subjects of different ages. It should also be more thoroughly verified by other techniques. A companion paper describes some of the important issues in extending and validating the model.

RÉSUMÉ

L'auteur propose un modèle de performance visuelle qui indique la vitesse et la précision avec lesquelles de jeunes adultes peuvent lire des lettres ou nombres imprimés de contraste différent à des niveaux d'éclairement utilisés couramment pour l'éclairage intérieur. Le modèle est en accord avec toute une gamme de données psychophysiques de réaction seuil et dépasse ces données en définissant les fonctions de réponse à différentes luminances. Bien qu'il soit utile aux ingénieurs éclairagistes pour prédire la performance visuelle, il englobe un plus vaste champ de stimuli visuels et de sujets d'âge différent. Il devrait être vérifié plus approfondiment par d'autres techniques. Le complément de ce document décrit les problèmes importants d'extension et de validation du modèle.

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Toward a Model of Visual Performance: Foundations and Data

Mark S. Rea

I. Introduction

Visual performance has been a central topic of research and discussion in illuminating engineering for many years (see Boyce, 1981; and Rea, 1982a, 1984 for references). This interest is driven largely by practitioners who want to know how lighting affects the performance of workers in industrial and commercial environments. A practitioner might want to know, for example, whether increased illumination levels can lead to faster or more accurate performance in an assembly task. Data and theory that could quantitatively relate lighting and productivity for economic evaluations are, perhaps, the most desirable research goals for lighting practitioners (Clear and Berman, 1981).

Achieving these goals would not, however, be a trivial accomplishment. Many factors associated with the lighting, the task, and the person influence the quantitative relationships between the environment and a person's productivity. Perhaps it is impossible to completely delineate the multiple interactions between lighting, task, and human variables. It should be possible, however, to more narrowly constrict consideration of the number of alternative relationships between these various factors and then to establish plausible and useful calculation procedures of suprathreshold visual performance for lighting practitioners.

The purpose of this paper is to present such a calculation procedure. The plausibility, and therefore utility, of this proposed model is based upon two propositions. First, *visual* performance must be extracted from *task* performance. The latter is generally an unknown combination of both visual and nonvisual factors that contribute to the behavioral response. The confounding of visual and nonvisual contributions limits the utility of a calculation procedure based on such studies because one does not know how much of the predicted behavior is based upon visual responses under the control of the lighting practitioner and how much is based upon nonvisual (psychological, intellectual, motor, motivational, and emotional) responses evoked by the multitude of other factors. Second, any model of visual performance must be consistent with the literature describing basic visual response. If visual performance can be extracted from task performance, then it should be possible to verify the extraction as

an adequate representation of visual processing from data available in the vision literature. Although complete agreement may be difficult, well-established principles in visual sciences limit the number of possible descriptions of suprathreshold visual performance.

This paper describes in some detail, then, the foundations of the proposed model in visual sciences as well as the attempts to extract visual performance from task performance at a simulated realistic task. It is not argued that this visual performance model is complete. A variety of other parameters (*eg.*, size, luminous uniformity, age of the observer) that are important to the complete specification of visual performance, as well as factors ultimately necessary for making economic evaluations of lighting for task performance (manual dexterity, motivation, aesthetics, interactions with other sense modalities), are not considered. Further, there are some (explicit) assumptions in the model that require further testing. Therefore, this paper and the model serve as a milestone rather than the goal for lighting practitioners. The paper hopefully establishes an appropriate algorithm for a model of suprathreshold visual performance, but it does not provide a complete economic analysis relating lighting and productivity. A subsequent paper (Rea, in press) describes some of the requirements for future studies attempting to describe visual performance more accurately.

II. Foundations

It is clear from a great deal of literature that suprathreshold sensory responses are characterized by compression. Small changes in stimulation about the adaptation level produce corresponding changes in sensation. Although the absolute magnitude of the sensation increases with increasing stimulus intensity, higher stimulation becomes progressively less effective in eliciting incrementally higher sensation. Finally, a level of stimulation will be reached where further increases in stimulus magnitude produce no further increase in sensation magnitude.

Sensory compression is exhibited in a wide variety of invertebrate and vertebrate species, including primates, in various sense modalities, and using a variety of psychophysical and electrophysiological measurement techniques (see Lipetz, 1969; and more recently Hood and Finkelstein, 1979, for references). This general description of sensory compression also charac-

terizes many other biological "communication" phenomena, including neural reception of internal metabolic changes (Koshland *et al.* 1982). In short, compression is widely accepted as a basic, general description of suprathreshold sensation including, for this paper in particular, suprathreshold visual sensation, or visual response, to luminous modulations.

Suprathreshold sensory compression has the following form, first employed by Naka and Rushton (1966a,b) in describing retinal responses in fish:

$$R/R_{\max} = I^n / (I^n + k^n) \quad (1)$$

where: R = response

$R_{\max}$ = maximum response

I = stimulus intensity

n = exponent

k = stimulus intensity producing half of maximum response

As already implied, this expression is quite robust in describing visual responses to luminous modulations. The exact values of n , k , and $R_{\max}$ in Equation 1 will vary with the experiment and depend upon such factors as the chosen response (*e.g.*, evoked potential or magnitude estimation), the response criterion (*e.g.*, a particular peak or trough from the pattern of evoked potentials), the site of recording (*e.g.*, the retina or the cortex), the chosen stimulus conditions (*e.g.*, flashes or gratings), any transformations of stimulus magnitudes (*e.g.*, logarithmic), and the species under investigation (*e.g.*, monkey, cat, or man).

The expression is believed to characterize a physiologically important mechanism in all receptors known as "self-shunting" (Lipetz, 1969). A single photoreceptor (rod or cone) in the retina, for example, is comprised of many photosensitive units connected electrically in parallel. Each small photosensitive unit has what is called an "ionic pump," that produces an electrical potential between the photoreceptor and its environment. Thus, the photoreceptor has a steady-state, resting potential maintained by these ionic pumps. When a photon is captured by one of the photosensitive units in the photoreceptor, the unit depolarizes briefly until the ionic pump can restore the resting potential. This depolarization is like an electrical shunt between the photoreceptor and its environment that produces a voltage drop in the whole photoreceptor. (This, in turn, can produce a chain reaction in subsequent, higher-order neurons that ultimately signal "light" to the brain.) Photon catches by other photosensitive units in the photoreceptor produce similar depolarizations, but each subsequent unit depolarization, or shunting, has relatively less influence on the total response (voltage) of the photoreceptor until, finally, still more photon catches produce no greater response from the photoreceptor. As previously stated, Equation 1 conveniently describes such response compression in photoreceptors.

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Compression is exhibited in neurologically higher centers as well as in retinal photoreceptors. One example of visual response compression at the visual cortex, adapted from Albrecht and Hamilton (1982), is shown in **Figure 1**. Presented are the variations in electrical potentials produced by single neurons in monkey cortex in response to the contrast changes of a luminous grating. The parameter values for Equation 1 describing the visual responses are given in the figure caption. Adaptation luminance was 27 cd m⁻² or 2.3 log trolands with the 3-mm diameter artificial pupil placed before the monkey's eye.

This particular set of data was used to illustrate visual response compression for a variety of reasons. First, the species investigated, *Macaca fascicularis*, has a visual system almost identical to man (Boynton and Whitten, 1970; Valeton and van Norren, 1983), and man is obviously the species of interest for lighting practice. Second, cortical events should be more indicative of the psychophysical responses important to lighting practice than neurologically earlier activity. (For example, retinal responses will not reflect processing from any of the higher visual areas.) Third, the recorded visual responses were to variations in luminous contrast, also employed as stimuli in the present experiment. Fourth, the technique for obtaining suprathreshold visual responses was completely different from that employed in the present experiment, so similarities between the results of the two independent experiments would be mutually reinforcing in the development of a suprathreshold visual response model. Finally, no other electrophysiological data with all of the above qualifications were found.

From the previous discussion it should not be inferred that only electrophysiological data can be described by Equation 1. Psychophysical data have also been characterized in this way. Hood and his coworkers (Hood *et al.*, 1978; Hood and Finkelstein, 1979; Hood *et al.*, 1979) have conducted studies specifically addressing the suitability of Equation 1 for describing psychophysical responses. They have found that this expression can be used to describe subjective estimates of flash brightnesses, by magnitude estimations, as well as detection thresholds. Boynton and Whitten (1970) have also used this expression in describing detection threshold data, and like Hood and his coworkers, have related psychophysical responses to those recorded electrophysiologically. Rea (1983) has also used this formulation to describe the data from a psychophysical study using measures of speed and accuracy at the numerical verification task employed in the present experiment.

Even in studies where this particular formulation has not been tried, Equation 1 can be used to describe compressive psychophysical responses. For example, Blackwell and Blackwell (1980) have presented data relating the Visibility Level (in this case the contrast) of Landolt rings to the probability of correctly identi-

fyng the ring orientation. The dashed line in **Figure 2** is based on Blackwell and Blackwell's "log ogive"; the solid line is based upon Equation 1. Clearly both formulations describe the data well.

Theoretical justification for a particular formulation must rely on criteria other than an adequate curve fit (Valeton, 1983). Both the log ogive and Equation 1 can be fitted to many data exhibiting compression. More work (e.g., Valeton and van Norren, 1983; Valeton, 1983) will have to be conducted to theoretically limit the range of possible "curve fitting strategies." Nevertheless, the robustness of Equation 1 has led to its current preference in the visual sciences for modeling compressive suprathreshold visual responses, and, therefore, forms the basis of the visual performance model presented here.

III. The Numerical Verification Task

In a previous report (Rea, 1981) it was shown that performance, defined in terms of time and errors, at a reading-writing task was strongly affected by the different luminous contrasts between the white paper, the luminance of which was held constant, and the (darker) inks. Further, it was shown that a single function could describe the relationship between performance and contrast, no matter how that contrast was produced. The purpose of the present experiment was to collect more data at the same task using a wider range of background luminances, and, with these data, formulate a visual performance model based upon Equation 1.

A. Methods and procedures

Except for a few minor differences, the stimulus materials, the experimental testing room, and the procedures were like those described in the previous numerical verification experiment (Rea, 1981). Subjects were seated at a desk and asked to compare, from top to bottom, two printed number lists, a reference sheet on the left and a response sheet on the right, for discrepancies. The time to complete the comparisons and the number of errors, both omission and commission, were recorded after every trial.

Data were collected in a black testing room with illumination provided to the work desk from a single fluorescent luminaire having a light emitting aperture of 95.5 x 95.5 cm. A sanded plexiglass diffuser was in the luminaire throughout the experiment. Illumination levels at the center of the task were (approximately) 50, 93, 171 and 700 lx, depending upon the experimental conditions. Illumination levels were adjusted slightly during the experiment to hold task background luminances (*i.e.*, the luminances of the reference sheets) constant at 12, 22, 41, and 169 cd m⁻² from the position of the subjects' eyes.

Lighting geometry, or direction of illumination, affects task contrast (Rea, 1981). The direction of illumina-

tion was changed in this experiment by pivoting the desk (and the subject) about a point at the center of the horizontal task. Eight desk positions were employed in the experiment (**Table 1**).

Subjects were comfortably positioned at a chin rest while seated at the horizontal desk. The viewing angle, from vertical, and distance to the center of the task were 42 degrees and 50 cm, respectively. From the subject's viewing position, the middle digits of the reference and response lists were separated by 7.1 degrees of visual angle. Similarly, the middle digits were 13 and 19 minutes of visual angle wide and high, respectively.

Every reference and response sheet was a column of twenty, five-digit numbers; each five-digit number in the column was separated by a horizontal line. A small calibration square was also printed at the top of each column for photometric measurements. Two sets of 32 reference sheets, printed in black gloss or gray matte ink, were used in this experiment. The photometric qualities of these two sets under gonio and (simulated) hemisphere conditions as well as under similar experimental conditions are described in the earlier report (Rea, 1981). Contrast measurements of the ink calibration squares on one example from each set of reference sheets at the eight experimental desk positions are shown in **Table 1**. Contrast (C_v) is calculated by the formula:

$$C_v = \frac{L_B - L_T}{L_B} \quad (2)$$

where: L_T is the luminance of the calibration square and L_B is the luminance of the paper adjacent to the calibration square.

Four groups of 32 high-contrast response lists were employed in this experiment. Three groups were like those used in the previous experiment. The mean frequency of errors in the fourth (new) set was also 3.0. The standard deviation of the list errors in the new set was 1.41; the standard deviations for the other sets were 1.19, 1.32 and 1.48. Contrasts of one example of the response sheets at the eight desk positions are also given in **Table 1**.

Four male and four female subjects between the ages of 19 and 24 ($M = 22$) years participated in the experiment. These subjects were different from those employed in the earlier experiment, but all had excellent, uncorrected vision as determined by a battery of visual screening tests from a Keystone Ophthalmic Telebinocular. The data from one female subject was not included in the analysis because she dramatically shifted her response strategy partway through the experiment.

The experimental protocol was almost identical to that employed in the earlier experiment. Subjects were asked to compare the reference and response number

Figure 1—A contrast response function recorded electrophysiologically from the visual cortex (adapted from Albrecht and Hamilton, 1982, Figure 5). Equation 10 (based on Equation 1) describes both the solid and the dashed lines. The dashed line was generated using a threshold term ($C_t = 0.023$ in Equation 10); the solid line did not include a threshold term ($C_t = 0.0$). The best fitting, by a least squares criterion, parameter estimates for the data using a threshold term (dashed line) are: $n = 1.6$, $k/L_B = 0.050$, and $VP_{max} = 1.00$. Comparable values without a threshold term (solid line) are: $n = 2.7$, $k/L_B = 0.073$, and $VP_{max} = 0.97$.

Figure 2—Accuracy in identification of Landolt ring orientation (from Blackwell and Blackwell, 1980, Figure 24). Dashed line is described by the "log ogive" (Equation 3 in Blackwell and Blackwell, 1980) where the free parameters α , γ , and μ (the logarithm of R_{max}) are 0.37, 0.110, and 0.0, respectively. The solid line is based on Equation 1 (or Equation 10, where $C_t = 0$) where $n = 9.61$, $k/L_B = 0.205$, R_{max} (or VP_{max}) = 1.00.

Figure 3—Performance plotted as a function of contrast (scaled logarithmically) at the four background luminances used in the numerical verification task. The reciprocal of the time to compare the reference and response lists ($1/S$) is used as the performance measure. The solid lines are best fitting curves using Equation 10, which is based on Equation 1, and the four contrast threshold values in Table 3.

Figure 4—The average time to compare the reference and response lists (S), in seconds (s), plotted as a function of the number of "ticks" (both hits and false positives) that subjects marked on the response lists.

Figure 5—The four estimates of the parameter n , from Table 3, plotted as a function of Θ_1 . $\Theta_1 = \log_{10}(\log_{10}(L_B))$, where L_B is the background luminance defined in Equation 2. The solid line, defined by the equation inset into the figure, provides interpolated values of the parameter n between 12 and 169 cd m^{-2} .

Figure 6—The four estimates of the parameter k , from Table 3, plotted as a function of Θ_2 . $\Theta_2 = \log_{10}(L_B)$, where L_B is the background luminance defined in Equation 2. The solid line, defined by the equation inset into the figure, provides interpolated values of the parameter k between 12 and 169 cd m^{-2} .

Figure 7—The four estimates of the parameter $VP_{\max}$, from Table 3, plotted as a function of Θ_2 . $\Theta_2 = \log_{10}(L_B)$, where L_B is the background luminance defined in Equation 2. The solid line, defined by the equation inset into the figure, provides interpolated values of the parameter $VP_{\max}$ between 12 and 169 cd m^{-2} .

Figure 8—Three-dimensional representation of the visual performance model. Relative visual performance (RVP), scaled linearly, is plotted as a function of contrast (C_v defined in Equations 2 and C2) and luminance (L_B defined in Equation 2), both scaled logarithmically. The levels of RVP for selected values of C_v between 0.08 and 1.0 and values of L_B between 12 and 169 cd m^{-2} are represented by the lines constituting the surface. The levels of RVP for values of C_v between 0.0 and 1.0 and values of L_B between 12 and 169 cd m^{-2} may be calculated from the equations in Appendix C.

Figure 9—Constant contrast lines from the visual performance model. The curves are labeled in units of contrast (C_v , in Equation 2).

Figure 10—Constant luminance lines from the visual performance model. The curves are labeled in units of background luminance (L_b , in Equation 2).

Figure 11—Constant performance lines from the visual performance model. The curves are labeled in units of RVP (Equation C10, in Appendix C). These lines are comparable to threshold functions at various constant criteria.

Figure B1—Electrophysiologically recorded cone response functions to luminous increments and decrements at two different adaptation luminances (Adapted from Valeton and van Norren, 1983, Figure 6). A single function, defined by Equation 1 (where $n = 0.74$, $k = 3.2$ log trolands, and $R_{max} = 1.0$), can be shifted in semilogarithmic space (linear response by log luminance) to describe the cone response data at these and other background luminances.

lists as "quickly and accurately" as possible during practice and experimental trials. Discrepancies found by the subjects were marked on the response list with a pen held in the right hand. Total elapsed time (S), misses, and false positives were obtained for each trial. Subjects were not given feedback about their performance during the experiment.

The experimental design was devised to hold constant or minimize, by counterbalancing or randomization, psychological effects like motivation and fatigue. This experimental design can be briefly described as follows. Every subject made the list comparisons under all four illumination levels. To ensure that presentation order was not confounded with illumination level, the illumination levels were counterbalanced across subjects. Eight desk orientations were presented in different orders to the subjects under each of the four illumination levels. Some of the desk orientation presentation orders were counterbalanced across illumination level within subjects. The remainder were counterbalanced across subjects. Four randomly distributed replications of the black gloss and of the gray matte reference lists were presented to the subjects at each of the desk orientations (8 trials/orientation). In all, each subject performed 256 experimental trials during a one-day session lasting approximately six hours. One subject was run per day. It should be noted that the exclusion of the data from one subject prevented complete counterbalancing across the subjects.

B. Results

The data (Appendix A) are quite similar to those published earlier for the numerical verification task (Rea, 1981, 1983; Slater, Perry and Crisp, 1983) and for other tasks (e.g., Poulton, 1969); the relationship between each performance measure and contrast, at a given adaptation level, can be described as suprathreshold sensory compression (Section II). At each background luminance, performance improves rapidly above contrast threshold. As contrast further increases, performance improves but at a decreasing rate until, finally, still higher contrasts produce little, if any, change in the level of performance. The relationships between the reciprocal of the total time to compare the two number lists ($1/S$) at each reference sheet background luminance (L_n) and contrast (C_v) (Table A1) are shown in Figure 3.* Best fitting curves, based upon Equation 1, were drawn through the four data sets to help illustrate the different trends and relationships.

The four sets of data in Figure 3 show the same general form of response compression. Further, each set of data is similar in form to those from cortical neurons in Figure 1, at least over the range of contrasts employed in the present experiment (i.e., above $C_v = 0.1$). While each set of data presented in Figure 3 shows the same general form of compression, it is also worth noting two important differences between the curves

at the different luminance levels. First, for matched contrasts, performance tends to be higher at higher luminances. Second, as contrast increases, performance tends to saturate more quickly at the higher luminances. Essentially, these two trends indicate that performance improves with higher task luminances. Not only does the absolute level of performance increase with higher luminances, but performance is also higher over a larger range of contrasts.

C. Refinements of the 1/S data

Evidence supports the argument that performance in this experiment was largely determined by visual parameters, and the effects of nonvisual factors were minimized. The experimental design, the photometric control of the stimuli, the similarity between time and error response functions, and the similarity between these data and those obtained in other vision experiments (e.g., Albrecht and Hamilton, 1982), all indicate that visual performance, relatively uncontaminated by nonvisual factors, was measured. This evidence might suffice in an argument favoring $1/S$ as the measure of visual performance at the numerical verification task. However, at least two refinements to the $1/S$ data are desirable to improve these data to characterize visual performance.

1. *Action time*—Weston (1935, 1945) argued that the time taken for subjects to mark targets, the so called "action time," in his Landolt ring search task should be subtracted from the total search time to characterize visual performance more accurately. The same argument can be made for transforming the time data obtained in the present experiment. The average total time taken to compare the two number lists can be plotted as a function of the average number of "ticks" (both hits and false positives) made by subjects in the experiment. As can be seen in Figure 4, a simple linear function with a slope of 0.8 can be used to characterize the relationship between these two variables.** Thus, the average time per "tick" is about 0.8 s. It was then a simple matter of subtracting 0.8 s for each hit and false positive in a trial (S_a) from the total time taken by subjects to compare the two number lists (S) in that trial. This transformation of the time data in Table A1 was used to estimate the so-called reading time (S_r) in the experiment. Thus,

$$S_r = S - S_a \quad (3)$$

2. *Time taken to read the response list*—The reading time taken to compare the number lists (S_r) is the sum of the time taken to read the reference list (S_{ref}) and the

*Appendix A discusses the reasons for limiting the discussion to $1/S$ as the measure of performance.

**A series of analyses of variance showed that response time ("ticks") was not systematically related to (i.e., did not interact significantly with) any of the experimental variables (luminance, ink pigment density, and desk orientation).

time taken to read the response list (S_{ref}). For a given adaptation luminance (L_B) in this experiment, S_{resp} should be approximately constant because the contrast of the response lists was high and, with the compressive response behavior obtained here and elsewhere (Section II), nearly constant. On the other hand, S_{ref} is expected to vary and to be determined by the contrast of the reference sheet on a particular trial (C_v). When the contrasts of the response and the reference lists are the same, at a given adaptation level, it is reasonable to assume that S_{resp} is equal to S_{ref} . Thus, S_{resp} is a constant (γ) equal to $\frac{1}{2} S_r$ under these conditions. The average response list contrast in **Table 1** was equal to 0.7. From the four curves in **Figure 3** it is possible to estimate the value of $1/S$ at the four luminance levels for a reference sheet contrast of 0.7 ($C_{0.7}$). Thus, a measure of visual performance (VP) can be estimated by taking into account S_a and γ , where:

$$VP = [(S_{L_B, C_v} - S_a) - \frac{1}{2}(S_{L_B, C_{0.7}} - S_a)]^{-1} \quad (4)$$

$$= (S_r, L_B, C_v - \gamma)^{-1} \quad (5)$$

$$= (S_{ref}, L_B, C_v)^{-1} \quad (6)$$

Equation 6 defines the measure of visual performance, VP , for this experiment. Namely, VP is the reciprocal of the time taken to read each reference list of a particular contrast (C_v) at a particular adaptation luminance (L_B). **Table 2** presents the values of $\overline{VP}$, the average values of VP .

D. Threshold contrast

Threshold contrasts are estimates of the transition from imperceptible to perceptible contrast at different background luminances, and, therefore, denote the lower limits of contrast perception in a visual performance model. Threshold contrasts have been commonly employed in psychophysical studies (e.g., Graham, 1965; Brindley, 1970) and are even evident in several electrophysiological studies (e.g., Albrecht and Hamilton, 1982; Tolhurst, Movshon and Thompson, 1981). Unfortunately, it is difficult to make estimates of threshold visibility with the procedures employed in the numerical verification task. Subjects tended to quit under difficult conditions so it was impossible to obtain data at the critical, steep transition between threshold contrasts and slightly perceptible contrasts. Threshold contrasts for the number lists had to be estimated at each background luminance by another technique.

Threshold contrasts of the number lists were obtained with a Visual Task Evaluator (VTE) (Blackwell, 1970) over several luminance levels, including the two lowest background luminances used in the numerical verification task. The relationships of these threshold data to background luminance have been described mathematically in an earlier report (Rea, 1982b). However, the VTE elevates the contrast threshold of fine

spatial details, like these numbers, relative to "free viewing" (Rea and Ouellette, 1984). To estimate contrast threshold without the intervening VTE optics, a gray number list was placed on the work desk and, by carefully adjusting the lighting geometry, and thus the veiling reflections from the sheet (Section III.A), it was possible to reduce the numbers to a "readability" threshold criterion at a luminance of 67 cd m⁻². By normalizing the "readability" contrast threshold function, obtained with VTE, to 0.055 at 67 cd m⁻², the contrast value measured following the free viewing method, it was possible to estimate the contrast thresholds (C_i) at the four luminance levels used in the present study (Appendix C, Equation C1). **Table 3** provides the four values of C_i , derived by these methods.

E. The formulation for visual response compression

Equation 1 may now be rewritten in the following form:

$$VP = [\Delta L^n / (\Delta L^n + k^n)] VP_{max} \quad (7)$$

where:

VP = the level of visual performance, as measured in units of the reciprocal of the time taken to read the reference sheet, from Equation 6;

n and k are as defined in Equation 1;

ΔL is the absolute value of a luminous increment or a luminous decrement from the threshold criterion at a given adaptation luminance.

Thus, for luminous decrements (dark ink on bright background) like those employed in this experiment,

$$\Delta L = L_T - L_T \quad (8)$$

where:

L_T is the luminance of the target at threshold

$$= L_B (1 - C_i)$$

L_T and L_B are as defined in Equation 2;

C_i is the threshold contrast at a given L_B , described in Section III.D, and can be determined from Equation C1 in Appendix C.

Alternatively, Equation 8 can be written as

$$\Delta L = L_B(C_v - C_i) \quad (9)$$

where:

C_v is the reference sheet contrast.

By using Equation 9 and rearranging terms, Equation 7 can be rewritten, for calculable simplicity, as

$$VP = \{\Delta C^n / [\Delta C^n + (k/L_B)^n]\} VP_{max} \quad (10)$$

where:

$$\Delta C = C_v - C_i$$

There are three unknowns in Equation 10, VP_{max} , n , and k . A nonlinear regression computer routine was used to provide the best estimates by a least squares criterion, of these three parameters at each adaptation luminance. The results of the regressions are presented in Table 3.

F. A general algorithm of suprathreshold visual performance

It is desirable to predict visual performance at more background luminances than those actually employed in this study. A series of interpolations was performed on the parameter estimates (n , k , and VP_{max}) in Table 3. Figures 5 to 7 show the three sets of parameter estimates plotted as a function of Θ_1 or Θ_2 , logarithmic transformations of background luminance. Second-degree polynomials were used to estimate, by a least squares criterion, the different parameter values between 12 and 169 cd m^{-2} . It was assumed (see Appendix B) that all of the parameter values in Equation 10 (except C_i) increase monotonically with background luminance. The logarithmic transformations of the abscissae were sometimes employed to limit non-monotonic behavior by the interpolation routines. The best fitting polynomials and expressions are presented with each figure.

These expressions enable one to calculate relative visual performance (RVP) for alphanumeric reading material of any contrast, where the paper is brighter than the ink and the luminance of the paper is between 12 and 169 cd m^{-2} (or, for white matte paper, between illuminances of 50 and 700 lx). Maximum RVP corresponds to a contrast of 1.0 at 169 cd m^{-2} . Appendix C describes the procedures for calculating RVP.

Figure 8 is a graphical representation of RVP as a function of contrast and luminance, both scaled logarithmically. Examination of this surface from several perspectives illustrate more clearly the influence of contrast and luminance on visual performance according to this model.

RVP is plotted as a function of luminance for several contrasts in Figure 9. Two features are readily apparent from this figure. First, visual performance changes very little from medium to high contrasts. For example, there is virtually no difference in RVP at contrasts between 0.5 and 1.0; changes in contrast are much more dramatic between lower contrasts (e.g., between 0.10 and 0.15). Second, the changes in RVP across luminance at high contrasts (e.g., 0.5) are slight, whereas, luminance is much more important to RVP at low contrasts (e.g., 0.15). These two points lead to the conclusion that visual performance will be relatively high and stable for medium to high contrast tasks, but veiling reflections and reduced illumination levels can be very important for low contrast tasks.

Figure 10 shows RVP plotted as a function of contrast at three luminance levels. Several points are worth noting in this figure. First, visual response compression is readily apparent in this figure; RVP is characterized by a steep initial slope and saturation as contrast increases. Second, the point of saturation is higher at higher luminances; RVP is always slightly better at higher luminances, even for medium and high contrasts. Third, the "knees" of the RVP response functions are higher and more prominent at higher luminances, indicating that a high level of visual performance can be maintained at lower contrasts the greater the level of illumination. Finally, this figure shows the shift in absolute contrast threshold, the lower limit of RVP, with higher luminance.

Figure 11, augments this last point concerning contrast threshold. Contrast, scaled logarithmically, is plotted as a function of luminance, also scaled logarithmically; the curves trace constant levels of RVP. These constant criterion curves are, in principle, identical to directly obtained threshold functions relating contrast and luminance. It is important to note in Figure 11, that the highest constant criterion levels of visual performance are unattainable at lower luminances, even at the highest contrasts.

IV. Discussion

Figures 8 through 11 help illustrate the predictions of the model as well as the similarity of these predictions to findings from a variety of electrophysiological and psychophysical studies.

A. Threshold contrast

Many electrophysiological and psychophysical studies have, for example, used threshold behavior to describe visual response (e.g., Boynton and Whitten, 1970; Albrecht and Hamilton, 1982; Tolhurst *et al.*, 1981). Threshold contrast has been shown repeatedly to decrease with adaptation luminance (e.g., Blackwell, 1946), and the model makes predictions of threshold consistent with these observations.

The exact shapes of the various threshold functions in Figure 11 may be different from other published data for a variety of reasons (Rea, 1982b). The independent (alphanumeric stimuli) and dependent (time) variables on which the model is based are somewhat unorthodox for the vision community, although they were specifically chosen to be "realistic" and therefore relevant to illuminating engineering. Further, these "threshold" curves were derived from the model and reflect the suprathreshold data obtained in the numerical verification task. They were not obtained from a lengthy threshold experiment in which subjects were asked to adopt various constant criteria and judge the visibility of stimuli at different contrasts and luminances. In principle, there should be no difference in the data obtained by either procedure, but it seems impractical,

if not impossible, to expect subjects to adopt and then maintain all of the various criteria necessary to generate the data required for functions comparable to those in **Figure 11**. Therefore, it is unlikely that a successful model of suprathreshold visual performance can be developed from threshold data alone.

The CIE model of visual performance (CIE, 1981a,b) is based on just one threshold function. Higher constant criterion functions, called Visibility Levels (VLs), are obtained by multiplying the single threshold curve by fixed multiples (CIE, 1981a,b). This assumption, that the various VL curves are parallel in log contrast versus log luminance space, is not justified by the data obtained in this experiment and is therefore inconsistent with the predictions from the RVP model (Appendix C).^{*} In this respect, at least, the RVP model presented here is probably better at making *a priori* predictions, and, therefore, in attempting to describe suprathreshold visual performance at a realistic, reading-writing task.

B. Suprathreshold response

Studies directly measuring suprathreshold visual performance have shown that it will increase with both contrast and luminance (e.g., Weston, 1935, 1945; Boyce, 1973; Smith and Rea, 1980; McNelis, 1973). The RVP model makes predictions similar to the data generated in these studies by predicting an interaction between luminance and contrast. The model predicts that suprathreshold visual performance will increase only slightly with luminance when the contrast is high and more strongly when contrast is low. As with the threshold data, however, the model predictions and the data from these various studies do not always agree quantitatively. It will be argued in a later paper (Rea, in press), however, that the results of properly controlled visual performance studies (e.g., McNelis, 1973) should yield results very similar to the predictions generated by the model. The contrast response functions obtained from cortical cells in monkeys (**Figure 1**), for example, are both qualitatively and quantitatively similar to predictions from the model.^{**} This marked similarity, known as "psychophysical isomorphism" (Kaufman, 1974; Dawis, 1981), is likely the result of the experimental control over the many "nonvisual" factors that can contribute to the measured responses. Still, it should be realized that the RVP model is based largely

upon the latency of response and most electrophysiological data, e.g., Albrecht and Hamilton (1982), are based upon the amplitude of response. The relationships between the amplitude and latency response functions can be complex (Ermolaev and Kleinman, 1983; van der Tweel *et al.*, 1979), but similarities have been shown (Vaughn *et al.*, 1966). More studies in electrophysiology may more clearly delineate the relationship between amplitude and latency.

C. Subjective impressions

It is also important to note, that the model seems to be consistent with our everyday experiences. One has little problem reading high contrast newsprint under virtually any domestic or commercial lighting system. As the model predicts, high contrast reading materials, like a newspaper, are relatively insensitive to variations in illuminance or contrast reducing veiling reflections. On the other hand, low contrast reading materials, like some blueprints or photoduplications, are quite sensitive to such variations. It is much more important for people viewing such material to have lighting systems that give high illumination and reduce disability glare and veiling reflections. The model quantitatively underscores the importance of these everyday occurrences.

V. Conclusions

These broad confirmations of the model aside, however, it must be stressed that the model still requires extension and testing. Not all of the important stimulus parameters have been studied, and there are a variety of inadequately tested assumptions built into the model. For example, the size of the printed text was not varied in the experiment. Also, targets brighter than the background (as with visual display terminals) have not been studied. Importantly too, it was assumed (Appendix B) that n , k , (or k_0) and VP_{max} should increase monotonically with luminance (**Figures 5, 6 and 7**). Further, it was assumed that contrast threshold data from different subjects could be linked with the suprathreshold data reported in this paper to make a more complete model.

Although these and other issues need to be investigated, it seems unlikely that the model is grossly inaccurate in representing suprathreshold visual performance. Visual response compression, which forms the basis of the model, is a widely observed phenomenon. The model makes predictions consistent with documented trends in threshold and suprathreshold behavior and, importantly, is consistent with our everyday experiences. Finally, a sensitivity analysis showed that reasonable variations in estimates of the parameter, n , did not significantly affect the model predictions over the range of contrasts and luminances encountered in commercial environments.

There is no question that the model must be extended and revised to some degree, but, based upon the

^{*}It is possible to change the shapes of the threshold curves in the CIE model, depending upon a variety of estimates of free parameters established after results are obtained (Rea, 1982b). For a given set of parameters, however, the constant criterion (VL) function would be parallel in a log contrast versus log luminance coordinate system.

^{**}Albrecht and Hamilton (1982) did not use a threshold term when fitting their data with Equation 1. Adding an appropriate threshold term makes the parameter estimates comparable to those for the model (**Figure 1**). Conversely, the deletion of a threshold term when fitting the present data, makes the parameter estimates like those published by Albrecht and Hamilton.

arguments made above, the model would appear to have utility for lighting practitioners as an interim algorithm for calculating relative visual performance at alpha-numeric reading tasks. Therefore, the RVP model should be considered as a milestone toward the ultimate goal for an economic model of task performance.

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VII. References

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Table 1—Stimulus sheet contrasts

Desk Angle*	Reference Sheets		
	Black gloss	Gray matte	Response Sheet
0	0.199	0.095	0.670
7.5	0.202	0.092	0.672
15	0.260	0.100	0.675
20	0.371	0.107	0.684
25	0.491	0.112	0.698
30	0.606	0.121	0.714
45	0.835	0.134	0.759
90	0.894	0.156	0.826

*These values are the clockwise azimuth angles, in degrees, of the vertical plane defining the subject's line of sight to the center of the task with respect to the center of the luminaire. The 0-degree azimuth angle, for example, corresponds to the vertical plane bisecting the subject's nose, the center of the task and the center of the luminaire.

Table 2—Visual Performance ($\overline{VP}$)

C_v	L_B			
	12	22	41	169
0.092	0.0389	0.0362	0.0463	0.0554
0.095	0.0386	0.0415	0.0467	0.0504
0.100	0.0441	0.0412	0.0513	0.0570
0.107	0.0443	0.0472	0.0511	0.0597
0.112	0.0457	0.0543	0.0585	0.0660
0.121	0.0551	0.0574	0.0638	0.0676
0.134	0.0560	0.0590	0.0602	0.0665
0.156	0.0551	0.0632	0.0666	0.0699
0.199	0.0640	0.0638	0.0687	0.0667
0.202	0.0610	0.0680	0.0712	0.0749
0.260	0.0688	0.0667	0.0711	0.0745
0.371	0.0658	0.0670	0.0650	0.0705
0.491	0.0703	0.0778	0.0826	0.0789
0.606	0.0717	0.0775	0.0706	0.0774
0.835	0.0720	0.0738	0.0743	0.0726
0.894	0.0671	0.0712	0.0775	0.0801

Entries are values of visual performance ($\overline{VP}$), the average of the reciprocal of the time required to read the reference sheet [$(S_{ref})^{-1}$].

L_B is the luminance of the reference sheet in units of $cd\ m^{-2}$.

C_v is the contrast of the numbers as defined in Equation 2.

Table 3—VP parameters

C_t	L_B	n	k	VP_{max}
0.0702	12.1	0.993	0.249	0.0726
0.0632	22.4	1.45	0.634	0.0740
0.0581	41.2	1.45	1.03	0.0752
0.0506	169	1.69	4.27	0.0762

Appendix A

Table A1 gives the response measure (total time, misses, false positives and score) averages for the combinations of sixteen contrasts and four background luminances produced in the experiment. Analyses of variance (ANOVAs) for the experimental design variables are presented in **Table A2** for each response measure. The response measure called score is based upon the other three and calculated by the formula:

$$\text{Score} = (T - E) 100 / (S + 5) \quad (A1)$$

where:

T = total number of comparisons per trial (always 20)

E = number of errors, both misses and false positives, committed per trial

S = total time to complete the comparisons per trial (in seconds).

This measure was devised by Smith and Rea (1980) to monotonically increase with visibility and to incorporate both speed and accuracy, traditional measures of visual performance (Weston, 1935, 1945). The score formulation is a somewhat arbitrary measure of performance, most strongly determined by total time (S). (There was a correlation of -0.95 between the trial scores and the trial times in this experiment.) In fact, errors play only a minor role in determining the score values. Nevertheless, and as noted in the earlier report (Rea, 1981), the contrast response functions for total time, misses, and false positives are nearly identical in these experiments.* Ideally then, the relative weightings of the primary measures would make little difference in a strictly linear characterization of performance combining time and errors. Score as defined in Equation A1 is not linear, however. The constant (5 s) in the denominator of Equation A1 introduces a nonlinearity into the score formulation. Although the constant is relatively unimportant at most response times observed in this experiment (usually longer than 25 s), it would obviously be more important at shorter response times.

It is still advantageous to minimize the importance of errors in a score formulation for this experiment, despite the similarity of the contrast response functions for all of the primary measures. The absolute levels of both error measures are low in these experiments. Even small, random fluctuations in the subjects' behaviors could strongly influence trial scores if these integer, dependent variables were more strongly weighted. To limit the influence of random perturbations in the false

* The marked similarity between the primary measures total time, misses and false positives, indicates that the classic, psychological "speed-accuracy trade-off" was not reflected in the response averages. This identity of the total time and the error responses is strong, but indirect, support for the hypothesis that these averaged results are largely based upon visual rather than nonvisual factors.

positive or miss responses, total time *should be* weighted more heavily than errors to characterize visual performance, assuming time and errors vary the same way with contrast. As stated in the previous paragraph, this was the case.

In summary, only measures based upon trial times are discussed as indices of visual performance in this report because a) the score formulation includes a small nonlinearity, b) misses and false positives are less

reliable measures of performance than total time, c) manuscript brevity, and, importantly, d) the contrast response function for the reciprocal of time is not substantively different from that for score, the reciprocal of misses or the reciprocal of false positives. The reciprocal of trial times was used because it is more convenient to think of the measure of performance increasing with increasing visibility.

Table A1—Means and standard errors (SE) for the four dependent variables used in the experiment.

	Score		Time (S)		Misses		False Positives	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
$L_B = 12 \text{ cd m}^{-2}$								
C_v								
0.092	42.2	1.55	41.9	1.69	0.786	0.173	0.071	0.050
0.095	42.0	1.37	42.2	1.57	0.643	0.156	0.107	0.079
0.100	45.7	1.94	38.9	1.86	0.786	0.149	0.071	0.050
0.107	45.0	1.58	38.8	1.47	0.786	0.166	0.071	0.050
0.112	46.0	1.83	38.2	1.65	0.893	0.165	0.036	0.036
0.121	50.6	2.03	34.4	1.45	0.786	0.173	0.036	0.036
0.134	50.8	1.66	34.1	1.44	0.714	0.169	0.036	0.036
0.156	51.2	1.55	34.4	1.16	0.321	0.104	0.000	0.000
0.199	54.9	1.99	31.9	1.37	0.464	0.131	0.000	0.000
0.202	54.7	2.12	32.6	1.74	0.357	0.092	0.000	0.000
0.260	56.6	1.98	30.8	1.23	0.393	0.119	0.000	0.000
0.371	55.7	2.04	31.5	1.53	0.429	0.120	0.036	0.036
0.491	57.5	2.15	30.5	1.52	0.429	0.174	0.000	0.000
0.606	58.5	2.16	30.2	1.46	0.250	0.098	0.000	0.000
0.835	56.9	1.88	30.1	1.27	0.607	0.181	0.000	0.000
0.894	56.2	1.93	31.2	1.24	0.321	0.127	0.000	0.000
$L_B = 22 \text{ cd m}^{-2}$								
C_v								
0.092	41.8	1.87	43.4	2.41	0.536	0.131	0.393	0.130
0.095	44.9	1.77	39.9	2.14	0.679	0.163	0.107	0.060
0.100	44.0	1.46	40.0	1.66	0.750	0.160	0.071	0.050
0.107	48.6	2.09	36.9	1.90	0.536	0.120	0.071	0.050
0.112	51.6	1.60	34.2	1.55	0.393	0.165	0.036	0.036
0.121	53.0	1.99	33.2	1.51	0.571	0.166	0.000	0.000
0.134	54.4	2.05	32.7	1.49	0.250	0.098	0.036	0.036
0.156	55.1	1.73	31.6	1.34	0.464	0.120	0.000	0.000
0.199	55.6	1.55	31.4	1.10	0.214	0.079	0.000	0.000
0.202	56.5	1.66	30.4	1.12	0.464	0.120	0.000	0.000
0.260	56.0	1.68	30.7	1.09	0.393	0.119	0.071	0.050
0.371	57.4	2.11	30.7	1.45	0.321	0.104	0.000	0.000
0.491	60.9	2.08	28.6	1.38	0.286	0.087	0.000	0.000
0.606	59.8	1.74	28.7	1.04	0.357	0.117	0.000	0.000
0.835	58.4	1.79	29.3	1.10	0.500	0.109	0.000	0.000
0.894	57.3	1.50	29.8	1.02	0.464	0.131	0.000	0.000

Table A1 (continued)

	Score		Time (S)		Misses		False Positives	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
$L_B = 41 \text{ cd m}^{-2}$								
C_v								
0.092	46.6	1.64	37.1	1.36	0.750	0.175	0.179	0.074
0.095	47.5	1.64	36.9	1.46	0.571	0.188	0.107	0.079
0.100	48.8	1.59	35.0	1.19	0.857	0.152	0.107	0.079
0.107	50.0	1.60	35.1	1.41	0.500	0.121	0.036	0.036
0.112	53.0	1.49	32.6	1.08	0.429	0.120	0.036	0.036
0.121	55.0	1.63	31.2	1.13	0.571	0.130	0.000	0.000
0.134	55.1	1.80	32.1	1.26	0.143	0.067	0.000	0.000
0.156	56.4	1.73	30.6	1.20	0.500	0.109	0.000	0.000
0.199	57.7	1.67	30.1	1.09	0.214	0.079	0.000	0.000
0.202	57.5	1.68	29.6	0.97	0.536	0.150	0.000	0.000
0.260	58.9	1.92	29.6	1.18	0.214	0.079	0.000	0.000
0.371	56.7	1.95	30.9	1.35	0.321	0.104	0.000	0.000
0.491	60.7	1.66	27.6	0.89	0.571	0.120	0.000	0.000
0.606	58.4	1.88	29.7	1.18	0.321	0.127	0.000	0.000
0.835	59.5	2.02	29.0	1.16	0.357	0.128	0.000	0.000
0.894	59.9	1.84	28.4	1.02	0.464	0.109	0.000	0.000
$L_B = 169 \text{ cd m}^{-2}$								
C_v								
0.092	52.0	1.84	33.3	1.42	0.679	0.137	0.071	0.050
0.095	49.8	1.80	35.1	1.57	0.643	0.180	0.107	0.060
0.100	52.1	1.58	32.8	1.04	0.607	0.107	0.107	0.060
0.107	54.3	2.01	32.0	1.23	0.536	0.150	0.000	0.000
0.112	56.3	1.73	30.4	1.08	0.536	0.109	0.000	0.000
0.121	57.6	1.81	30.1	1.06	0.321	0.116	0.000	0.000
0.134	57.0	1.92	30.3	1.18	0.464	0.120	0.000	0.000
0.156	57.7	1.51	29.6	0.94	0.429	0.130	0.000	0.000
0.199	56.6	1.63	30.3	1.02	0.464	0.167	0.000	0.000
0.202	59.7	1.86	28.6	1.05	0.393	0.139	0.036	0.036
0.260	59.2	1.68	28.7	0.97	0.464	0.141	0.000	0.000
0.371	58.6	1.99	29.5	1.17	0.393	0.119	0.036	0.036
0.491	60.9	1.80	28.0	0.99	0.393	0.119	0.000	0.000
0.606	60.0	1.69	28.2	0.89	0.464	0.120	0.000	0.000
0.835	60.1	2.36	29.0	1.31	0.357	0.106	0.000	0.000
0.894	61.5	1.75	27.8	0.97	0.286	0.101	0.000	0.000

Table A2—Analyses of variance (ANOVAs) for the four dependent variables

1. Dependent Variable = SCORE

EFFECT	SS	DF	MS	F	P
L	7,514.1	3	2,504.7	78.628	.001
O	9,335.3	7	1,333.6	41.865	.001
I	25,829	1	25,829.0	810.84	.001
A	93,437	6	15,573.0	488.87	.001
LO	1,043.5	21	49.690	1.5599	—
LI	1,390.8	3	463.62	14.554	.001
LA	6,278.2	18	348.79	10.949	.001
OI	3,333.9	7	476.27	14.951	.001
OA	2,197.2	42	52.315	1.6423	.005
IA	1,497.3	6	249.55	7.8338	.001
LOI	525.82	21	25.039	0.78602	—
LOA	7,826.9	126	62.118	1.9500	.001
OIA	667.66	42	15.897	0.49903	—
LIA	960.93	18	53.385	1.6759	.05
LOIA	2,855.7	126	22.664	0.71147	—

2. Dependent Variable = TIME (S)

EFFECT	SS	DF	MS	F	P
L	4,608.8	3	1,536.3	89.798	.001
O	5,029.0	7	718.43	41.994	.001
I	12,034	1	12,034.0	703.40	.001
A	49,333	6	8,222.2	480.60	.001
LO	751.82	21	35.801	2.0926	.005
LI	1,093.5	3	364.51	21.306	.001
LA	4,220.5	18	234.47	13.705	.001
OI	2,161.0	7	308.72	18.045	.001
OA	1,357.0	42	32.310	1.8886	.001
IA	353.83	6	58.971	3.447	.005
LOI	429.94	21	20.473	1.1967	—
LOA	5,452.8	126	43.276	2.5296	.001
OIA	308.63	42	7.3483	0.42952	—
LIA	781.44	18	43.413	2.5376	.001
LOIA	2,427.7	126	19.268	1.1262	—

L = light level

O = desk orientation

I = ink pigment density

A = subject

Table A2 (Continued)

3. Dependent Variable = Number of MISSES

EFFECT	SS	DF	MS	F	P
L	3.6490	3	1.2163	2.5296	-
O	4.9682	7	0.70974	1.476	-
I	15.563	1	15.563	32.366	.001
A	49.671	6	8.2785	17.217	.001
LO	8.9358	21	0.42552	0.88494	-
LI	2.3008	3	0.76693	1.5950	-
LA	13.910	18	0.77276	1.6071	-
OI	7.8878	7	1.1268	2.3435	.025
OA	14.481	42	0.34479	0.71705	-
IA	7.6596	6	1.2766	2.6549	.025
LOI	9.2662	21	0.44125	0.91766	-
LOA	53.224	126	0.42242	0.87849	-
OIA	14.046	42	0.33442	0.69550	-
LIA	7.6172	18	0.42318	0.88008	-
LOIA	48.035	126	0.38123	0.79283	-

4. Dependent Variable = Number of FALSE POSITIVES

EFFECT	SS	DF	MS	F	P
L	0.1808	3	0.060268	1.78902	-
O	1.6585	7	0.23693	6.9984	.001
I	1.2857	1	1.2857	37.978	.001
A	1.5056	6	0.25093	7.4121	.001
LO	0.81920	21	0.039009	1.1523	-
LI	0.16518	3	0.05506	1.6264	-
LA	0.43638	18	0.024244	0.71612	-
OI	1.3571	7	0.19388	5.7268	.001
OA	3.0212	42	0.071933	2.1248	.001
IA	0.8471	6	0.14118	4.1703	.001
LOI	1.1562	21	0.05506	1.6264	.05
LOA	4.0011	126	0.031755	0.93799	-
OIA	1.6975	42	0.040418	1.1939	-
LIA	0.63951	18	0.035528	1.0495	-
LOIA	3.8516	126	0.030568	0.90293	-

L = light level

O = desk orientation

I = ink pigment density

A = subject

Appendix B

A. VP_{max}

The assumption that VP_{max} increases with background (adaptation) luminance has support from the data by Valeton and van Norren (1983). In their study, a micro-electrode was placed adjacent to a single photoreceptor in the retina of a monkey. Changes in electrical potential were recorded for changes in light level about a given adaptation luminance. Adaptation luminances ranged from darkness to 7 log photopic trolands. A single function, based upon Equation 1, described the relative cone response data for both increments and decrements about any given adaptation luminance.

Figure B1 shows the single-cone response function that was shifted vertically (arithmetic ordinate) and horizontally (logarithmic abscissa) to fit their data at different adaptation luminances. As adaptation luminance increases the curve shifts systematically toward the right along the abscissa and downward along the ordinate. Thus, the absolute levels of the maximum and minimum responses change relative to the zero response crossings (there is zero response at the adaptation luminances). With increases in the adaptation luminance, the absolute value of the maximum response, for increments, decreases while the absolute value of the minimum response, for decrements, increases.

In the present experiment only luminous decrements were used. Thus, one expects the absolute value of the decrement response to increase with background luminance, based upon the data from Valeton and van Norren. This is consistent with data in Figure 3 and with the interpolation routine employed to estimate the values of VP_{max} (Figure 5).

B. n and k

Table 3 shows a general tendency for n and k to increase with background luminance for the data in this experiment. For the model it was assumed that estimates of n and k at background luminances between 12 and 169 cd m^{-2} could be estimated from monotonically increasing interpolations (Figures 6 and 7). The assumption that k increases with adaptation luminance is clearly correct since its magnitude is heavily dominated by the background luminance (L_B) over the range of the model. The parameter k_0 , however, may be defined as the abscissa value, relative to the origin, producing half of maximum response, and it can be estimated from k in Table 3. Dividing each estimate of k by the corresponding background luminance gives values of k_0 . It is also true that k_0 tends to increase with background luminance, further supporting the assumption that k increases with background luminance.

The assumption that n increases with adaptation luminance is somewhat more tenuous, however. Although there was a tendency for n to increase monotonically with background luminance in this experiment, the true values

of n might not increase with light level. Given this uncertainty in the true values of n , a sensitivity analysis was conducted to see how predictions of relative visual performance (RVP in Appendix C, Equation C10) would change if n were constant a) at the lowest estimate of n in Table 3 ($n = 1.0$), b) at the highest estimate ($n = 1.7$), and c) at the average estimate ($n = 1.4$). Variations in the estimates RVP never exceeded 10 percent and rarely exceeded 4 percent over the entire range of the model. Thus, reasonable variations in the parameter n do not seriously affect the model predictions.

Appendix C

The procedure for calculating relative visual performance (RVP) in Figure 11 is given below. Strictly speaking, the model is applicable to young adults reading positive contrast (dark ink on bright background) letters or numbers, each character subtending a visual angle of 0.2 degrees in width. The range of luminances in the model is between 12 and 169 cd m^{-2} . The reciprocal of time necessary to read the alphanumeric stimuli "as quickly and accurately as possible" is the measure of visual performance.

1. Select task background luminance, L_B , within the range of

$$12 \leq L_B \leq 169 \text{ cd m}^{-2}.$$

2. Calculate threshold contrast, C_t , at the selected L_B , where

$$C_t = 0.0418 [(0.308/L_B)^{0.4} + 1.0]^{2.5} \quad (\text{C1})$$

3. Select task luminance contrast, C_v , where L_B is greater than the target luminance, L_T , and

$$C_v = \frac{L_B - L_T}{L_B} \quad (\text{C2})$$

4. Calculate the parameters n , k , and VP_{max} , where

$$n = 0.882 + 4.38 \times \Theta_1 - 6.05 \times \Theta_1^2 \quad (\text{C3})$$

where $\Theta_1 = \log_{10}[\log_{10}(L_B)]$

$$\log_{10}k = -2.25 + 1.77 \times \Theta_2 - 0.217 \times \Theta_2^2 \quad (\text{C4})$$

where $\Theta_2 = \log_{10}(L_B)$

$$VP_{max} = 0.0628 + 0.0120 \times \Theta_2 - 0.00268 \times \Theta_2^2 \quad (\text{C5})$$

5. Calculate the predicted level of visual performance, VP , where,

$$VP = \{\Delta C / [\Delta C^n + (k/L_B)^n]\} VP_{max} \quad (\text{C6})$$

where:

$$\Delta C = C_v - C_t$$

For values of $\Delta C < 0$, $VP = 0$

6. Visual performance relative to that at $L_B = 169 \text{ cd m}^{-2}$ and $C_v = 1.0$ (RVP) may be determined by the following equation:

$$RVP = VP/f \quad (\text{C7})$$

where:

$$f = 0.0760 = VP_{max} \text{ at } L_B = 169 \text{ cd m}^{-2} \text{ and } C_v = 1.0$$

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