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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

THE CORRELATION OF MODELS FOR VISION AND VISUAL PERFORMANCE

CIE 145:2002

UDC: 612.84

Descriptor: Vision

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The International Commission on Illumination (CIE) is an organisation devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in 37 countries and one geographical area and of 9 associate members.

The objectives of the CIE are :

1. To provide an international forum for the discussion of all matters relating to the science, technology and art in the fields of light and lighting and for the interchange of information in these fields between countries.
2. To develop basic standards and procedures of metrology in the fields of light and lighting.
3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
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2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par 7 Divisions, ayant chacune environ 20 Comités Techniques. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.

Tous les quatre ans, une Session plénière passe en revue le travail des Divisions et des Comités Techniques, en fait rapport et établit les projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. Elle occupe comme telle une position importante parmi les organisations internationales.

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Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in 37 Ländern und einem geographischen Gebiet und aus 9 assoziierten Mitgliedern.

Die Ziele der CIE sind :

1. Ein internationaler Mittelpunkt für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Meßtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird in 7 Divisionen, jede mit etwa 20 Technischen Komitees, geleistet. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtenwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind von der ganzen Welt anerkannt.

Tagungen werden alle vier Jahre abgehalten, in der die Arbeiten der Divisionen überprüft und berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Technical Committee 1-19 of Division 1 “Vision and Colour” and has been approved by the Board of Administration of the Commission Internationale de l’Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

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THE CORRELATION OF MODELS FOR VISION AND VISUAL PERFORMANCE

SUMMARY

In the framework of a research project on vision models, the visual performance data of different authors have been compared with respect to their relation to background luminance, contrast and size of the critical object. Rea and Ouellette presented a model based on their own data on "Reaction Time", that allows the calculation of Visual Performance (VP) according to their definition for given visual task conditions. However, their definition of VP differed from those used in all of the other studies considered here.

As part of this research project a model for VP was developed, based on the very comprehensive study of H. C. Weston in 1945. He used, as performance criteria, the speed with which the form of a target could be detected and a term comprising accuracy of recognition. Investigations of Muck and Bodmann, using similar criteria, composed of search time and accuracy, have been compared with the Weston model and showed good agreement. Likewise, the data of Simonson and Brozek, McNelis, Smith and Rea, and Loe and Waters have been examined.

The differences between the Rea and Weston models can be attributed to the different criteria used for measurements of Visual Performance. In Rea's case, the inverse of the time needed to see a target varying in size and contrast was used as a measure; In Weston's case it was a composite of visual acuity, time and errors made. The differences observed are mainly due to the sensitivity to contrast: Rea's model does not show significant dependency on contrast but Weston's does.

It became evident that a strong relationship between visual acuity and performance exists. The influence of age on visual acuity was found to be of major importance to Visual Performance also.

LA CORRELATION DE MODELES POUR LA VISION ET LA PERFORMANCE VISUELLE

RESUME

Dans le cadre d'un projet de recherche sur les modèles de vision, les données sur les "performances visuelles" obtenues par divers auteurs ont été comparées au point de vue de leur relation avec la luminance du fond, le contraste et la taille de l'objet critique. Rea et Ouellette ont présenté un modèle basé sur leurs propres données de "Temps de réaction", qui permet le calcul d'une "performance visuelle" (VP) selon leur définition, pour des conditions déterminées de tâches visuelles. Cependant, leur définition de la VP diffère de celles utilisées dans toutes les autres études considérées ici.

Dans une partie de ce projet de recherche un modèle de la VP a été développé, basé sur l'étude très complète de H. C. Weston en 1945. Il utilisa, comme critère d'aptitude, la vitesse avec laquelle la forme d'une cible peut être détectée et un terme relatif à l'exactitude de reconnaissance. Des investigations de Muck et Bodmann, utilisant un critère analogue combinant temps de reconnaissance et exactitude, ont été comparées avec le modèle de Weston et ont montré un bon accord. De même, les données de Simonson et Brozek, de Smith et Rea, et de Loe et Waters ont été examinées.

Les différences entre les modèles de Rea et Weston peuvent être attribuées aux différents critères utilisés pour les mesures de "performance visuelle". Dans le cas de Rea, l'inverse du temps nécessaire pour percevoir la cible, dont la taille et le contraste sont variés, a été utilisé comme mesure; dans le cas de Weston c'était une combinaison de l'acuité visuelle, du temps passé et des erreurs faites. Les différences observées sont principalement dues à la sensibilité au contraste: le modèle de Rea ne montre pas de dépendance significative vis à vis du contraste, contrairement à celui de Weston.

Il apparaît évident qu'il existe une étroite relation entre l'acuité et l'aptitude visuelles. L'influence de l'âge sur l'acuité visuelle s'est également révélée être un élément primordial vis à vis de la performance visuelle.

DIE BEZIEHUNGEN ZWISCHEN MODELLEN FÜR DEN SEHPROZESS UND DER SEHLEISTUNG

ZUSAMMENFASSUNG

Im Rahmen eines Forschungsvorhabens über Modelle für den Sehprozeß wurden die Daten verschiedener Autoren über die Sehleistung miteinander verglichen, im Hinblick auf die Beziehung dieser Daten zu Hintergrundleuchtdichte, Kontrast und Größe der kritischen Objekte. Rea und Ouellette entwickelten ein Modell auf der Basis selbst erhobener Daten zur "Reaktionszeit", das die Berechnung der Sehleistung ($\text{Visual Performance} = \text{VP}$) auf der Basis der von ihnen gewählten Definition für vorgegebene Randbedingungen der Sehaufgabe zuläßt. Jedoch unterscheidet sich ihre Definition der VP von der in allen anderen Untersuchungen, die hier betrachtet wurden.

Im Rahmen des in dieser Publikation behandelten Forschungsvorhabens wurde ein Modell der VP entwickelt, das sich auf eine sehr eingehende Studie von H. C. Weston aus dem Jahr 1945 stützt. Dieser nutzte als Leistungskriterium die Geschwindigkeit, mit der die Gestalt eines Musters erkannt werden konnte sowie eine Größe, die die Genauigkeit der Wahrnehmung beschrieb. Untersuchungen von Muck und Bodmann, die ähnliche Kriterien, zusammengesetzt aus Erkennungszeit und Wahrnehmungsgenauigkeit, verwendeten, wurden mit dem Weston-Modell verglichen und ergaben gute Übereinstimmung. Gleichmaßen wurden die Daten von Simonson und Brozek, McNelis, Smith und Rea sowie Loe und Waters überprüft.

Die Unterschiede zwischen dem Rea- und dem Weston-Modell können auf die unterschiedlichen Kriterien zur Messung der Sehleistung zurückgeführt werden. Im Rea-Modell wurde als Maß der Kehrwert der Zeit verwendet, die benötigt wurde, um Muster unterschiedlicher Größe und unterschiedlichen Kontrastes zu erkennen. Im Weston-Modell war es eine Kombination von Sehschärfe, Zeit und Fehlerrate. Die beobachteten Unterschiede beruhen im wesentlichen auf der Empfindlichkeit gegenüber Kontrasten: das Rea-Modell zeigt keine bedeutsame Abhängigkeit vom Kontrast, das Weston-Modell hingegen durchaus.

Offenkundig besteht eine starke Beziehung zwischen Sehschärfe und Sehleistung. Der Einfluß des Alters auf die Sehschärfe wurde ebenfalls als sehr bedeutsam für die Sehleistung befunden.

INTRODUCTION

A study on the relationship between different investigations of Visual Performance has been undertaken to provide a basis for lighting recommendations. In the recent past, only one model, that of Rea, had been available (Rea, 1991) and it was unclear whether this model of Visual Performance, reflects also the results following from earlier and later investigations.

For this reason Visual Performance data have been collected from the literature and evaluated with respect to the criteria used and to the experimental conditions. The data of the most comprehensive study by H. C. Weston in 1945 (Weston, 1945) were used as a basis for modelling visual performance. The conclusions from Weston's results are compared with those derived from Muck and Bodmann's experiments (Muck, 1961), Simonson and Brozek's (Simonson, 1948), Smith and Rea's (Smith, 1978), McNelis' (McNelis, 1973) and those of Loe and Waters' (Loe, 1973).

Any comparison between these results must consider the compatibility of the criteria used.

The influence of age on visual performance and the relationship of Visual Performance (VP) to Visual Acuity (VA) also had to be investigated. The completion of visual tasks described by the term Visual Performance incorporates the resolution of details. The visual information, as it applies to Visual Acuity tasks, is therefore processed by high frequency channels (parvocellular channel). Therefore, it can be expected that a relationship exists between Visual Acuity and Visual Performance. However, this has been denied on the grounds that Visual Acuity constitutes a threshold criterion, as opposed to Visual Performance, which is measured at supra-threshold levels. Special attention is given to this question.

DEFINITION OF TERMS

Visual Performance , VP:

Performance of the visual system as measured for instance by the speed and accuracy with which a visual task is performed.

Relative Visual Performance, RVP:

A proportional measure of visual performance potential expressed in terms of the maximum value achievable.

Visual Acuity, VA:

Capacity of the visual system to discriminate fine details. Measure of spatial discrimination such as the reciprocal of the value of the angular separation in minutes of arc of two neighbouring objects which the observer can just perceive to be separate.

Relative Contrast Sensitivity, RCS:

Proportional value of contrast sensitivity. Contrast sensitivity is the reciprocal of the least perceptible contrast.

MODEL OF WESTON'S DATA

The well-known and classical experimental investigations of Visual Performance, were carried out by H. C. Weston (Weston, 1945). He used arrays of Landolt C rings of differing contrast on backgrounds with various luminance levels. The observer had to indicate the orientation of each ring. Weston developed a criterion for the overall performance that was composed of

$$\text{Accuracy} = \frac{\text{correctly identified rings}}{\text{correct} + \text{missed rings}} \quad (1)$$

and

$$\text{Speed} = \frac{\text{correctly identified rings}}{\text{minute}} \quad (2)$$

For the total time needed to identify the rings the time for physical arm movements was subtracted in order to obtain the real time for the visual task. His performance was then defined as:

$$VP = \text{Accuracy} \cdot \text{Speed} \quad (3)$$

In this study, the size of the critical detail (gap in the ring), the contrast of the ring and the background luminance were varied. The results, obtained with young observers, can be numerically expressed by the equations:

For high contrast $C > 0,35$ Target $\alpha \geq 1,5'$

$$VP = 0,5384 \cdot (\alpha - 1,499)^X \cdot (\log L_b + 0,09196)^Y \cdot (C - 0,2534)^Z \cdot AF \quad (4a)$$

where

$$X = 0,1194 \cdot (\log L_b + 1,923)^{0,08403} \cdot (C + 1,516)^{-0,6549}$$

$$Y = 0,8135 \cdot (\alpha - 1,182)^{-0,7831} \cdot (C + 1,054)^{-3,062}$$

$$Z = 0,5745 \cdot (\log L_b + 0,2669)^{-0,3902} \cdot (\alpha - 0,8302)^{-0,7637}$$

For low contrast $C < 0,35$

$$VP = 0,6577 \cdot (\alpha - 1,4999)^X \cdot (\log L_b + 0,035)^Y \cdot (C - 0,08521)^Z \cdot AF \quad (4b)$$

where

$$X = 0,082 \cdot (\log L_b + 0,11339)^{-0,6378755} \cdot (C + 0,02243)^{-0,23}$$

$$Y = 0,1452 \cdot (\alpha - 0,0041)^{-0,18451} \cdot (C - 0,099)^{0,1168}$$

$$Z = 1,291 \cdot (\log L_b + 0,264)^{-0,38675} \cdot (\alpha - 0,218)^{-0,523}$$

with L_b = background luminance cd/m^2

$$C = \text{target contrast} = \frac{\Delta L}{L_b} = \frac{L_b - L_{\text{target}}}{L_b}$$

α = target size in minutes of arc

and AF = age factor following from Eq. 6

The curves in Figures 1 to 3 have been calculated using Eqs. 4a and b. The model shows agreement with Weston's data with a slight departure for the smallest target size of $1,5'$ and lowest target contrast (Fig. 3.).

This system was created in order to provide a basis for comparison with other author's data and in particular those of Rea and Ouellette (Rea, 1990).

Eq. 4 reflects the Visual Performance derived from the data of Weston with VP in his scale. *In order to relate it to the highest performance achievable we have chosen for VP a value of 1 based on a $4,5'$ critical detail of contrast $C = 0,9$ at a background luminance of $L_b = 1000 \text{ cd/m}^2$. This means that the value of VP obtained from Eq. 4 has to be multiplied by 1,728.*

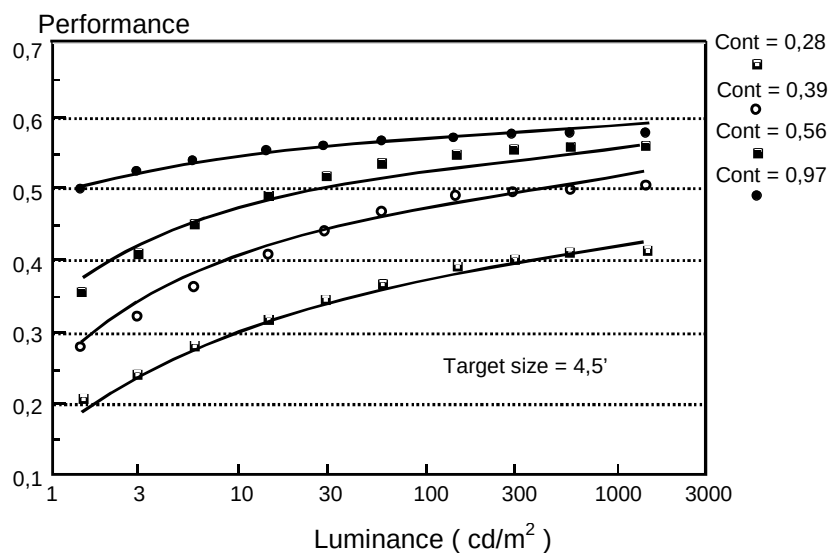


Fig. 1. Comparison between Weston's performance data with resulting curves calculated with Eqs. 4a and b for a target size of 4,5'.

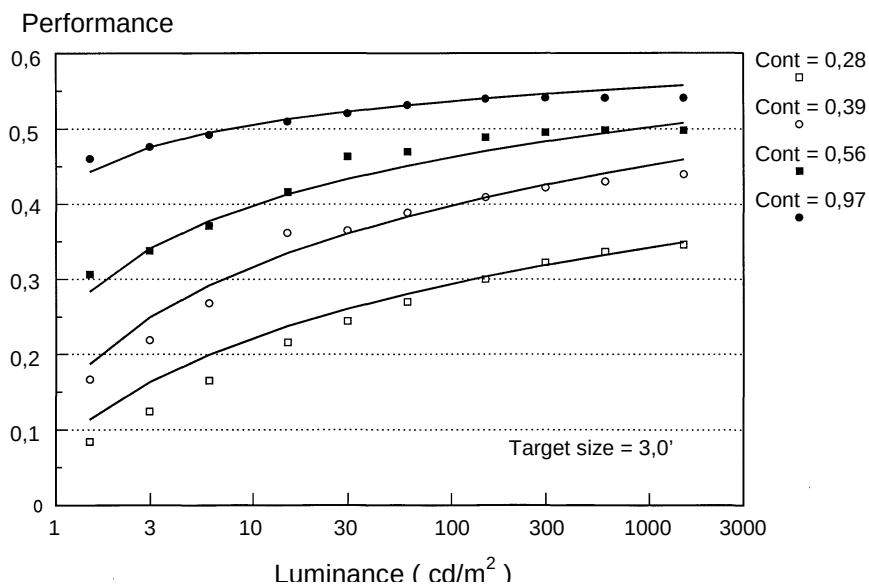


Fig. 2. Weston's performance data in comparison with the model following from Eqs. 4a and b for target sizes of 3'.

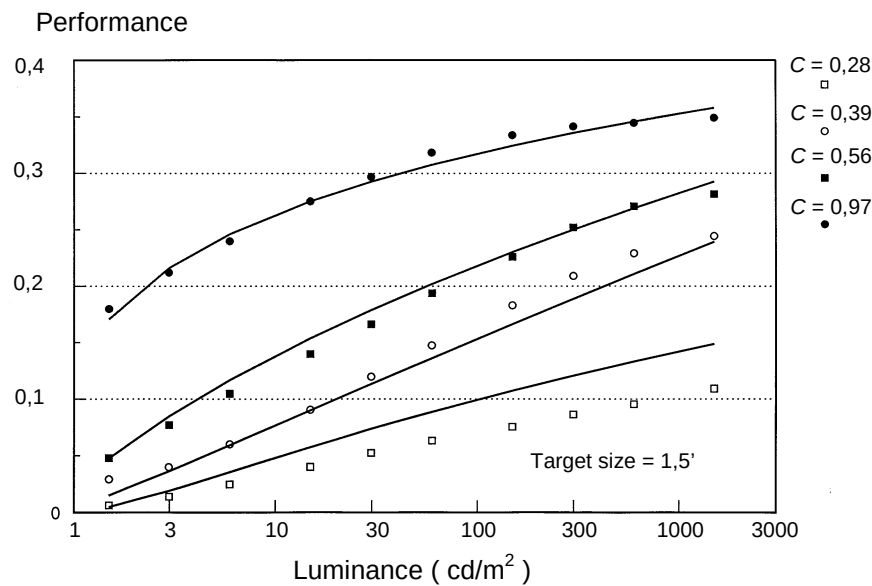


Fig. 3. Weston's performance data compared with calculated functions after Eqs. 4a and b for target sizes of 1,5'. The target sizes equal the critical detail. This is the gap size of the Landolt rings.

VISUAL ACUITY COMPARISON

The model of Weston's performance was used to show the relationship between the Visual Acuity data of Adrian and Spafford (Adrian, 1993). An interesting comparison is the ratio between Visual Acuity and Visual Performance for the same conditions of contrast and luminance. This relationship is plotted in Figs. 4 and 5.

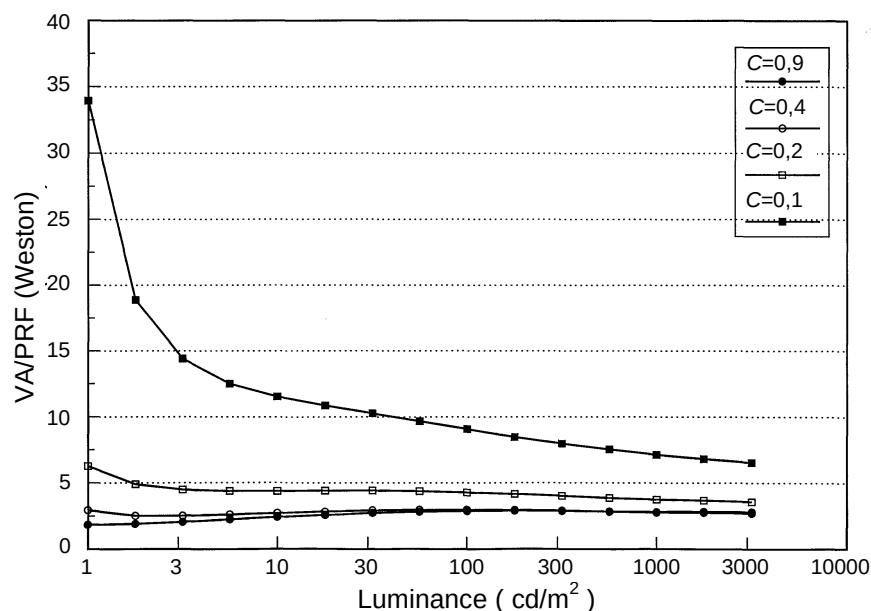


Fig. 4. Ratio of Visual Acuity to Weston's Visual Performance, for varying target contrast as parameter. The calculation was done for a Target Size of 4,5'. Luminance in cd/m^2 . $VA=f(L,C)$ was calculated with a formula as in reference Adrian, 1993.

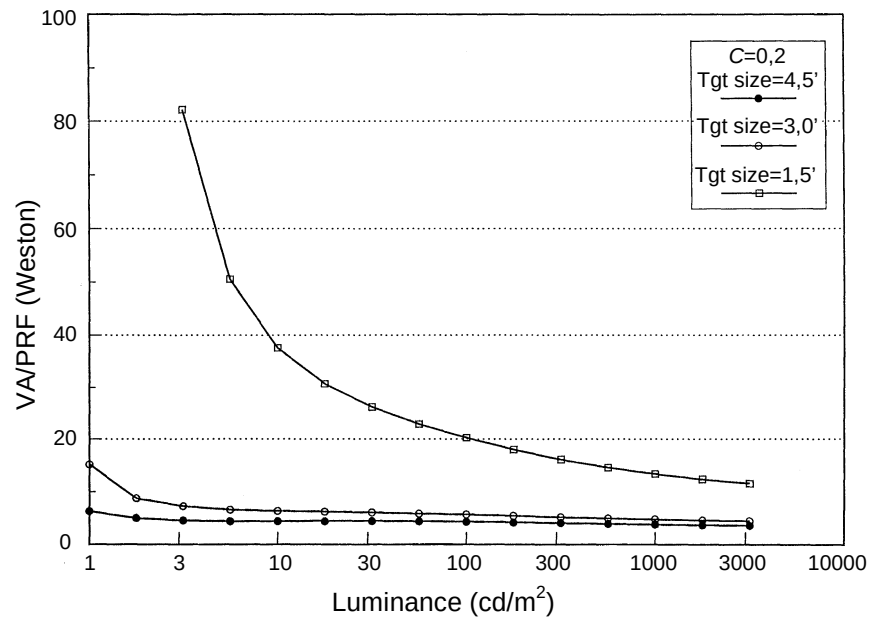


Fig. 5. Ratio of Visual Acuity to Weston's Visual Performance for varying target sizes in minutes with contrast 0,2.

It can be seen from the figures that Weston's Visual Performance is closely correlated with Visual Acuity over a large range of luminance, contrast and target size. The ratio of these two metrics is determined by the size and contrast of the target and varies very little with the background luminance. At low luminance levels, the ratio increases dramatically for small targets of low contrast. This indicates that the target size approaches the physical visual resolution limits of the eye at low luminance levels. Furthermore, it seems to indicate that with low contrast and luminance, VP becomes small possibly due to a presumed increase in time to do the task, while VA is based on constant observation time of 2 s and therefore remains unaffected. In other words, VA here does not contain a variable time component as does VP. This might be the reason for the deviation of the calculated curves in Figs. 4 and 5 from a horizontal line for small target sizes of low contrast.

This assumption is supported by results of extensive reading speed experiments of Bailey, Clear and Berman (Bailey, 1993). They presented charts with unrelated words of different size and contrast of $C = 0,29$; $0,78$ and $0,985$. The effective luminance of the background was expressed as a weighted average over 25% target and 75% surround area. The surround area ranged from 11 cd/m^2 to 5480 cd/m^2 . The height of the letters was expressed in point sizes. One point is $1/100$ of an inch (10 pts equal 2,54 mm). The stroke width was taken to be $1/5$ of the height. This relates to a Visual Acuity of 1 for a 2 pt letter size at a reading distance of 35 cm, if the stroke width is considered as the critical detail. Bailey et al. (Bailey, 1993) reported that the resolution limit was indeed around a letter size of 2 pts. The results from 15 subjects of predominantly young age had been expressed as reading speed in words per second as a function of letter size and contrast. In order to show that the reading time for a word increases dramatically for lower contrast letters and sizes approaching the resolution limit, the data of Bailey et al. had been linearly averaged at each letter size ranging from 2 pts to 20 pts.

In Figure 6, the average data are plotted inversely as reading time per word for the three contrast levels investigated. It becomes evident that above 3 times the threshold level of resolution the reading time is unaffected from size and contrast. For near acuity threshold however, such as letter sizes of 3 pts, the reading time for letters with $0,29$ contrast increases around 5 times and nearly doubles for the contrast of $0,78$ over that obtained with sizes > 10 pts.

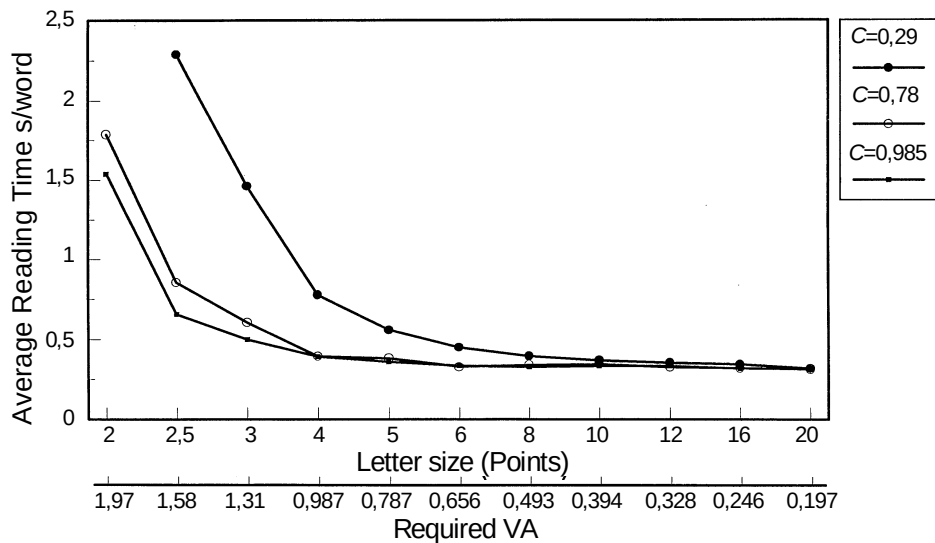


Fig. 6. Average data of reading time per word versus letter size with 0,29; 0,78 and 0,985 contrast from Bailey et al. (Bailey, 1993).

In Figs. 4 and 5, VA is always valid for 2 seconds observation time while the Visual Performance drops, which explains the increase of the curves especially for low contrast levels and smaller targets.

REA'S VISUAL PERFORMANCE MODEL

Rea (Rea, 1986), and later Rea and Ouellette (Rea, 1990), conducted a series of experiments and developed a mathematical model of the results which has allowed for calculation of the Relative Visual Performance (RVP) based on various lighting parameters. They conducted two separate experiments. The first was a numerical verification task (Rea, 1986) in which the subject was required to compare two lists of numbers and detect any inconsistencies. The contrast and the background luminance of the test sheet were varied but the target size was not. Reading speed (time to complete the comparisons of the reference and response number lists) and the number of errors were recorded serving as a measure of Visual Performance. The number of errors in the test was later discarded and only reading speed was used as the measure of performance. They reported that the errors proved to be insignificant in the performance measure.

The second experiment was a reaction time experiment in which the subject responded to the detection of a target, which is projected on a Visual Display Screen (Rea, 1990). This experiment allowed changing the target size as well as luminance and contrast of the target, but did not require the resolution of detail. The low frequency channel (magnocellular channel), however, processes the information of this type of detection, as opposed to the high frequency resolution Weston's studies necessitated.

The models based on these two experiments were compared by Rea and then, after applying some correction factors, claimed to be congruent. A graph showing the two models is presented in Fig. 7. The target size used to calculate the performance based on the reaction time is 4,5'. The target size in the numerical verification task was the angular size of the letter height used in the experiment. The shapes of the curves are not similar and it is difficult to understand the claim of congruency of the two models. The obvious difference of the curves can only be explained by the very different criteria applied. The numerical verification task requires high resolution, while the reaction time experiment does not and is processed by the magnocellular channel.

Rea and Ouellette suggested the model of their reaction time experiments be used to calculate Visual Performance which is different from the "Reading Task Performance".

Rea's model used the retinal illuminance as well as the solid angle of the critical detail to calculate the threshold contrast for a visual task. The difference between the actual contrast and the threshold contrast is then used to describe the visual performance. There are difficulties in using this type of formulation. The first is determining the retinal illuminance. Rea provides a calculation for pupil size for young observers which makes this task simpler. The second difficulty is the calculation of the solid angle. An analysis of the visual task must be performed to determine the critical detail. This is an area of controversy. Rea states that the critical detail of a reading task is determined by the solid angle of the inked area of the letter; while for a Landolt Ring the task is the solid angle of the gap. Most authors use the stroke width of the letter as the critical detail for a reading task as in a visual acuity test. Whatever critical detail is used, the solid angle is complicated to calculate. Rea states that this can be made simpler using a video imaging system to determine the angle.

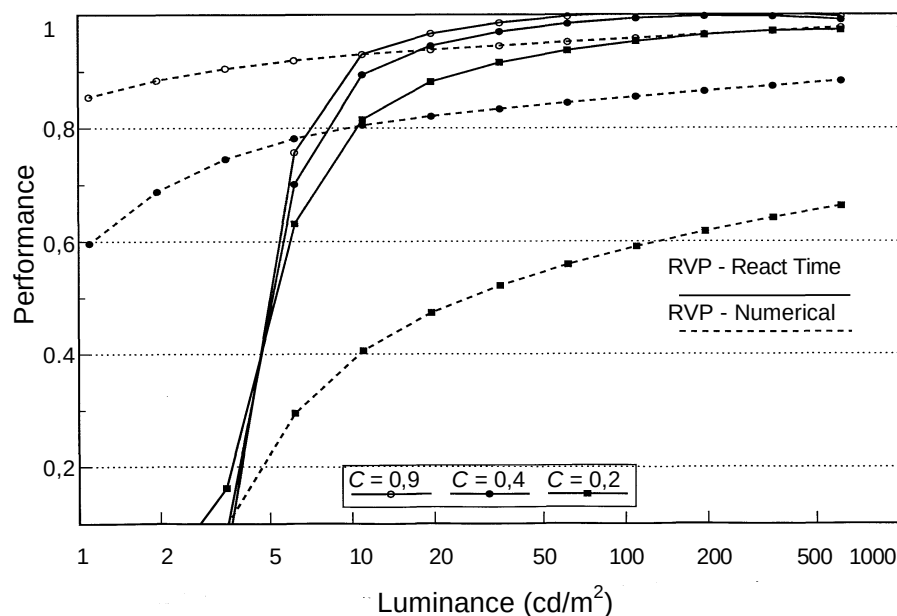


Fig. 7. Computation of the Numerical Verification Task and the Reaction Time models of Rea (Rea, 1986) and Rea and Ouellette (Rea, 1990). Calculated with the algorithms as in References.

THE INFLUENCE OF AGE ON VISUAL PERFORMANCE

With age we observe a change in the ocular media, specifically in the cornea and the crystalline lens. Aside from the decrease in total transmittance of the cornea and more strongly of the lens, the spectral transmission of these media decreases more in the blue part of the spectrum giving a yellowish tint that is most pronounced in the lens. Fig. 8 depicts the spectral transmission at different ages and shows that the major change takes place early in life. The graph is composite of two sets of measurements. The results above 400 nm wavelength are reported by Lerman (Lerman, 1980), however below 400 nm data quoted by Boettner have been used (Boettner, 1967). The measurements referred to in Lerman's book had been obviously falsified by fluorescence in the near UV.

The slight opacity that develops in the lens with age causes increased straylight. A 75 year old eye has approximately 2,5 times more scattered light than that of a 25 year old (Adrian, 1991).

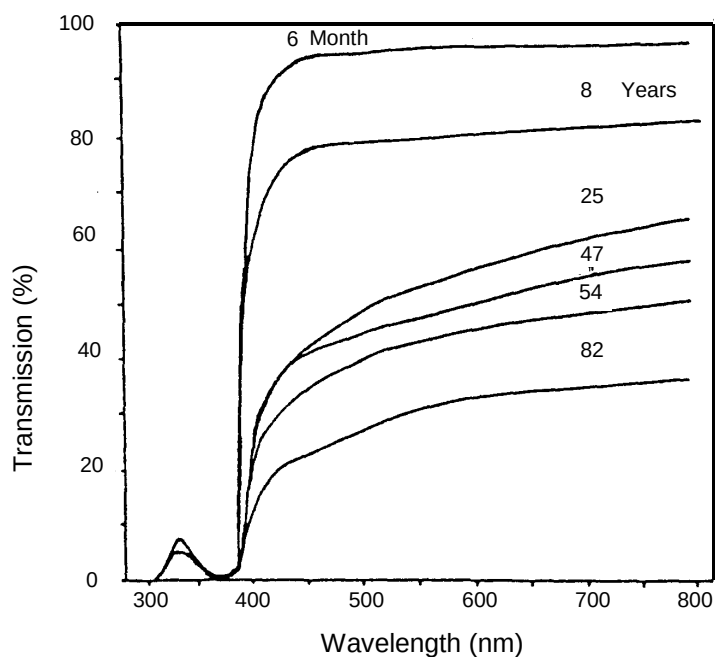


Fig. 8. Spectral transmission of the human lens of different ages according to Lerman and Boettner (Lerman, 1980; Boettner, 1967).

The total ocular transmittance *OMT* measured with “white” light is depicted in Fig. 9. It is based on the transmittance of a 30 year old eye and can be numerically expressed by the equation:

$$OMT = \frac{(Age - 110,2)^2}{69,8} + 7,90 \quad (5)$$

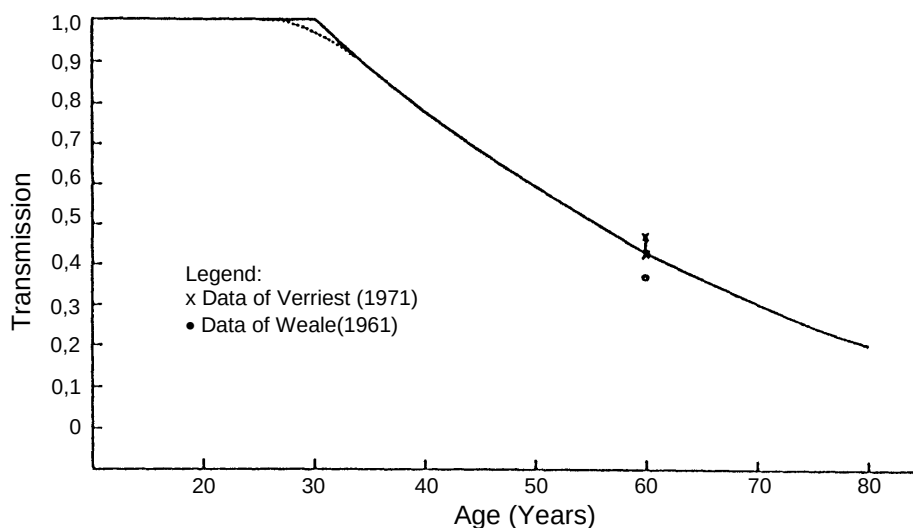


Fig. 9. Total transmittance of the ocular media of the human eye as a function of age.

The function is derived from experimental results of Blackwell (CIE 19.2-1981). It agrees quite well with two data of Weale and Verriest for a 60 year old person.

We read from this figure that an 80 year old eye would have on average only 21% of the total transmission of a 30 year old.