THE INFLUENCE OF THE SPECTRAL POWER DISTRIBUTION FOR EQUAL VISUAL PERFORMANCE IN ROADWAY LIGHTING LEVELS

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Abstract

With decreasing luminance levels the spectral sensitivity of the eye changes and it becomes more blue sensitive. This goes in concert with the fading of colours until, in low levels, we perceive brightness only. It can be expected that the basic visual functions such as Contrast Sensitivity, Visual Acuity and Performance as well as the pupil size are dependent on the perceived brightness and not on the photopic luminance, which in the range of mesopic an scotopic vision is an inappropriate measure as it is based on V(λ) only.

A photometric quantity that accounts for the changing spectral sensitivity of the eye is called the equivalent luminance L_{eq}. An algorithm has been developed to allow for its direct calculation. This equations system permits the evaluation of the above mentioned visual functions on the basis of perceived brightness. The results show that the brightness expressed in terms of L_{eq} indeed controls the visual functions. Consequently, the equivalent luminance L_{eq} for light of different spectral power distributions can be calculated for levels of mesopic vision to show the effect on visual performance. As the spectral sensitivity of the eye is shifting to the blue with lower light levels, blue and blue rich power distribution of the light appear brighter and allow to achieve higher visual performance.

Introduction

In order to investigate visual performance in lower light levels we need an appropriate luminance measure in the range of mesopic vision. The knowledge of the relative spectral sensitivity of the eye in that range called VQ(λ) is imperative. Because of the rod cone interaction which occurs in mesopic vision, the VQ(λ) curves are dependent on the luminous intensity level. Thus, the need arises for an adequate visual evaluation of radiance which results in brightness sensation.

$$L_{eq} = K_{m,L_{eq}} \int L_e V(\lambda, L_{eq}, \varepsilon)\, d\lambda \quad eq.1$$

In 1964 the CIE suggested a set of curves to describe the relative spectral sensitivity of the eye in the range of mesopic vision (1). This set of curves was partially based on data of J.A. Kinney

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obtained for a 2° field on 10° extra foveal location (2). These curves are depicted in Figure 1. They are embraced by the CIE $V(\lambda)_{2°}$ -function and the scotopic $V'(\lambda)$ function. The restrictions involved in that system which the CIE suggested for preliminary use, prompted further research that included the effect of the field size. This was done in 1972 and published in English in 1984 (3). Three young emmetropic observers matched in a bipartite field the brightness of spectral lights to the reference light of 530 nm for illuminance levels ranging from 30 trol to 0.0003 trol in steps of 10 trolands. This was carried out for field sizes of 3°, 9.5° and 64°, which was the limit given by the apparatus. The subjects observed through an artificial pupil of 2 mm diameter. The method and procedure of the investigation is described in more detail in Ref. 3. The resulting data allow to obtain the "equivalent luminance, L_{eq}", that takes the actual spectral sensitivity of the eye into account. L_{eq} reads:

with K_m, photometric equivalent dependent on Leq

L_e, the spectral radiant density

$V(\lambda, L_{eq}, \varepsilon)$ the actual spectral sensitivity of the eye termed VQ_ε

In photopic luminance levels VQ_ε becomes $V(\lambda)$

$VQ_\varepsilon \rightarrow V(\lambda)_\varepsilon$ photopic

in scotopic levels we find good agreement with $V'(\lambda)$

$VQ_\varepsilon \rightarrow V'(\lambda)_\varepsilon$ scotopic

Stiles suggested a $V(\lambda)$ curve obtained with a 10° field based on colour matching functions that was recommended by the CIE for large field photometry (4). The results obtained with the 9.5° field compare very well with Stiles 10° data which indicates, that $V(\lambda)_{10°}$ holds also for brightness matching and correctly describes the large field spectral sensitivity(3).

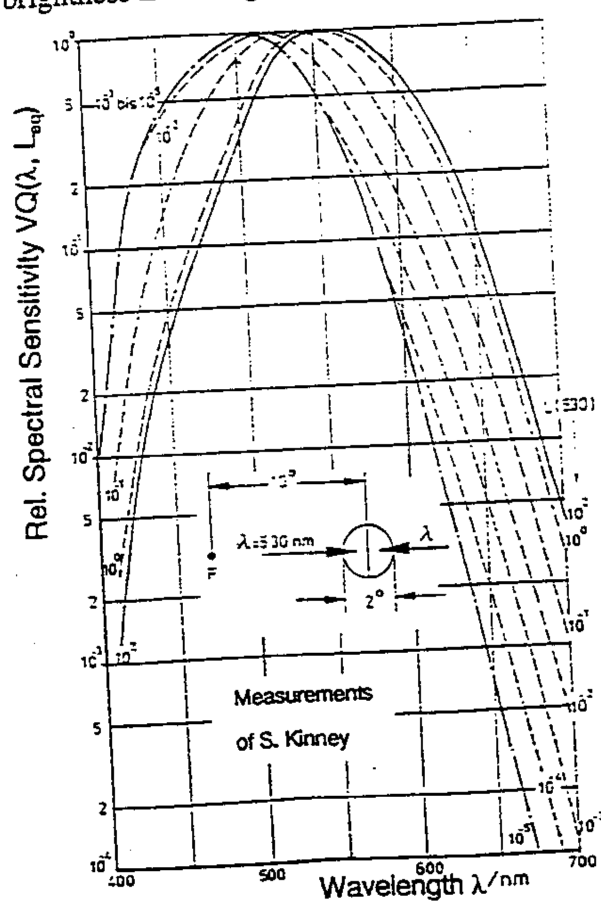

Fig. 1
Relative Spectral Sensitivity $VQ(\lambda, L_{eq})$ as suggested by the CIE in 1963 (1) for preliminary use. The dashed curves are adopted from measurements of S. Kinney (2) using a field of 2° in size at 10° extrafoveal location.

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Development of the model

In order to calculate L_{eq} as a basis to evaluate visual performance it is desirable to use equations that can also be applied to measure the equivalent luminance. An algorithm was developed on the basis of the data reported in Ref. 3. Fig. 1 reveals that the curves can be approximated by parabolae which read in a general form:

$$\log(VQ) = A(\lambda - H)^2 \quad eq.2$$

An analysis of the data for the best fit of the parameter A revealed:

$$A = J\left(1+\left[\frac{\log L + K}{T}\right]^2\right)^{1/2} - MN\left(e^{[10\log L]}\right) \quad eq.3$$

Log is always based on 10. For the parameter H we find:

$$H = \left(\frac{P}{Q + (\log L + R)^2}\right) + S \quad eq.4$$

With equation 3 and 4 inserted into equation 2, we obtain the following expression termed Model 1:

$$\log VQ_\varepsilon(\lambda, L) = \left[J\left(1+\left[\frac{\log L + K}{T}\right]^2\right)^{\frac{1}{2}} - M\,N\left(e^{10\log L}\right)\right] \times \left(\lambda - \left[\frac{P}{Q + (\log L + R)^2} + S\right]\right)^2 \quad eq.5$$

where

	ε = 3°	9.5°	ε= 64°
J	2.902E-10	7.578-06	9.914E-09
K	1.840E+00	2.171+00	2.049+00
T	3.692E-05	7.787-02	9.196E-04
M	1.607E-04	1.5479-04	1.474E-04
N	4.569E-12	1.8805-12	-1.386E-13
P	3.029E+02	1.558+02	1.017E+02
Q	5.118E+00	2.7976+00	1.858E+00
R	-1.188E+00	-1.79765+00	-1.188E+00
S	4.975E+02	4.98807+02	4.988E+02

In order to improve the model especially to render the fitting less dependent on the field size, a "window function" can be superimposed leading to slight modification of the model. (Model 2).

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The Model describes the set of data of which some samples are shown in Fig. 2 and 3. These are typical examples out of a set of 18 following from six luminance levels and 3 field sizes. Larger deviations occur, generally in regions of sensitivity smaller than 10%.

Basic Visual functions and Leq.

The Contrast Sensitivity

The relative contrast sensitivity RCS based on 550 nm wavelength at 1cd/m^2 is shown in Fig. 4 for six narrow band spectral lights ranging from 431 nm to 660 nm, measured over 3 decades of background luminance. The curves diverge towards lower levels of L_b with the sensitivity highest in blue and lowest in red.

The reason for this effect is that lights of 431 nm dominant wavelength are perceived much brighter at 0.01 cd/m^2 luminance than for example red of 660 nm. It is clear that RCS is decreasing in concert with longer wavelength of the spectral lights.

The relative contrast sensitivity, however, is found the same for all spectral lights when plotted versus the equivalent luminance L_{eq} that reflects the *perceived brightness*. The data points for RCS fall around one curve that is close to that for ~530 nm as shown in Figure 5.

The Visual Acuity

I measured the Visual Acuity using Landolt rings of high contrast (C = .92) of my own eye that was set in the state of Cycloplegia and was corrected for longitudinal chromatic aberration. (5) The investigation ranged over 2 decades of luminance below 10 asb (3.18 cd/m^2). The used small-band interference filters did not allow to produce higher levels. In Fig. 6 the average out of 4 sessions are shown for the four spectral lights used. In this graph we observe that for L_b = 10 asb the acuity was found the highest with 587 nm (yellow), the same in light of 618 nm (red) and 519 nm (bluish-green) and the lowest in blue of 473 nm. in low levels of luminance L_b this trend is reversed and the blue and bluish-green spectral lights yield higher values of visual resolution than yellow and red. Again this is attributable to the lower brightness that lights of longer wavelength produce at the same luminance level in the mesopic range. This is clear from Fig. 7 where the same data points as in Fig. 6 are plotted versus L_{eq}. The straight lines become parallel reflecting that the resolution of the eye decreases with L_{eq} for every spectral light with the same slope. Confirming control measurements had been performed for the points VA = 0.35. For three wavelengths the necessary luminance levels had been sought which yielded VA = 0.35. The results are entered in the graph and fit the lines well.

Moreover, it is evident that in all levels of Leq the visual resolution in blue is the lowest, it reaches a maximum at 587 nm and drops again at 618 nm but not down to values obtained with 473 nm.

The reasons for that may be found in the density of S, M and L cones. Myopia did not occur, as the cycloplegic eye had been corrected for that. The minification due to the used minus lenses had been accounted for. Diffraction effects on the pupil fringe especially in the red portion of the spectrum had been very small due to the large pupil that occurs in cycloplegia and had no limiting effect on the resolution. The graph shows that the visual resolution in the long wavelength part of the spectrum is higher, than in the shorter spectral region. This is in all likelihood due to the considerably greater receptor density formed by M and L cones.

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The pupil size

Similar consideration can be given to the pupil size in the mesopic range. The apparent pupil size has been measured at five different wavelength spread over the spectrum in "Ganzfeld" observations. (6) The average of different readings gained from several sessions of the authors eye (35 years at the time) are shown in Figure 8. In near photopic luminance levels, (6 to 20 cd/m^2) the pupil diameter is found to be equal for all wavelengths of light except for 473 nm where smaller pupils are resulting if the luminance measurement is based on $V(\lambda)_2$. It appears that the pupil mechanisms has a higher blue sensitivity than $V(\lambda)_2$ predicts. This is often attributed to rod intrusion, although rods contribute minimally in levels around 30 asb or ~10 cd/m^2 and above. The deviation disappears when large field photometry is used (10° field) which describes the spectral sensitivity of the eye in "Ganzfeld" condition more appropriately. The higher blue sensitivity has a simple explanation rooted in the fact that for photopic photometry the $V(\lambda)$ curve is used to reflect the spectral sensitivity of the light adapted eye. The $V(\lambda)$ function is based on a 2° field size in which the comparison with a reference field of equal brightness or minimum flicker is executed. The pupil size however, is measured with the eye exposed to a large field e.g. ≥ 10° in which we obtain a different spectral sensitivity as indicated in Fig. 10. It shows the $V(\lambda)$ curve obtained with a 2° field size as used in the definition of photopic luminance. For a larger field of 10° follows a curve that shows a distinct deviation in the blue part of the spectrum. The occurring difference can be fully attributed to the absorption of the Macular Pigment that covers the foveal region and does not affect the measurements taken in a larger field extending beyond the macular region (3). This implies that we have to measure the luminance using the V10° (λ) function (large field photometry) to properly interpret the pupil response that was obtained in a large field. The luminance as defined on the basis of $V(\lambda)_{2°}$ would be inappropriate for evaluation of the pupil response under "Ganzfeld" conditions.

However, the differences in pupil size in mesopic levels as in Figure 8 disappear if pupil diameters are plotted versus the equivalent luminance Leq as Figure 9 reveals. This shows that the perceived brightness controls the pupil size.

The pupil size plays an important role for Visual Acuity that is affected by optical aberrations in the eye. Atchison, Smith and Efron showed that for the corrected eye, Visual Acuity measured with high contrast optotypes at a chart luminance of 120 cd/m^2 was the highest for pupils between 2 to 3 mm (11). For larger pupils VA decreases due to higher spherical aberration. VA drops towards smaller pupils due to increased diffraction on the pupil fringe.

Visual Performance

Loe and Waters (7) investigated visual performance in lights of different power distributions. They applied a method similar to that used by H.C. Weston 1945. The subjects had to read a chart of Landolt rings of different contrast and size. Visual Performance VP was expressed as the number of the correctly identified ring gaps to the total number of rings read and the speed with which the reading was performed.

This criterion represents a high resolution task and the necessary time to do it, and covers truly visual tasks as occurring in most of our visual activities and visual demands in photopic vision. Loe and Waters performed the experiments in light of five different power distribution of practical lamps. The results are supported by findings of Halonen(9) who employed a similar

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criterion, and Vrabel et al.(10) using a test also containing accuracy and the time to complete it. Vrabel et al. used targets of low and high contrast (C = .24 and C = 0.9) in luminance levels of ~150 cd/m^2 from five different light sources with dissimilar spectral power distributions. The luminance level L was clearly photopic. Halonen varied L between 155 and 310 cd/m^2 finding also no significant difference of performance.

These findings resemble the contrast sensitivity function as in Figure 4 that showed no significant differences between the spectral lights used in photopic luminance levels. The near monochromatic lights had a more pronounced spectral diversity than those from different lamps. Nonetheless, we may expect, however, the visual performance to change for dissimilar spectral power distributions such as that of sodium low pressure and metal halide lamps in low luminance levels.

The experiments of A. Lewis on performance

Lewis (12) investigated different aspects of visual performance under light of Tungsten, low and high pressure Sodium, Mercury high pressure and Metal halide lamps, lamps that show distinctly different spectral power distributions. Five emmetropic and trained subjects between 20 and 23 years participated in measurements of contrast sensitivity and reaction time using square wave gratings. The luminance ranged from 0.1 to 10 cd/m^2. The findings were in line with Fig. 4 and 6 reflecting that dominantly blue light appears brighter in lower luminance levels and therefore leads to higher contrast sensitivity and visual acuity.

In order to compare different spectral light distributions with regard to their apparent brightness in lower luminance levels, the ratio of the equivalent luminance L_{eq} and the photopic luminance L has been plotted in Fig. 11. This was done for five different light sources over the luminance ranging from photopic to scotopic levels. The ratio L_{eq}/L was termed "Figure of Merit" as it shows the advantage or shortcoming of a spectral light distribution over the others. The higher the figure of merit, the higher will be the achievable Visual Performance. Figure 11 is based on illuminant A (2860K). As Lewis has based his results on Tungsten as reference which has approximately that Color temperature. The data L_{eq}/L are contained in Table 1. With decreasing luminance, which entails the shifting of the spectral sensitivity of the eye towards shorter wavelength, the figure of merit increases for lights containing more blue over those with more reddish components such as High pressure and especially low pressure sodium lamps.

The data of the relative contrast sensitivity, the reciprocal of the reported thresholds holding for all spatial frequencies (0.5, 1, 3 and 10 cpd), was measured in Metal Halide and are plotted in Fig. 12 together with the figure of merit. Although deviations have to be expected, that data confirmed the calculated function. The same applies to the graph in Fig. 13 in which the same relationship for low pressure sodium (LPS) is given. For LPS–light the figure of merit decreases with lower luminance. The data are summarized in Table 2.

While the course of the contrast sensitivity (1/Threshold) as in Fig. 12 and 13 could be expected according to Fig. 11, there was a surprising discrepancy found in Mercury High Pressure as Fig. 14 reveals. The calculated curve decreased for lower luminance levels while the data reported by Lewis showed an upward trend. The origin of the discrepancy was finally found in the different spectra of the HPM lamp. The original calculation was done using a spectrum measured by Osram-Sylvania depicted in the upper part of Figure 15. Below is the spectrum of the lamp used by Lewis in his experiments. It has been obviously an irregular lamp sold as a "Barn Lamp" of

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60 watt. The calculation of L_{eq} has been repeated with the spectrum of that lamp as in the lower part of Fig. 15. Indeed Lewis' data points fell around the calculated curve based on the "Barn Lamp" Spectrum. The data are contained in Table 3. This investigation resembling a "double blind" experiment confirms once more that L_{eq} reflecting the perceived brightness of the lights determines visual functions such as contrast sensitivity.

In a second set of experiments the reaction time after onset of a rectangular grating at a level of 5 times over the threshold contrast was measured. The observer had to correctly identify the orientation (horizontal or vertical) of the grating. The subjects triggered the onset by pressing a button. As the criterion has been the time in milliseconds that could not be associated to luminance it appeared reasonable to form the ratio of the speed of detection 1/Reaction Time resulting in Metal Halide and Low Pressure Sodium Light in which differences were most pronounced. This was compared to the ratio of the "Figure of Merit" in those lights. Fig. 16 shows the resulting graph. It expresses the difference in achievable speed of reactions. The graph confirms the trend of the Visual Performance, that was expressed by a criterion comprising Form Perception and time.

Further experiments are described that incorporate the time needed to perform a so-called "Realistic Task". In a transparency a photograph was presented depicting a woman standing on the side of a road, once facing the road and once turning her face away from the observer. The task was to correctly identify which way the woman was facing. In order to show the difference between the results obtained in Metal Halide and Sodium low pressure, the ratio between the figures of merit and the detection speed has been plotted similar to Fig. 16 and is shown as Figure 17. The data confirm that visual performance of the chosen "Realistic Task" is equally related to the perceived brightness the spectral light distributions produces.

Search for SPD to Improve Visual Performance

In Figure 11 the "Figure of Merit" is depicted for 5 typical lamps showing that the blue-content in the spectrum increases the brightness perceived in mesopic light levels. The question arises, what spectrum of practical lamps would produce even higher L_{eq}/L ratios. Investigating these questions led to Fluorescent lamps of "Daylight" type. A calculation of that type of spectrum was done and compared with the four discharge lamps as used in the described experiments. Figure 18 shows the results of such a calculation. Daylight fluorescent lamps have a spectrum that yield high L_{eq}/L ratios, presumably due to the continuum in the blue superimposed by bands that does not occur in high pressure discharge lamps without coating.

Conclusion

It has been shown that the basic visual functions such as contrast sensitivity, visual acuity (resolution of detail) and visual performance that appears to be a composite of visual acuity and time required for the task are determined by the perceived brightness in which these functions are measured. In photopic levels the brightness is expressed by luminance. In mesopic and scotopic levels the equivalent luminance reflects the perceived brightness and appears to be the physiologically reasonable and appropriate measure. The results suggest that the equivalent luminance L_{eq} is suitable to predict the achievable level of visual performance in various spectral light distributions.

In the Tables 4 to 6 the results of the figure of merit for each distribution as a function of the mesopic luminance levels are condensed. It reads that the Metal Halide Lamps achieve the

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highest figure of merit. However, this is offset by the efficacy of the Lamps, so that the lowest performer, the Low Pressure Sodium Lamp, appears to be even with the Metal Halide at levels around $10^{-1} cd/m^2$.

References

1. Commission Internationale d'Eclairage. Compte Rendue. quinzieme session. Paris, Juin, 1963. CIE Publication no 11B. 1964:209-20. Vienna: Bureau Central de la Commission.

2. Kinney, JAS. Comparison of scotopic, mesopic and photopic spectral sensitivity curves. J Opt Soc Am 1958; 48:185-90.

3. Kokoschka, S., Adrian, W. Influence of field size on the Spectral Sensitivity of the Eye in the Photopic and Mesopic Range. Amer. Journ. Optom. and Physiol. Optics. Vol. 62(1984): 119-26.

4. International Commission on Illumination. Principles of Light Measurements. Publication no 18 (E-1.2). Commission Internationale d' l'Eclairage, 1979, Vienna: Bureau Central de la Commission.

5. Adrian, W. Neuere Untersuchungen der spektralen Sehschärfe und ihre Bedeutung für das Farbensehen. Farbe, Tagungsband Luzern 1965; 187-202.

6. Adrian, W. Pupil size and Wavelength of light of equivalent luminance. In: Colour 79: Proceedings of the 1st International Colour Association (AIC) Congress, Stockholm, 1969. Göttingen: Muster-Schmidt Verlag, 1970: 181-7.

7. Loe, D.L., Waters, I.M. Visual performance in illuminating of differing spectral quality. Environmental Research Group. University College, London, UK, March 1973.

8. Adrian, W., Gibbons, R. Visual performance and its Metric. Light and Engineering. Vol. 2, Nb. 3, 1994. Allerton Press, New York, pp. 1-34.

9. Halonen, L. Effects of lighting and task parameters on visual acuity and performance. PhD Thesis, Helsinki, University of Technology, 1993, Otakaari Fin-02150 Espoo.

10. Vrabel, P.L., Bernecker, C.A., Mistrick, R.G. Visual performance and visual clarity under electric light sources. JIES, Winter 1995, p. 69-80.

11. Atchison, D.A., Smith, G.,Efron, N. The effect of pupil size on Visual Acuity in Uncorrected and Corrected Myopia. Amer. Journ. Optom. and Physiol. Optics, Vol. 56, No. 1(1979) p. 315-323.

12. Lewis, A.L. Visual performance as a function of spectral power distribution of light sources at luminances used for general outdoor lighting. Report to the LRI, New York, 1995. To be published in JIES Winter 1997.

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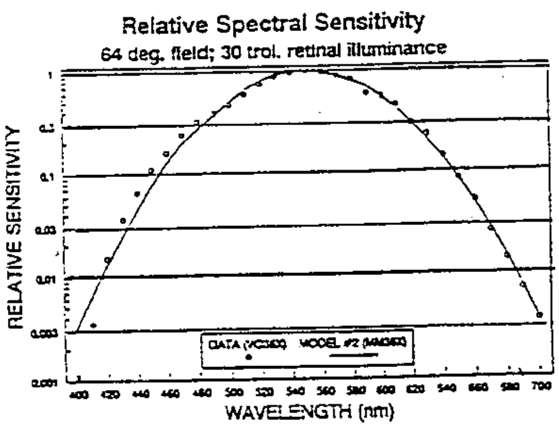

Fig. 2 Relative Spectral Sensitivity for a 64° field of 30 troland calculated using equation 5 (curve) in comparison with measured data (open circles).

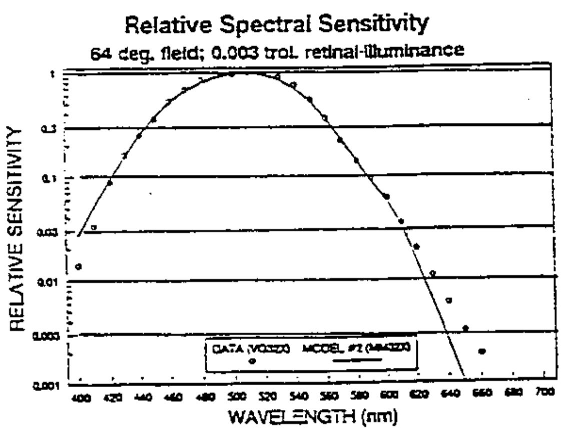

Fig. 3 Relative Spectral Sensitivity as in Figure 2 but for 0.03 troland retinal illumination. The shift of the maximum from 555 nm to around 510 nm becomes obvious.

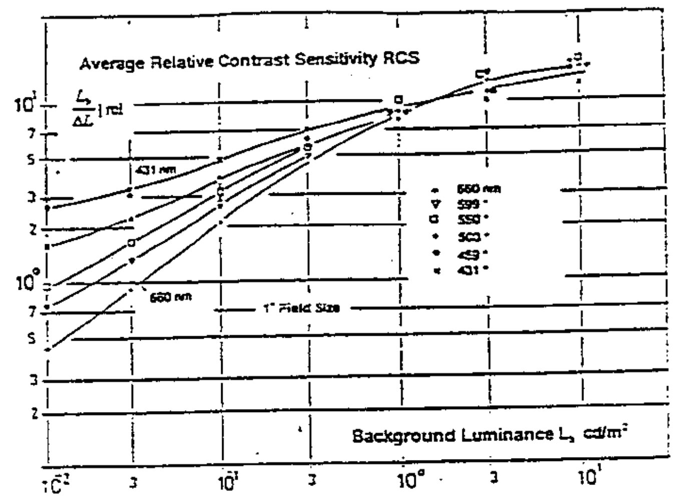

Fig. 4 Contrast Sensitivity for spectral lights of 5 different wavelengths. The measuring field of 1° appeared in a surfield of the same light. The curves are based on 550 nm as RCS equals 10 at a background luminance of 1 cd/m².

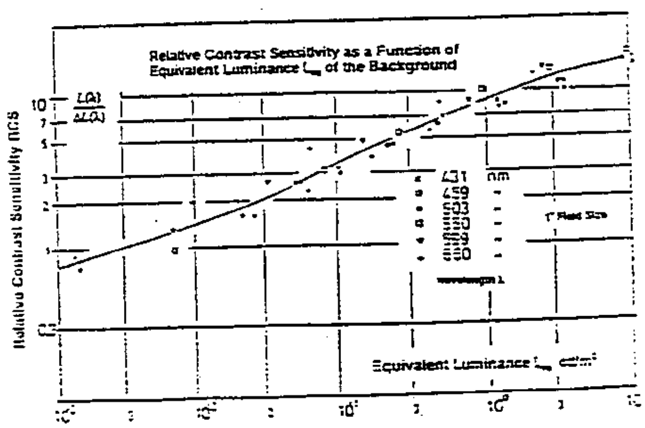

Fig. 5 Contrast Sensitivity RCS as in Fig. 5 but plotted versus the equivalent luminance L. The data points seem to fall around one curve, that indicates that CS is dependent the perceived brightness only.

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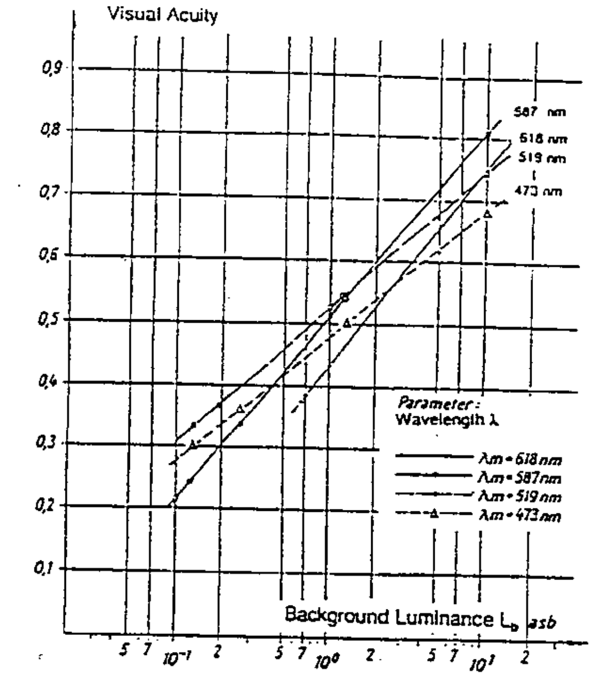
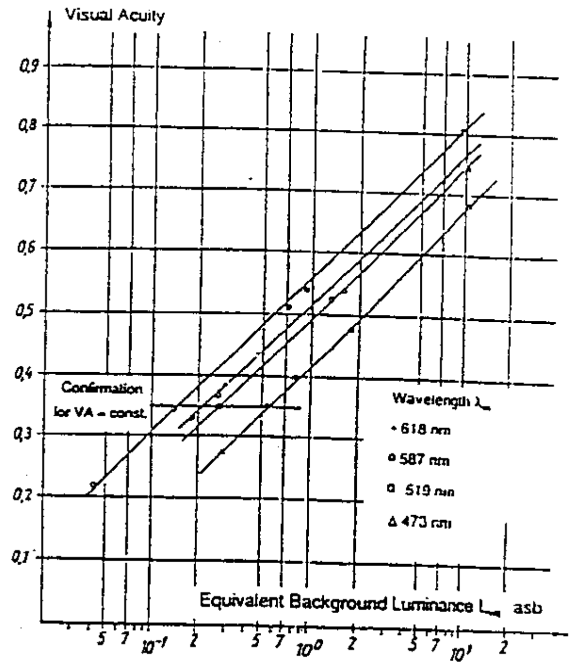


Regression of Visual Acuity Data of Subject Ad. from Different Experimental Sessions with Cycloplegic Eyes Corrected for Chromatic Aberration.

Fig. 6



Regression of Visual Acuity Data of Subject Ad. From Different Experimental Sessions with Cycloplegic Eyes Corrected for Chromatic Aberration as a Function of the Equivalent Luminance of the Background.

Fig. 7

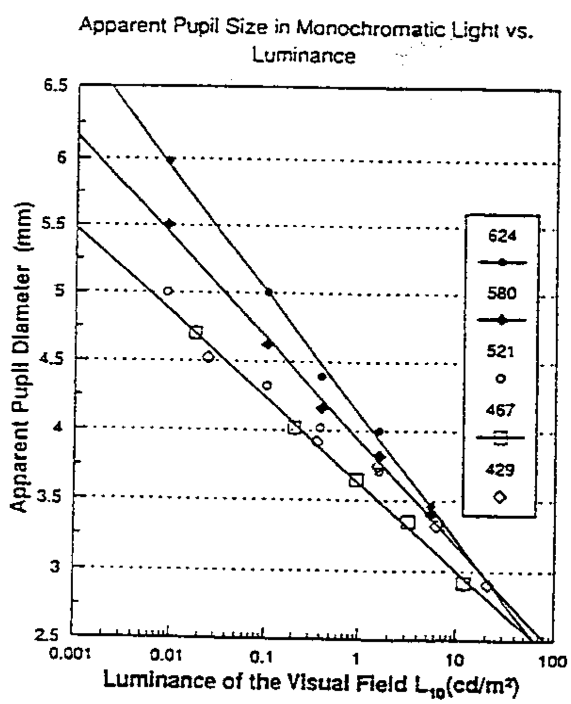


Fig. 8 Data of pupil diameter for Luminance levels using V_{10}-(λ) for six narrow band spectral lights. It can be seen that for increasingly mesopic levels blue produces smaller pupils which does not hold for higher L_{10} levels at the border of the photopic range.

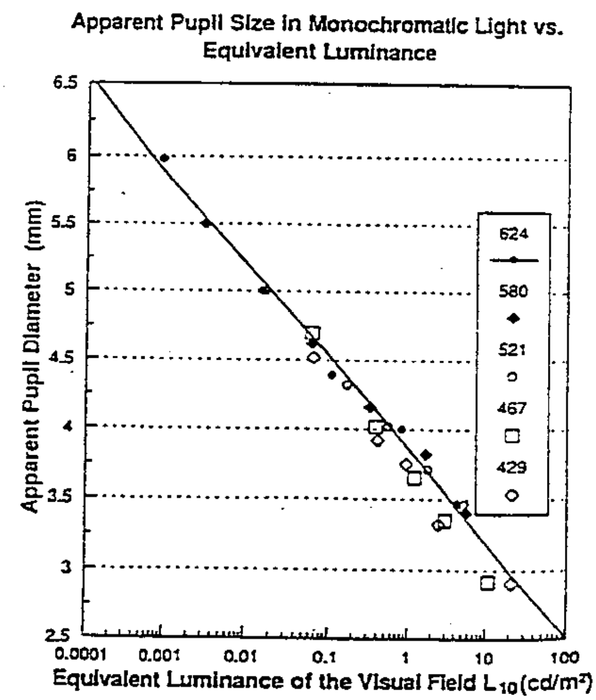


Fig. 9 Data as in Fig. 2 which are plotted versus the equivalent luminance Leq that has been calculated for the six spectral lights throughout the mesopic range. The graph depicts that the pupil size is falling on one line and shows no significant differences with wavelength. This indicates that the 'correlate to perceived brightness, which is Leq, controls the pupil size.

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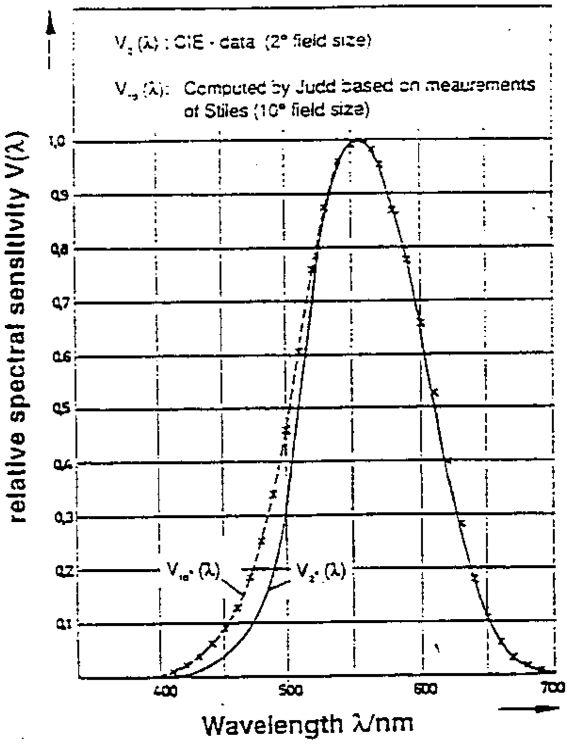

Fig. 10 Relative spectral sensitivity of the eye following from a 2° and 10° field size in which the measurements were done. The $V_2(\lambda)$ reflects the standard observer of the CIE used for the definition of photometric units. The $V_{10}(\lambda)$ as derived by Judd shows good agreement with 9.5° brightness match measurement (Kokoschka, Adrian (81)).

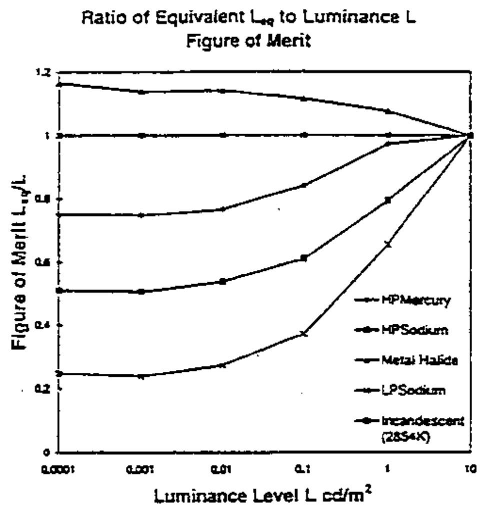

Fig. 11

Ratio of the equivalent luminance L_{eq} to the photopic luminance L for 5 spectral light distributions ranging from photopic to scotopic levels. The calculation is based on illuminant A (2854 K) that resembles. Incandescent light. L_{eq}/L is termed "Figure of Merit".

Ratio of Equivalent L_{eq} to Luminance L
Figure of Merit

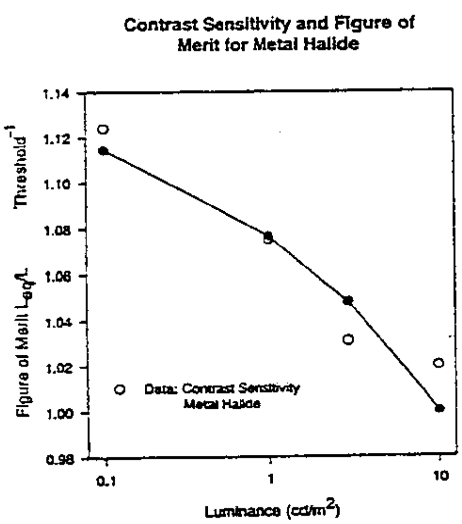

Fig. 12 Comparison of the calculated figure of merit L_{eq}/L with data of contrast sensitivity measured with square wave gratings of 0.5, 1, 3 and 10 cycles per degree (Ref. 10). In light of Metal Halide lamps.

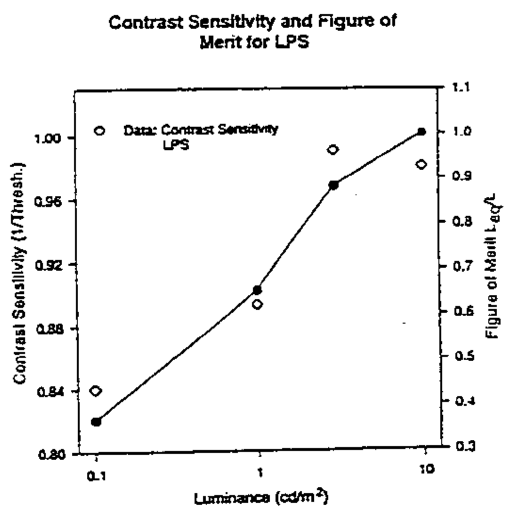

Fig. 13 Comparison of measured contrast sensitivity as in Fig. 8 but here for light of low pressure Sodium lamps.

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Data Contrast Sensitvity (Square wave grating) in HPM - Lewis compared with HPM - Osram

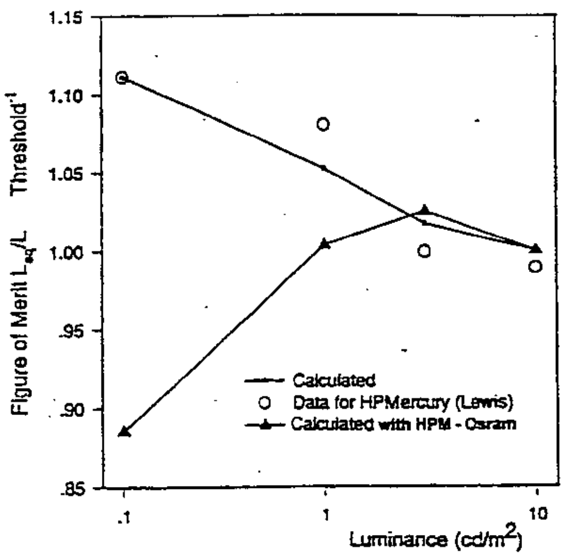

Fig. 14 The spectral power distribution of a 50 watt HPM lamp as used by Lewis differs considerably from the distribution as obtained from a 400 Watt HPM (source Osram – Sylvania). The contrast sensitivity measured with square wave gratings of 0.5, 1, 3 and 10 cycles per degree would show appropriate tendency from HPM – light of a 400 Watt lamp. However with the light used in the experiments good correlation between L_{eq}/L and contrast sensitivity (1/Threshold) can be observed.

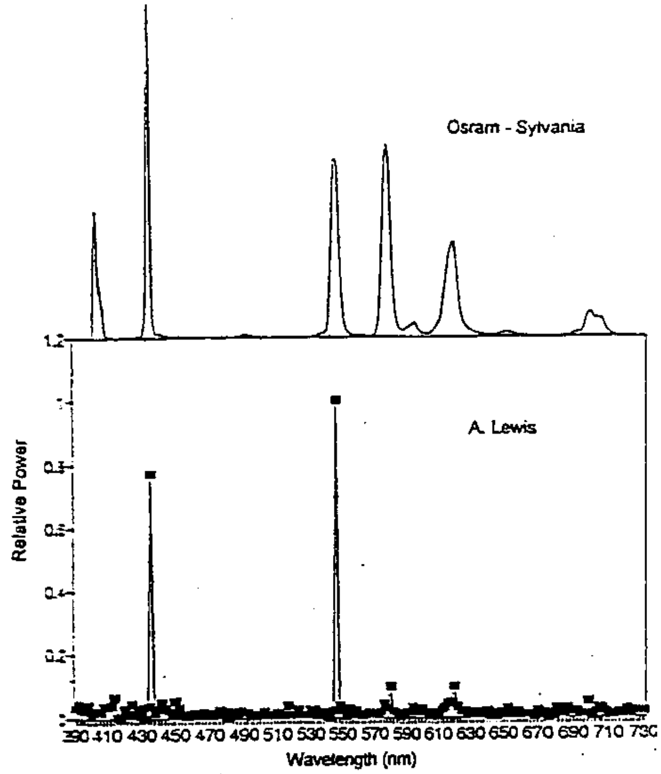

Fig. 15 Comparison of measurements of the spectral light distribution for mercury high pressure lamps between Osram - Sylvania and the lamp used by A. Lewis. The discrepancy accounts for the difference in performance.

Ratio of Speed of Reaction to Detect the Orientation of a Grating compared with Figure of Merit Ratio MH/LPS.

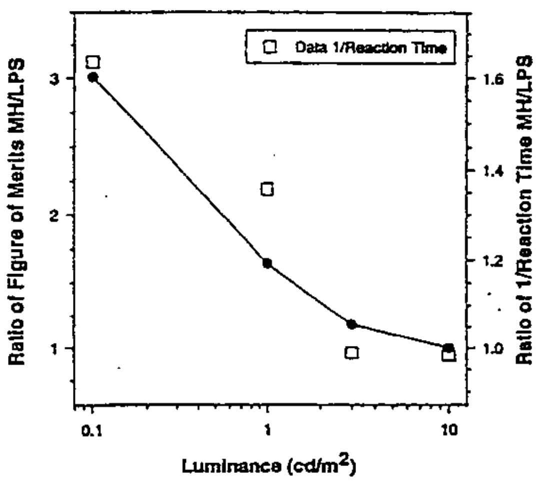

Fig. 16 Reaction time RT to detect the orientation of a square wave grating (horizontal or vertical) with a Viability level of 5. The ratio 1/RT for Metal Halide to 1/RT for sodium low pressure light is compared with Ratio of the Figure of merits for the same spectral light distributions. These two functions are linearly related.

Ratio of Speed of Reaction for a "Realistic Task" and Figure of Merit ratio MH/LPS vs Luminance.

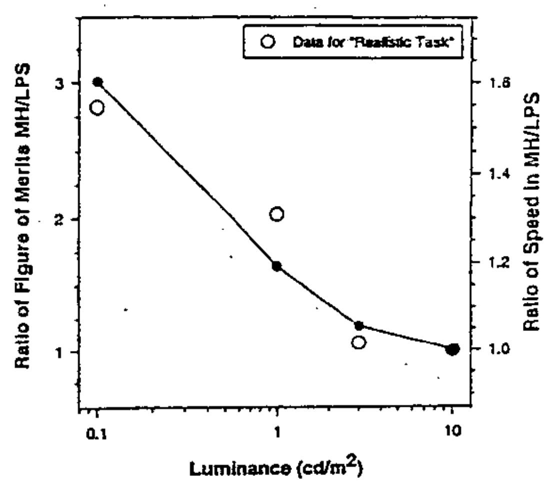

Fig. 17 Ratio of 1/Reaction time for a "realistic task" for Metal Halide MH and Sodium low pressure SLP from Ref. 10 to the ratio of the Figure of Merits for MH and LPS. The data have been related to 1 at 10cd/m^2.

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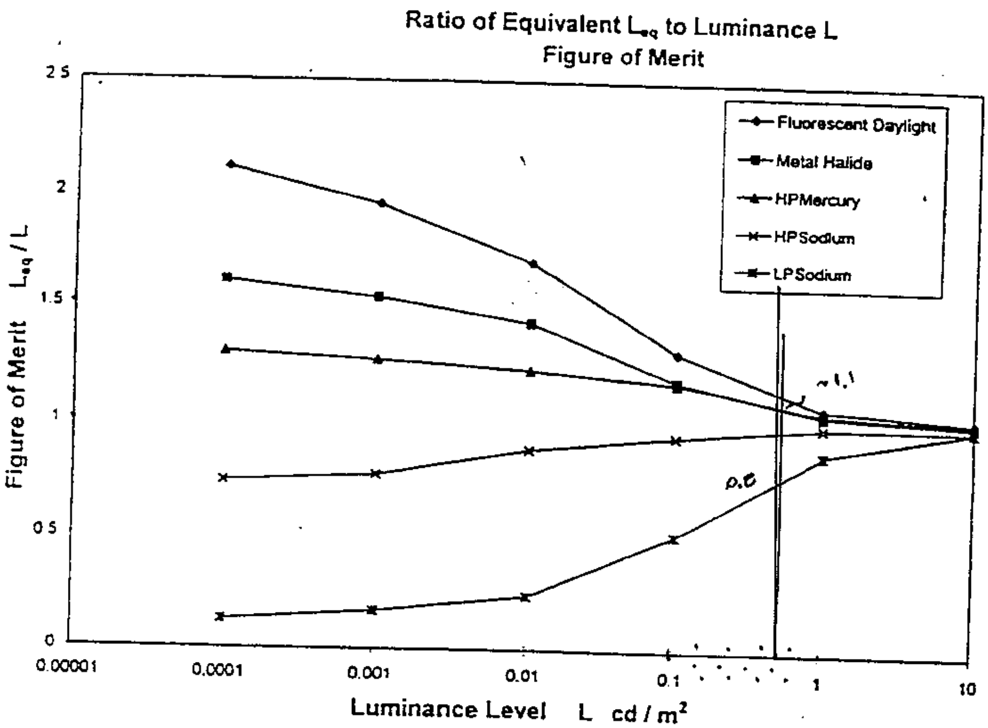

Fig. 18 Calculated ratios L_{eq}/L "Figures of Merit" in mesopic light levels for different spectral power distributions. In this calculation the distribution of Daylight Fluorescent has been incorporated to demonstrate that even higher Figure of Merits can be achieved than those of Metal Halide lamps.

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	HPMercury	HPSodium	Metal Halic	LPSodium	Incandescent (2854K)
0.0001	0.74985	0.510407	1.16566	0.247795	1
0.001	0.747769	0.505582	1.13823	0.237297	1
0.01	0.765898	0.536664	1.141182	0.271988	1 Ref 2850K
0.1	0.839991	0.608905	1.114372	0.370187	1
1	0.972564	0.794267	1.075461	0.655316	1
10	1	1	1	1	1

	HPMercury	HPSodium	Metal Halic	LPSodium	Incandescent (2854K)
0.0001	1.003172	0.682838	1.559455	0.3315	1.33783
0.001	0.978904	0.662694	1.495	0.30996	1.31032 Ref 2050K
0.01	1.004687	0.709678	1.47554	0.633837	1.297888
0.1	1.098677	0.771586	1.3603	0.487753	1.2279
1	1.104187	0.921247	1.2057	0.782552	1.126362
10	1	1	1	1	1

Table 1 Values of ratios Leq/L termed "figure of Merit" for five different Spectral Light distributions based on illuminant A = 2850k, which relates to incandescent and on illuminant. P = 2050 k, the Platinum standard. The distributions follow spectral power measurements of Osram-Sylvania (Salem MA)

	Metal Halide		Low Pressure Sodium	
L c/m²	1/Thresh. data	Figure of Merit Leq/L	1/Thresh data	Figure of Merit Leq/L
0.1	1.124	1.114	0.84	.37017
1	1.075	1.076	0.893	.65531
3	1.031	1.048	0.99	.88262
10	1.02	1	0.98	1

Table 2 Contrast Sensitivity 1/Threshold data obtained with square wave gratings of 0.5, 1, 3 and 10 cycles per degree and the "figures of Merit" Leq/L for Metal Halide and low pressure Sodium Light. Data of Lewis.

Luminances cd/m²	1/Threshold Lewis data	rel. 1/Threshold based on L = .1	HP Mercury Osram Leq/L	HP Mercury Lewis Leq/L
.1	1.09	1.111	.8854	1.111
1	1.06	1.08	1.0034	1.052
3	.98	.9988	1.0246	1.0166
10	.97	.9887	1	1

Table 3 Contrast sensitivity data as 1/Threshold measured with square wave gratings of 0.5, 1, 3 and 10 cycles per degree in light of High pressure Mercury The "Figure of Merit" Leq/L followed from Osram-Sepvania measurements and those from Lewis as in Figure 15.

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Table 4. Neccessary relative lumens of different lamps to achieve equal Visual Performance based on 100/lm at L = 10 cd/m²

L cd/m²	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	3	10
Metal Halide MH	86	88	88	90	93	95	100
High Pressure Mercury HPM	133	134	130	119	103	98	100
High Pressure Sodium HPS	194	198	186	164	126	107	100
Low Pressure Sodium LPS	404	421	367	210	153	113	100

Table 5. Luminous Efficacy of Lamps based on clear 400W type (180 Watt LPS). Typical Time Mean

	Lumen	lm/w	Watt/100 lm
Metal Halide MH 400W	25 000	62.5	1.6
High Pressure Mercury HPM 400W	19 000	47.5	2.1
High Pressure Sodium HPS 400W	45 000	112	0.9
Low Pressure Sodium LPS 180W	27 000	150 *	0.66 *

Source: Philips, Osram Sylvania

*Principally due to a rise in lamp Watts during life.

Table 6. Relative Power in Watts based on 100 lm at 10 cd/m² to achieve equal visual performance. This table is developed with the data in Table 5 and the required lumens for equal viual performance as in Table 4.

L cd/m²	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	3	10
Metal Halide MH	1.38	1.40	1.40	1.44	1.49	1.52	1.6
High Pressure Mercury HPM	2.79	2.81	2.73	2.5	2.16	2.06	2.1
High Pressure Sodium HPS	2.12	1.78	2.03	1.48	1.13	0.96	0.9
Low Pressure Sodium LPS	2.66	2.78	2.42	1.39	1.01	0.75	0.66

The values are relative to the level of 10 cd/m². It is understood that in a scene illuminated with 100 lm at 10 cd/m² it would require only 10^{-2} lumens to produce the level of 0.1 cd/m² if nothing else has changed.

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