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80 YEARS OF $V(\lambda)$ USE: A REVIEW

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ABSTRACT

The photopic spectral luminous efficiency function $V(\lambda)$ has been the basis of all photometry since 1924. For almost as long, the erratic nature of the blue end of the $V(\lambda)$ has been obvious. The reasons which led the researchers of that time to propose the curve, which we presently know as $V(\lambda)$, have remained unknown for many. It is not widely known that most of the photometric measurements to establish the $V(\lambda)$ were actually performed under mesopic adaptation conditions. Subsequently, the $V(\lambda)$ function was a revision of the I.E.S. curve but the details of how the I.E.S. curve was determined have apparently not been preserved. This paper gives an extensive overview on the establishment procedure of the $V(\lambda)$ and highlights the differences in the experimental settings and data of several researchers, whose works contributed to the establishment of $V(\lambda)$.

1. INTRODUCTION

The CIE (1926) introduced the values of the photopic spectral luminous efficiency function $V(\lambda)$ in its 6th session in 1924. At that time, the values of the $V(\lambda)$ function were recommended for general use as provisional only, since it was obvious that they might be incorrect at the extreme regions of the visible spectrum or in special viewing conditions. The values of the $V(\lambda)$, that is to say visibility data, were proposed by Gibson and Tyndall in 1923 as a result of a comparison of their own work with that of their predecessors (Gibson & Tyndall, 1923). The president of U.S. National Committee of the International Commission on Illumination (CIE) had requested the U.S. National Bureau of Standards to make measurements of visibility using the step-by-step equality of brightness method, and the assignment was appointed to Gibson and Tyndall by a committee appointed by the Bureau of Standards.

Gibson and Tyndall undertook the challenge and, in cooperation with the Nela Research Laboratories and under the sponsorship of General Electric Co., made a new determination of visibility of radiant energy by the step-by-step equality of brightness method. In 1923 Gibson and Tyndall published a paper in which they proposed a new visibility curve based on the comparison of their own work to the carefully reviewed experimental visibility data of Coblentz and Emerson (1918), Hyde, Forsythe, and Cady (1918), Ives (1912e), Nutting (1914), Reeves (1918), So (1920) and the average data recommended or adopted by Ives (1919), Priest (1920; 1922a,b), and I.E.S. (Illuminating Engineering Society). The visibility curve, finally proposed by Gibson and Tyndall, was actually a revision of the I.E.S. curve. Unfortunately, the details of how the original I.E.S. curve was determined have not apparently been preserved. According to CIE (1990) Technical Report «*Information does not seem to exist concerning the psychophysical method used, whether observers participated at all wavelengths, the luminance of the reference field, the visual angle subtended by the field, whether the I.E.S. function is the result of a study from one laboratory or multiple laboratories, none of which are identified.*» The authors of the present paper as well as Kaiser (1981) in his work have also unsuccessfully tried to track down the origins of the I.E.S. curve.

The present paper introduces the experimental data and the experimental setups of Coblentz and Emerson, Hyde et al., Ives, Nutting, Reeves, So, and Gibson and Tyndall with further information about the parameters used. Table 1 presents the experimental and extrapolated relative sensitivity values of the seven aforementioned studies and the average data recommended or adopted by Ives (1919), Priest (1920; 1922 a, b), I.E.S. and Gibson and Tyndall (1923). Table 2 summarizes the methods used by the different researchers as well as the experimental parameters and the number and age of the subjects. The experimental parameters are described by the visual angle of the photometric field, the size of the ocular slit or the artificial pupil inserted, the amount of light entering the eye in trolands, natural pupil luminance for the corresponding field size, and the spectral wavelength range measured. The troland and natural pupil luminance values are calculated from the given field illuminance or luminance values and it may become as surprise for many that the calculated values actually lie in the mesopic region. The present paper provides an extensive overview on how the final visibility curve, namely the $V(\lambda)$ curve, was constructed by Gibson and Tyndall, and describes the requirements that Gibson and Tyndall considered that the visibility curve should meet. Finally, the present paper discusses alternative visibility curves that Gibson and Tyndall might have obtained, had they not been guided by the prevailing theories of that time, and how these alternative curves differ from the present $V(\lambda)$ and $V_m(\lambda)$ curves.

2. NATURAL PUPIL LUMINANCE CALCULATIONS

2.1. Troland

In photometric measurements using an ocular slit or an artificial pupil, the value describing the retinal illuminance should be considered rather than the field luminance (Trezona, 1983). The use of an artificial pupil, smaller than the natural pupil, decreases the amount of light entering the retina and makes the photometric field appear dimmer. In calculating the retinal illuminance absorption, scattering and reflection losses as well as the dimensions of the particular eye under consideration should be taken into account (CIE/IEC, 1987). However, as the individual variation in these parameters is small (Trezona, 1983), the retinal illuminance is proportional to the product of the area of the limiting pupil and the luminance of the surface. Consequently, the amount of light entering the eye is described by trolands, which is defined to be equal to the product of the area of the pupil in mm^2 and the luminance in cd/m^2, as follows,

$$e_t = L \times p, \tag{1}$$

where e_t is the amount of light entering the eye in trolands, L is the luminance of the surface in cd/m^2, and p is the pupil area in mm^2.

In the present paper, troland values for each presented study is calculated, whenever it was possible within the given values, in order to enable comparison between the different studies. If the studies reported illuminance value (lx) of the white reference field, rather than the luminance value (cd/m^2), the luminance value was estimated by the present authors assuming a perfectly diffusing and reflecting surface of the photometric field. Consequently, the troland values calculated in the present paper are overestimations rather than underestimations of the absolute values.

2.2. Natural Pupil Luminance

As the troland values are difficult to assess for anyone not used to coping with them, Trezona (1983) defined in her paper a new quantity, natural pupil luminance, as «*the light source to which the observer is adapted, subtending a large angle* (>50°), *viewed with the natural pupil and producing the same retinal illuminance as the source under consideration, which is viewed with an artificial pupil.*» By the definition:

$$\text{Trolands} = L \times p = L_N \times p_N, \tag{2}$$

where L is the luminance of the surface in cd/m^2, and p is the area of the artificial pupil in mm^2, L_N is the natural pupil luminance for a large field, and p_N is the area of the natural pupil. Thus, the natural pupil luminance corresponds to the illumination level, to which the observer is adapted.

Table 1

The experimental visibility data of Coblentz and Emerson (1918), Hyde, Forsythe, and Cady (1918), Ives (1912e), Nutting (1914), Reeves (1918), So (1920) and the average data recommended or adopted by Ives (1919), Priest (1920; 1922a,b), and I.E.S. (Illuminating Engineering Society). Table is a revision of the Table 3 in the paper of Gibson and Tyndall (1923)

Wave length (nm)	Experimental data							Adopted or recommended averages			
	Flicker method					Step-by-step method					
	Ives (1912e)	Nutting (1914)	Coblentz & Emerson (1918)	Reeves (1918)	So (1920)	Hyde, Forsythe & Cady (1918)[1]	Gibson & Tyndall (1923)	Ives (1919)	Priest (1920, 1922a,b)[2]	I.E.S.[3]	Gibson & Tyndall (1923)[4]
400		0.0021	0.01			0.00009	0.005	0.0024		0.0004	**0.0004**
410		0.0036	0.017			0.00062	0.012	0.0032	0.00062	0.0012	**0.0012**
420		0.0065	0.024			0.0041	0.022	0.0096	0.0041	0.004	**0.004**
430		0.0115	0.029			0.0115	0.033	0.018	0.0115	0.0116	**0.0116**
440	0.029	0.022	0.033			0.022	0.043	0.029	0.022	0.023	**0.023**
450	0.047	0.038	0.041			0.036	0.051	0.041	0.036	0.038	**0.038**
460	0.073	0.064	0.056			0.055	0.069	0.058	0.055	0.06	**0.06**
470	0.107	0.101	0.083			0.087	0.103	0.09	0.087	0.091	**0.091**
480	0.154	0.149	0.125			0.138	0.143	0.138	0.138	0.139	**0.139**
490	0.235	0.215	0.194			0.216	0.196	0.215	0.216	0.208	**0.208**
500	0.363	0.314	0.316	0.275	0.312	0.328	0.318	0.341	0.328	0.323	**0.323**
510	0.596	0.456	0.503	0.474	0.455	0.515	0.523	0.493	0.515	0.484	**0.503**
520	0.794	0.646	0.71	0.686	0.683	0.698	0.732	0.638	0.698	0.67	**0.71**
530	0.912	0.815	0.862	0.841	0.848	0.847	0.878	0.795	0.847	0.836	**0.862**
540	0.977	0.925	0.954	0.935	0.952	0.968	0.964	0.919	0.968	0.942	**0.954**
550	1,00000	0.986	0.994	0.993	0.993	0.996	0.998	0.992	0.996	0.993	**0.995**
560	0.99	0.995	0.998	0.985	0.994	0.995	0.991	0.999	0.99	0.996	**0.995**
570	0.948	0.949	0.968	0.935	0.953	0.944	0.947	0.953	0.948	0.952	**0.952**
580	0.875	0.871	0.898	0.836	0.877	0.855	0.863	0.879	0.875	0.87	**0.87**
590	0.763	0.762	0.8	0.71	0.769	0.735	0.754	0.777	0.763	0.757	**0.757**
600	0.635	0.634	0.687	0.58	0.65	0.6	0.634	0.633	0.635	0.631	**0.631**
610	0.509	0.498	0.557	0.446	0.534	0.464	0.511	0.491	0.509	0.503	**0.503**
620	0.387	0.368	0.427	0.319	0.422	0.341	0.389	0.362	0.387	0.38	**0.381**
630	0.272	0.268	0.302	0.214	0.308	0.238	0.279	0.24	0.272	0.262	**0.265**
640	0.175	0.166	0.194	0.14	0.205	0.154	0.184	0.164	0.175	0.17	**0.175**
650	0.104	0.105	0.115		0.113	0.094	0.1125	0.101	0.104	0.103	**0.107**
660	0.063	0.058	0.0645		0.067	0.051	0.0642	0.06	0.051	0.059	**0.061**
670	0.044	0.032	0.0338		0.036	0.026	0.0349	0.038	0.026	0.03	**0.032**
680	0.026	0.016	0.0178		0.02	0.0125	0.0178	0.022	0.0125	0.016	**0.017**
690		0.0081	0.0085			0.0062	0.0092	0.013	0.0062	0.0081	**0.0082**
700		0.0036	0.004			0.0031	0.0045	0.007	0.0031	0.0041	**0.0041**
710			0.00203			0.0015	0.0022		0.0015	0.0021	**0.0021**
720			0.00097			0.00074	0.00108		0.00074	0.001	**0.00105**
730			0.00048			0.00036	0.00051			0.00052	**0.00052**
740			0.00028			0.00018	0.00026			0.00025	**0.00025**
750			0.0002			0.00009	0.00014			0.00012	**0.00012**
760						0.00005	0.00007			0.00006	**0.00006**
770							0.00004				

The values on grey are extrapolated.

[1] The data of Hyde et al. (1918) is based on the experimental data of Hartman (1918) in the wavelength region 400–490 nm, on the experimental data of Hyde et al. (1918) in the wavelenght region 500–660 nm, and on the experimental data of Hyde & Forsythe (1915) in the wavelength region 670–760 nm.

[2] The values of Priest (1920, 1922a,b) are the values of Hyde et al. (1918) in the wavelength region 410–550 nm, the values of Ives (1912) in the wavelength region 560–650 nm, and the values of Hyde et al. (1918) in the wavelength region 660–720 nm.

[3] The values of I.E.S. curve are from the paper of Gibson and Tyndall (1923).

[4] The values proposed by Gibson and Tyndall, presently known as (λ).

Table 2

The methods used by Coblentz and Emerson (1918), Hyde, Forsythe, and Cady (1918), Ives (1912e), Nutting (1914), Reeves (1918), So (1920) as well as the experimental parameters and the number and age of the subjects. The experimental parameters are described by the visual angle of the photometric field, the size of the ocular slit or the artificial pupil inserted, the amount of light entering the eye in trolands, natural pupil luminance for the corresponding field size, and the spectral wavelength range measured

			Photometric field				Subjects	
Author	**Method**	**Viewing**	**Size**	**The amount of light entering the eye in Trolands**	**Natural pupil luminance for corresponding field size (cd/m^2)**	**Spectral wavelength range**	**Number**	**Age**
Ives (1912e)	Flicker method	Ocular slit 0.5 x 2 mm	2°	95 Td	2.095 cd/m^2	481–655 nm	18	18–40
Nutting (1914)	Flicker method	Ocular slit 0.57 x 2.57 mm	2°	163 Td	3.66 cd/m^2	490–640 nm, extension for 5 subjects to 400–700 nm	21	
Coblentz & Emerson (1918)	Flicker method	Ocular slit 0.52 x 2.63 mm	2°	Variable: 22 Td at 490–690 nm 7 Td at 435–490 nm 7 Td at 690–750 nm	Variable: 0.47 cd/m^2 at 490–690 nm 0.146 cd/m^2 at 435–490 nm 0.146 cd/m^2 at 690–750 nm	490–690 nm, extension for about 20 subjects to 435–750 nm	125	19–59 Average 29
Hyde, Forsythe, & Cady (1918)	Step-by-Step equality of brightness matching	Artificial pupil 0.6 mm^2	Lummer-Brodhun 7°	Variable: 29 Td at 560 nm 6 Td at 500 nm 17 Td at 650 nm	Variable: 0.705 cd/m^2 at 560 nm 0.135 cd/m^2 at 500 nm 0.401 cd/m^2 at 650 nm	500–660 nm	29	
Reeves (1918)	Flicker method					490–640 nm	13	
So (1920)	Flicker method		1.5°	Approximately 168 Td	Approximately 3.58 cd/m^2	500–680 nm	20	16–48
Gibson & Tyndall (1923)	Step-by-Step equality of brightness matching	Ocular slit from 0.2 x 1.25 mm to 0.8 x 1.25 mm depending on the wavelength region	3°	Variable: 43 Td at 580 nm 11 Td at 490 nm 9 Td at 680 nm	Variable: 0.97 cd/m^2 at 580 nm 0.24 cd/m^2 at 490 nm 0.195 cd/m^2 at 680 nm	490–680 nm, extension for 38 subjects to 430–740 nm	52	

For field sizes smaller than 50° Trezona presented a modified term, where the information of the field size is included for example as follows «natural pupil luminance (2° field)». In this case the natural pupil diameter d is calculated as a function of the field size θ in degrees and field luminance L in cd/m^2 with the following equation,

$$d = 5 - 3\tanh\left\{\left(0.4 - \frac{0,389}{\theta} + \frac{0.547}{\theta^2}\right) \times (\log_{10} L + 2.989 \log_{10}\theta - 5.076)\right\}. \qquad (3)$$

For small photometric fields it is appropriate to use the above concept of natural pupil luminance. Therefore, in addition to the troland values, the values of natural pupil luminances for the corresponding field size of each study are also calculated in the present paper and presented in Table 2. The calculations ignore the Stiles-Crawford effect since all the photometric fields subtended 2° or more, except in the study of So, and because the natural pupil luminances in all studies were below 10 cd/m^2 which is the cone activity predomination level given by Trezona (1983).

3. EXPERIMENTAL CONDITIONS OF THE STUDIES TO ESTABLISH VISIBILITY DATA

3.1. 1912 Flicker Photometer Data of Ives

Ives (1912e) measured the relative spectral sensitivity of 18 normal observers with the method of flicker photometry. Ives chose the flicker photometer to be the most appropriate method based on his previous studies with a flicker photometer and an equality of brightness photometer (Ives, 1912a). According to Ives, flicker photometry possessed the greatest sensibility and the most reproducible results.

A photometric field of 2° was used with a constant reference field illumination of 300 lx viewed through an ocular slit of 0.5 mm × 2 mm. This procedure yields to troland value of about 95 Td. The small photometric field was surrounded by a bright field of about 25°, maintained approximately at the same brightness. This bright surrounding was used for a greater viewing comfort of the observer, as reported by Ives. The spectral sensitivity of the 18 observers was measured in wavelength region from 481 to 655 nm. From the gained data Ives extrapolated an extension to 440 nm in the blue end and to 680 nm in the red end of the visible spectrum. The average values of the flicker measurements, as well as the extrapolated values, are presented in Table 1.

In 1919 Ives gave a recommendation of the standard conditions of photometric measurements (Ives, 1919). As a result of his previous studies (Ives, 1912 a, b, c, d, e), he recommended the use of a flicker photometer with a photometric field of 2° in diameter and the field brightness of 2.5 millilamberts (equal to 7.96 cd/m^2) for the natural pupil. According to Ives, a great advantage of this choice was that under these conditions the flicker photometer yielded the same results as the method of direct comparison of brightness.

3.2. 1914 Flicker Photometer Data of Nutting

Nutting (1914) determined the values of his visibility curve by measuring the spectral sensitivity of 21 subjects with the method of flicker photometry. The visibility data was obtained for the wavelength region from 490 to 640 nm, and in addition an extension was performed for five observers to cover a larger region of the visible spectrum from 400 to 700 nm. The reference field illuminance of 350 lx was kept constant throughout the measurements. The 2° photometric field was viewed through an ocular slit of 0.57 mm × 2.57 mm. These settings correspond to troland value of about 163 Td.

Nutting apparently revised his visibility data, and the revised values were published in the paper of Hyde et al. in 1918 (Hyde et al., 1918). However, the paper of Hyde et al. does not provide any information on why or how the revision of the Nutting's data was calculated. In all likelihood, the revised data of the Nutting's visibility curve was furnished to Hyde et al. by Nutting in person, with no written document preserved. In 1920 Nutting published the same revised visibility data in his 1919 Report of Standards Committee on Visual Sensitometry (Nutting, 1920) with, again, no reference on how the revised values were calculated. The revised values of Nutting data are presented in

Table 1, as these were the values reviewed by Gibson and Tyndall in 1923.

3.3. 1918 Flicker Photometer Data of Coblentz and Emerson

The objective of the work of Coblentz and Emerson (1918) was the determination of the visibility curve, with the method of flicker photometry, based upon a large group of observers. The total number of observers was 130, of which 7 were known to be partially or totally color blind. Coblentz and Emerson used primarily the method of flicker photometry, but also the equality of brightness method was used at five wavelengths in order to determine whether there was a systematic difference in measurements made by these two methods. However, since the majority of the observers were not able to make accurate settings with the equality of brightness photometer, Coblentz and Emerson concluded that the data did not appear to provide convincing evidence that the visibility curves determined with these two methods differed from each other.

The flicker measurements were made using a 2° photometric field viewed through an ocular slit of 0.52 mm × 2.63 mm. The reference field illuminance was kept constant at 50 lx in the wavelength region from 490 to 690 nm, which corresponds to about 22 trolands. For approximately 20 observers the measurements were extended to 750 nm in the red end and to about 435 nm in the blue end of the visible spectrum. This was accomplished by reducing the reference field illuminance to 15 lx, which equals to about 7 trolands.

The final visibility curve values of Coblentz and Emerson were proposed for wavelength region from 400 nm to 750 nm, being based on flicker data of 125 observers, two of which were partially color blind. These values are presented in Table 1.

3.4. 1918 Step-by-Step Equality of Brightness Data of Hyde, Forsythe, and Cady

In 1918 Hyde, Forsythe, and Cady measured the relative spectral sensitivity of 29 observers with the step-by-step equality of brightness method (Hyde et al., 1918). They used a Lummer-Brodhun photometric field of 7° and the measurements were made at 18 different wavelengths distributed at approximately equal intervals from 500 nm to 660 nm, which was the range of wavelengths studied. No attempt was made to keep the illuminance of the reference field constant, so the brightness of the reference field varied substantially. Hyde et al. assumed that the brightness of the reference field corresponded approximately to illuminances of 30 lx at 500 nm, 150 lx at 560 nm, and 90 lx at 650 nm. Since an artificial pupil of 0.6 mm^2 was employed, these illuminance values give troland values of 6, 29, and 17 Td, respectively.

The step-by-step measurements of Hyde et al. covered only the central region of the visible spectrum from 500 to 660 nm. To expand their visibility data to cover a major region of the visible spectrum, they decided to choose the data of Hyde and Forsythe (1915) to represent the red end of the spectrum from 670 to 760 nm and the data of Hartman (1918) to represent the blue end of the spectrum from 400 to 490 nm. This combination of three different data sets necessitated a slight change of the Hyde et al. values at 650 and 660 nm. As a result of combining the visibility data of the three different studies, Hyde et al. provided relative visibility data covering practically the entire visible spectrum from 400 to 760 nm. The values of the visibility curve proposed by Hyde et al. are presented in Table 1.

3.5. 1918 Flicker Photometer Data of Reeves

Reeves (1918) used the method of flicker photometry in measuring the spectral sensitivity of 13 observers. The measured wavelength region extended from 490 to 640 nm and the reference field illuminance had a constant value of 140 lx throughout the investigated spectral region. The photometric field was viewed through an artificial pupil, but the original paper of Reeves does not provide the information about the sizes of either the photometric field or the artificial pupil. Consequently, it is not possible to calculate the troland values. However, if we assume that the size of the artificial pupil was of the same size as used in the other studies of that time, we can calculate indicative troland value for the study of Reeves. The average artificial pupil area that was used in the studies of Ives, Nutting, Coblentz and Emerson, Hyde et al., and Gibson and Tyndall is very close to

1 mm^2, which would give an indicative troland value of about 45 Td for the study of Reeves. However, it is advisable to consider this value only as an estimate of the actual value.

The data of Reeves was revised by Hyde et al. (1918) to the same basis of energy-distribution for the acetylene flame as that employed by Nutting in his final corrected values. The values of the Reeves' visibility curve, revised by Hyde et al., are presented in Table 1, as these were the values reviewed by Gibson and Tyndall in 1923.

3.6. 1920 Flicker Photometer Data of So

An interesting contribution to the visibility data of several American subjects was given by the Japanese researcher So (1920). So measured the visibility data of 20 Japanese subjects with the flicker photometry method. He used a photometric field of 1.5° viewed through an ocular slit, the size of which was not reported. However, according to So, the natural pupil illuminance was adjusted to 50 lx which corresponds to approximately 168 trolands. The measured visibility data of So covered the spectral wavelength region from 500 to 680 nm.

The values of the visibility curve determined by So are presented in Table 1. Ethnological differences between the American and Japanese subjects appear to have no significant effect on the character of the visibility curve.

3.7. 1923 Step-by-Step Equality of Brightness Matching Data of Gibson and Tyndall

In 1923 Dr. Hyde, as the president of U.S. National Committee of the International Commission on Illumination CIE, requested the U.S. Bureau of Standards to make further measurement of visibility using the step-by-step equality of brightness method (Gibson & Tyndall, 1923). The step-by-step measurement in particular was requested in view of the fact that only one reliable and extensive investigation of visibility had been made using the step-by-step equality of brightness method by Hyde et al. as against several using the flicker method. The director of the Bureau of Standards appointed a committee consisting of Messrs. Skinner, Crittenden, and Priest, who advised Gibson and Tyndall (Gibson & Tyndall, 1923).

The measurements of Gibson and Tyndall (1923) were made for 52 observers in wavelength region from 490 to 680 nm, and for 38 of these observers the measurements were extended to include wavelength region from 430 to 740 nm. The luminance of the reference field varied with different wavelengths, the maximum field luminance being 170 cd/m^2 at 580 nm. The reference field luminance decreased to the edges of the measured spectrum, being 42.5 cd/m^2 at 490 nm and 34 cd/m^2 at 680 nm, and even lower at the ends of the visible spectrum. The photometric field of 3° was viewed through an ocular slit, whose size was 0.2 mm × 1.25 mm in wavelength region from 490 to 700 nm and two to four times larger at the ends of the measured spectrum. The reference field luminances used by Gibson and Tyndall correspond to troland values of about 43 Td at 580 nm, 11 Td at 490 nm, and 9 Td at 680 nm.

Gibson and Tyndall divided the 52 observers into two groups of 26 in each, named «good» and «poor», on the basis of their ability to duplicate the ratio values in the main spectral region on different days. The «good» observers were given a double weight in the final average curve of the Gibson and Tyndall step-by-step measurements. The values of the final average curve based on the experimental data of Gibson and Tyndall are presented in Table 1. The values beyond the measured wavelength region from 430 to 740 nm were extrapolated.

4. COMPILATION OF VISIBILITY DATA

Substantial contribution to the paper of Gibson and Tyndall (1923) was given from their extensive analysis and critical review of the previously introduced data of Coblentz and Emerson (1918), Hyde et al. (1918), Ives (1912 e), Nutting (1914), Reeves (1918), So (1920), and the average data recommended or adopted by Ives (1919), Priest (1920; 1922 a, b), and I.E.S. Gibson and Tyndall carefully compared their own results with those of their predecessors and, informed by the prevailing theories of the day, noted that the visibility curve must satisfy two requirements. Firstly, the average visibility curve should give approximately 581.6 nm centre of gravity for a Planckian radiator at

2077 K. The wavelength centre of gravity is that wavelength which divides the area under the «visibility curve» in half (Kaiser, 1981). Secondly, the visibility curve had to be a representative average of the extensive visibility data as directly measured.

Gibson and Tyndall deduced that the I.E.S. visibility data fulfilled these two requirements adequately well and decided to consider the I.E.S. data as a basis for the new visibility curve. However, the I.E.S. curve was not a good representative of the accumulated data of the several studies reviewed by Gibson and Tyndall in the wavelength region from 510 to 550 nm. Thus, Gibson and Tyndall chose the values of Coblentz and Emerson's data, which were very close to the experimental data of Hyde et al., in this region and pieced together with the I.E.S. curve. This change shifted the wavelength center of gravity from its desired value of 581.6 nm. Accordingly, a corresponding increase in values greater than the center of gravity was needed to retain the balance. In the wavelength region from 650 to 690 nm the majority of the reviewed data lay above the I.E.S. curve. Therefore, Gibson and Tyndall slightly increased the values of the I.E.S. curve in the wavelength region from 650 to 690 nm, continuing the changes to 620 nm to produce a smooth curve. Slight additional changes were reported by Gibson and Tyndall at 560 nm and at 720 nm. Fig. 1 illustrates the construction of the $V(\lambda)$ curve in the way it was put together from several pieces.

The other parts of the visibility curve recommended by Gibson and Tyndall, i.e. wavelength regions 400–500 nm, 570–610 nm, 700–710 nm, 730–760 nm, were directly copied from the I.E.S. curve. Indeed, a major part of the present spectral luminous efficiency function $V(\lambda)$ is based on a curve, whose origins are not known. Thus it seems impossible to say exactly which methods the $V(\lambda)$ is based on, except in the wavelength region from 510 to 600 nm where it is based on the flicker data of Coblentz and Emerson.

Attention in the compilation process should be drawn especially to the blue end of the visibility curve where the I.E.S. data were accepted by Gibson and Tyndall, as they say «*for lack of any good reason for changing them, but the relative as well as the absolute values are very uncertain and must be considered as tentative only*». The revised I.E.S. visibility curve as given by Gibson and Tyndall was presented to the CIE and, as is generally known, the CIE introduced the values of the spectral luminous efficiency function $V(\lambda)$ in its 6th session in 1924 (CIE, 1926). The values of the $V(\lambda)$ function were recommended by CIE for general use as provisional ones, since it was obvious that the values might be incorrect at the extreme regions of the visible spectrum or in special viewing conditions. Despite the given notice considering particularly the short wavelengths, $V(\lambda)$ established itself in practical use. During the following decades it became evident that the $V(\lambda)$ function was underestimating the spectral sensitivity at the short wave-

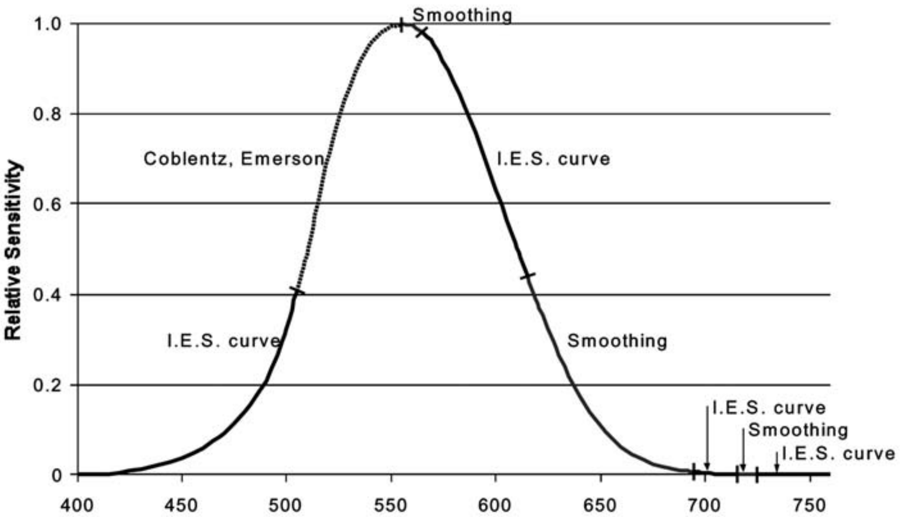


Fig. 1. Construction of the $V(\lambda)$ curve

lengths. Finally, in 1951 Judd clearly pointed out the low sensitivity of the $V(\lambda)$ curve below 460 nm and proposed a modification to the 1924 $V(\lambda)$ function (Judd, 1951). However, Judd's modification was slightly too sensitive below 410 nm and in 1978 Vos (Vos, 1978) presented second-order correction to Judd's modification. The $V_m(\lambda)$ function, modified first by Judd and then by Vos, was approved as a supplement to, not a replacement of, the $V(\lambda)$ function by the CIE in 1988 (CIE, 1990).

5. DISCUSSION

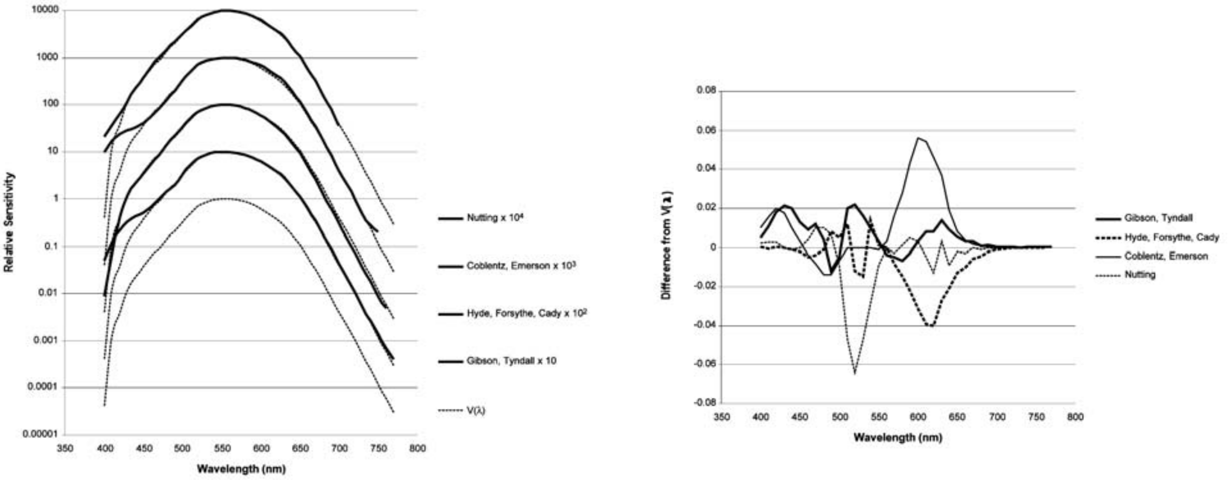
The $V(\lambda)$ function is frequently assumed to be based on experiments conducted under high (He, 1997) or photopic (CIE, 1978; Murdoch, 1985) light levels. This assumption is, both correct and incorrect at the same time, as evident from the paper of Hyde et al. (1918) where they state that «*It is seen that everywhere over the range of wavelength investigated the brightness was reasonably high and probably beyond that of the Purkinjé region except possibly at the extreme blue end of the spectrum.*» So, according to Hyde et al. the brightness was *reasonably high* but at the same time possibly in the Purkinje region. It is also to be noted here that the wavelength region measured by Hyde et al. was from 500 to 650 nm, thus the *extreme blue end of the spectrum* is considerably different from the present comprehension of the same matter. Furthermore, in the paper of Ives (1919), after recommending the field brightness of 7.9 cd/m^2 for natural pupil, he continues «*This brightness is about as high as can be easily handled with the photometric standards in ordinary laboratory use. It is, however, at the lower limit of the modern working illuminations, and considerably below normal daylight illuminations.*» In the 1910s and 1920s the *modern* working illuminations were substantially lower than working illuminations adopted today using the present lighting technology. Also, compared to today's laboratory settings, the photometric measurements of that time were obviously not conducted under «high light levels». Rather, the measurements in the early 20th century were conducted under the highest *possible* light levels.

The reference field illuminances and luminances used by Coblentz and Emerson, Hyde, Forsythe, and Cady, Ives, Nutting, Reeves, and So correspond to the natural pupil luminances presented in Table 2. The calculated natural pupil luminances, which are equivalent to the subject's adaptation luminance level, vary between 0.135 and 3.66 cd/m^2. It is today acknowledged that the upper luminance limit of the mesopic region cannot be precisely defined, as it is dependent on e.g. the size and eccentricity of the photometric field. According to the research of Kokoschka and Adrian (1984), the spectral sensitivity of the eye as measured by the brightness sensation shows a distinct dependency on the field size.

The CIE (1978) defines the upper luminance limit of the mesopic region as «at least several cd/m^2» or «about 3 cd/m^2», the value of 3 cd/m^2 is also presented in the IESNA Lighting Handbook (2000). According to the review by Le Grand (1972), the limit between the mesopic and photopic luminance regions is about 5 cd/m^2 for a 3° central field and according Kokoschka (1997) as well as Wiltshire (1997) the upper limit of the mesopic luminance region extend to about 10 cd/m^2. Thus, the adaptation luminance levels used by the several researchers presented in the present paper are actually in the mesopic region, or at least very close to the limit between the mesopic and photopic region. This implies that the investigations to establish the $V(\lambda)$ actually concerned mesopic vision, where both rods and cones contribute to vision, in vision beyond the central fovea. According to the review by Le Grand (1968) the area of the central fovea, from which rods are entirely absent, is in diameter from 0.5° to 1.67°. In the presented investigations the photometric field sizes varied from 1.5° to 7°.

Nevertheless, the drawback in the blue end of the $V(\lambda)$ function is not due to the lighting conditions under which it was established but rather the procedure (how it was compiled). In the compilation process Gibson and Tyndall were guided by the prevailing theory of the rule of the centre of gravity, and the requirement that the visibility curve had to be a representative average of the extensive visibility data as directly measured. Moreover, the decision to consider the I.E.S. curve as a basis for the new curve influenced the compilation process.

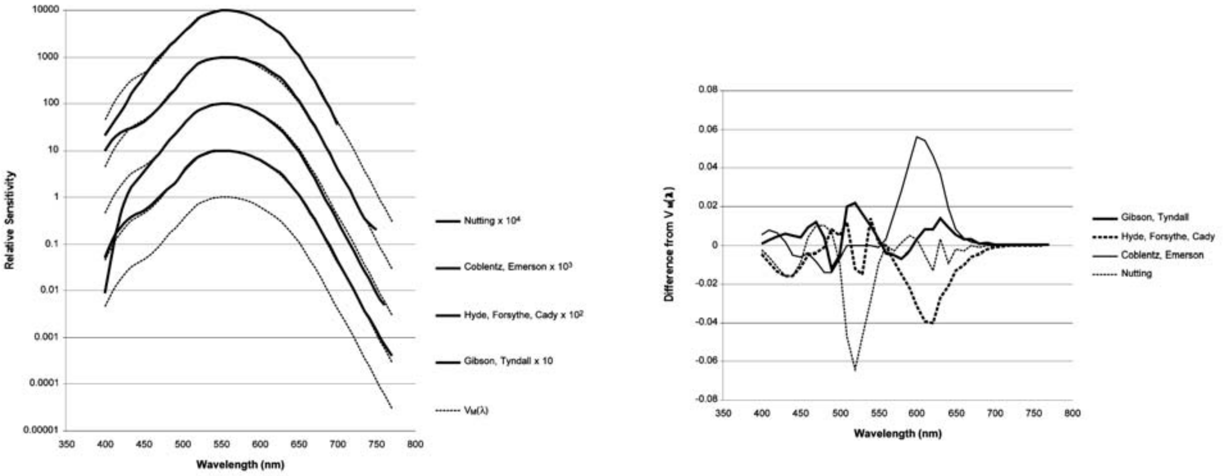
At present we are free to consider the experimental visibility data reviewed by Gibson and Tyndall, ignoring the outmoded requirements and



a) *b)*

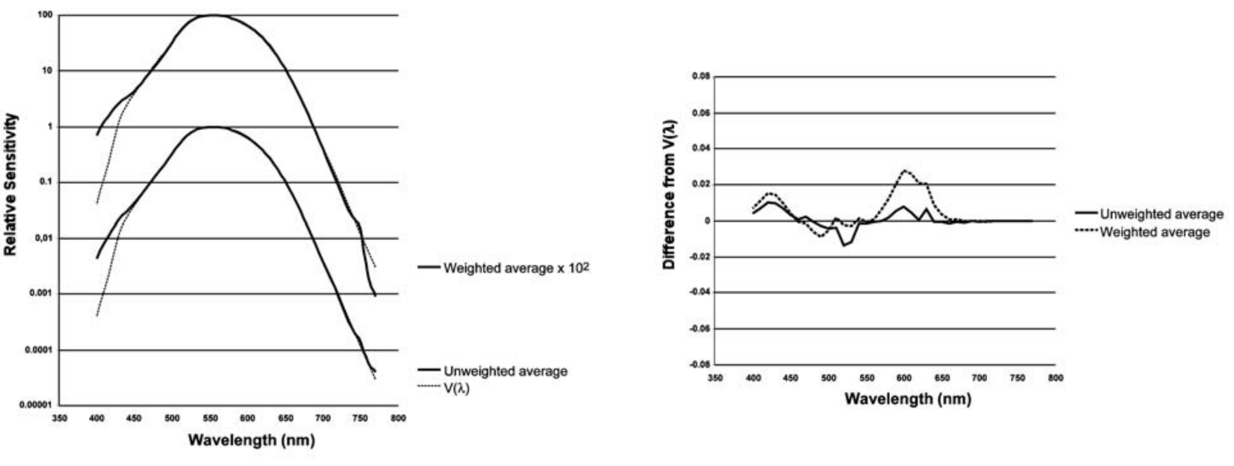
Fig. 2. *a* — The spectral sensitivity curves based on the experimental data of Gibson and Tyndall (1923), Hyde et al. (1918), Goblentz and Emerson (1918), and Nutting (1914) against the $V(\lambda)$. For clarity, the data of Gibson and Tyndall, Hyde et al., Coblentz and Emerson, and Nutting are multiplied by 10, 100, 1000, 10000, respectively; *b* — The differences in spectral sensitivity curves of Gibson and Tyndall, Hyde et al., Coblentz and Emerson, and Nutting, from the $V(\lambda)$ curve in relative sensitivity units

speculating on alternative visibility curves that Gibson and Tyndall could have obtained. In concentrating on the erratic blue end of the $V(\lambda)$ curve we can examine the experimental data of Gibson and Tyndall, Coblentz and Emerson, Hyde et al., and Nutting, since these were the four studies that provided the experimental visibility data in the blue wavelength region down to 400 nm. Fig. 2*a* illustrates these four visibility curves against the $V(\lambda)$ curve in logarithmic scale and Fig. 2*b* illustrates the absolute difference of these four curves from the $V(\lambda)$ curve in relative sensitivity units. It is evident that most of the data lie above the $V(\lambda)$ curve in the wavelength region from 400 to 460 nm, except the curve of Hyde et al. which follows the $V(\lambda)$ curve quite closely. Fig. 3*a* and 3*b* illustrate the same four visibility curves in analogous manner than Fig. 2*a* and 2*b*, now against the Judd modified $V_m(\lambda)$ curve. Fig. 3*a* and 3*b* present that the values of the Gibson and Tyndall as well as the



a) *b)*

Fig. 3. *a* — The spectral sensitivity curves based on the experimental data of Gibson and Tyndall (1923), Hyde et al. (1918), Goblentz and Emerson (1918), and Nutting (1914) against the $V_m(\lambda)$. For clarity, the data of Gibson and Tyndall, Hyde et al., Coblentz and Emerson, and Nutting are multiplied by 10, 100, 1000, 10000, respectively; *b* — The differences in spectral sensitivity curves of Gibson and Tyndall, Hyde et al., Coblentz and Emerson, and Nutting from the $V_m(\lambda)$ curve in relative sensitivity units

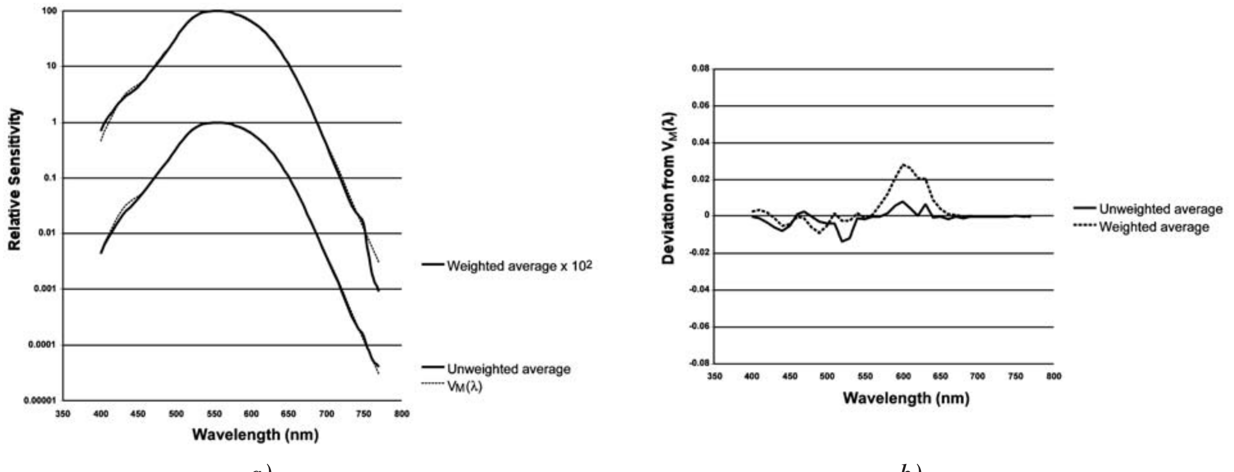


a) *b)*

Fig. 4. *a* — The spectral sensitivity curves based on the unweighted and weighted average of the experimental data of Gibson and Tyndall (1923), Hyde et al. (1918), Coblentz and Emerson (1918), and Nutting (1914) against the *V*(λ). For clarity, the unweighted average is multiplied by 100; *b* — Differences in the unweighted and weighted average curves of Gibson and Tyndall, Hyde et al., Coblentz and Emerson, and Nutting from the *V*(λ) curve in relative sensitivity units

Coblentz and Emerson visibility curve are in close agreement with the $V_m(\lambda)$ curve in the short wavelengths.

Now, if we calculate an unweighted average of the four aforementioned studies and an average weighted by the number of observers in each study, we obtain two curves, both of which are in better agreement with the modified $V_m(\lambda)$ curve than the $V(\lambda)$. Fig. 4*a* presents the unweighted and weighted averages against the $V(\lambda)$ curve in logarithmic scale and Fig. 4*b* presents the absolute difference of these average curves from the $V(\lambda)$ curve in relative sensitivity units. Furthermore, Fig. 5*a* and 5*b* present the two average curves against the $V_m(\lambda)$ curve in analogous manner than Fig. 4*a* and 4*b*. Interestingly, the unweighted average is actually in better overall agreement with the $V_m(\lambda)$ curve than the weighted average. This implies that had they not been guided by the rule of the center of gravity, Gibson and Tyn-



a) *b)*

Fig. 5. *a* — The spectral sensitivity curves based on the unweighted and weighted average of the experimental data of Gibson and Tyndall (1923), Hyde et al. (1918), Coblentz and Emerson (1918), and Nutting (1914) against the $V_m(\lambda)$. For clarity, the unweighted average is multiplied by 100; *b* — Differences in the unweighted and weighted average curves of Gibson and Tyndall, Hyde et al., Coblentz and Emerson, and Nutting from the $V_m(\lambda)$ curve in relative sensitivity units

dall might have obtained a curve in very close agreement with the modified $V_m(\lambda)$ curve. After all, both the weighted and unweighted averages are *representative averages of the experimental visibility data as directly measured*, as the second requirement guided by Gibson and Tyndall states.

The $V(\lambda)$ curve has been the basis of all photometry for over 80 years. The question for the vision and lighting community is whether we will go on with the $V(\lambda)$ for the next 80 years or whether we are willing to take up the challenge to re-establish the basis of photometry? Is the lighting community ready to leave behind a practice that has been used for 80 years in trade, research, and all lighting practice? Is it willing to rework the whole system? It is at least worth bringing to general knowledge the actual process which led to the $V(\lambda)$ and acknowledging its limitations in order to start a discussion on the future of $V(\lambda)$ not least because all today's lighting research is based on the 80 years old $V(\lambda)$.

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